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Concept Study of Variable Area Fan Nozzle for Ultra-High By-Pass Ratio Turbofan Engine

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Abstract

The next generation of the UHBPR turbofan engines can have BPRs of up to 20. These engines require a significant step forward in the low pressure system technologies. Such a new low pressure technology can be achieved through an innovative fan design with a low fan pressure ratio and a radically increased fan diameter compared to the current conventional turbofan engines. The aerodynamic stability of such large fans is, most likely, very sensitive against the backpressure variations. The back pressure regulation of such a large fan, specially during the take-off operation, can be achieved through the introduction of a Variable Area Fan Nozzle [VAFN]. The European Union supports within the 7th Framework the research activities for these new low pressure systems through the program ENOVAL [1].

Nomenclature

BPR	By-pass ratio
ENOVAL	Engine module validator
EEC	Electronic engine control
FP	Funding Program
IFS	Inner fixed structure
LE	Leading edge
SFC	Specific fuel consumption
TRU	Trust reverser unit
TRL	Technology readiness level
TE	Trailing edge
UHBPR	Ultra-high by-pass ratio
VAFN	Variable area fan nozzle

Keywords

Ultra-high by-pass ratio turbofan engine, variable area fan nozzle, by-pass ratio, inner fixed structure, core engine fairing, nozzle flaps, nozzle throat cross-section area.

Introduction

This paper introduces different types of VAFN concepts, suitable for a given range of nozzle area variations. An approach to derive the design space for a typical variable nozzle is described, two concepts are selected for detailed design studies. A method to determine the nozzle throat area and a study of the throat area behavior on both the concepts is shown. A comparative assessment on their individual design parameters was performed and at the end of both concept descriptions, the main 3D design parameters, together with their actuation possibilities, are discussed.

VAFN for the UHBPR turbofan

The target of the ENOVAL project is to support the reduction in CO_2 and noise emissions by investigating UHBPR turbofans with a new low pressure technology. The aim is to design an innovative fan with a reduced fan pressure ratio and with a large diameter [3]. A VAFN can be used to improve the fan system stability (stall and flutter limits) associated with those large diameter fans. It offers the potential to respond to the regular and quick changes in the fan operating points, allowing it to work at the optimum efficiency.

With the introduction of large fans in UHBPR engines, together with low pressure system technologies, the fan tip Mach numbers will decrease [3]. This will result a lower noise from the fan side. A VAFN could play an important role in reducing the overall noise signature. Because during take off, a VAFN with an increased nozzle exit cross-section, can reduce the jet exit velocity and therefore the jet noise which depends on the nozzle exit velocity [4].

Functionality of a VAFN

A general function of a nozzle is to regulate the expansion process of the exhaust gas by converting the pressure energy of the flow into kinetic energy.

The key function of a VAFN is to modulate the effective nozzle area of the fan system as an integral part of the engine. That means, a VAFN system varies the fan nozzle cross-section area at a specific flight stage, resulting in a better performance behavior. Specific variable values, such as back-pressure for the fan, can be used to operate the fan in its optimized performance point at each flight stage. The functionality of a typical VAFN system can be realized through the following three major units:

- Schedule -unit

  This function represents the interaction between the EEC unit and the VAFN. The schedule unit of the VAFN collects the actual flight and engine parameters and triggers the deployment of the VAFN to the required nozzle exit-area. This unit ensures a two way transfer of the data and the failure reports between the monitoring unit and EEC unit.

- Monitor-unit

  The monitor unit detects failures in the VAFN deployment and the aero line position and infers the actual nozzle area during the whole VAFN operation. This unit reports any failures back to the schedule unit for commanding changes in the nozzle area.

- Deployment-unit

  The deployment unit (actuator module) acts on the signals and move the VAFN by the calculated magnitudes. It enables the positioning of the VAFN to provide the aero line which is required by the power plant.

Concept development methodology

There are two major nozzle parameters which cover most of the functional requirements for a VAFN. These are the effective throat area and the nozzle pressure ratio. Both values have been used for the performance data calculation of the engine. It can be interpreted that these two values of the VAFN system are representative for most of the other operational and functional requirements.

Initially, a patent search was done to get an overview of the existing VAFN concepts. The study was focused on the concepts, which are suitable for the large turbofan engine with ultra high bypass ratio. A research in different patent databanks [2] showed that most of the concepts were developed for smaller turbofan engines or military jet-engines. For large turbofan engines two major design spaces were identified. One with enough design space under the inner fixed structure (IFS), also known as core engine fairing. Another potential design space for the VAFN is the nacelle structure near the nozzle exit. Both design spaces were considered to develop the various VAFN concepts.

Before creating the first preliminary concepts, a simplified study was done to assess the consequence of the variation in the throat section area. The aim was to derive the dimensions of the design space for the VAFN for a given range of nozzle exit area change and to determine the basic dynamic behavior of the VAFN. The 2D aero lines (nacelle and IFS) of the datum configuration from ENOVAL project were used. Three configurations, radial displacement of the outer radius, the axial displacement of the nozzle TE and the radial displacement of the inner radius, were examined to study the change in nozzle throat area as a function of the displacement magnitudes. Figure 1 shows an overview of the three configurations with their variable parameters.

For each configuration, only one end of the throat section was moved. The results showed that the second configuration, with the axial translation of the nacelle, required the largest displacement compared to the range of the other two configurations with the radial translation. Due to the consumption of the large design space for the translation and also due to the existence of many similar VAFN concepts in the market [2], the configuration 2 with the axial translation was not considered further. The following work was therefore focused on the other two configurations with the radial change in throat area section.

Due to the fact that the change in the throat area section with the third configuration occurs at much lower radius than that of the first configuration, the design space for the throat area change required by the third configuration is larger. The same applies for the variation resulting a throat area change. As the UHBPR turbofan engine offers a nozzle structure at a much larger radius than the conventional turbofan engine, the magnitude of translation of the VAFN structure at the nacelle is smaller than that at a conventional sized nacelle.

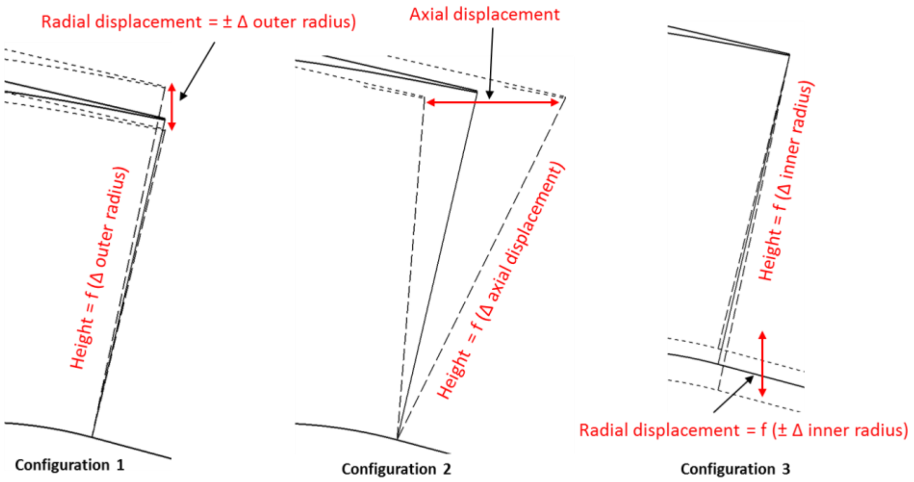

Figure 1: Basic kinematics configurations

Preliminary VAFN concepts at the outer nacelle

Considering the range of the radial change at the outer nacelle, few different designs for a VAFN were accessed. The use of flaps was preferred at the outer nacelle as they offer the required radial change at the throat section with a relatively small amount of movement, mostly angular. The following two designs were selected for the concept development. In both of the designs, the nacelle structure in the vicinity of the nozzle was replaced by segments of movable flaps.

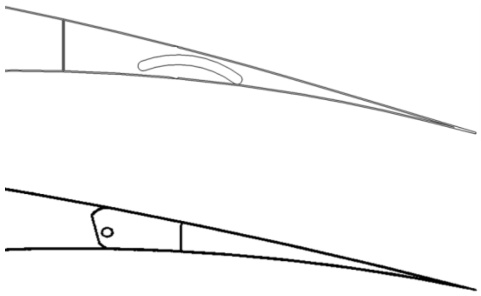

Figure 2: Preliminary VAFN concepts at outer nacelle. Flaps at rails (top), flaps at pin (down).

Each segment is a rigid structure and consists of an inner and outer skin of the nacelle. In the first design (top in Figure 2), the flaps were placed on rails using roller bearings on both sides. In the second design, the flaps were fixed rotationally with bearings around the pin like fixture. Considering the 3D design, the angular size of each flap sector segment (blue in Fig. 3), depends on the number of flaps at each side of the cowl. Between two flap-segments and similarly between a flap-segment and the stationary walls (pylon and lower cover wall), there are rigid (fixed) portions of the nacelle (right side in Fig.3). They provide the necessary design space for the fixtures containing the rail or pin mechanism which holds the flap segments at their position. The pin or the rail mechanism is fixed at an inclined surface into the fixture (see example of rail at right side in Fig. 3). This design feature (placement of the rail or the pin at inclined surface) provides the moving flap segments a rotational axis which lays in the BPD domain (position of rotational axis is shown in detailed Figure 7). This design feature enables the moving flap segments to produce less steps and gaps between them and the stationary structure of the nacelle. The flap segments can be moved into the internal space, between the outer and inner skin of the stationary nacelle structure upstream of the flaps. The sealing segments will be used to prevent leakage and to reduce the aerodynamic losses due to steps and gaps between the moving and fixed edges of the VAFN. The difference between both the designs at the outer nacelle regarding variation of the throat section plane is that the configuration with the pin fixture results in a radial variation in throat section plane and the other design is a combination of angular and axial variation in throat section plane. Due to this combined motion at the rail fixture, this concept offers a good possibility to reduce uneven gaps and steps in the structure.

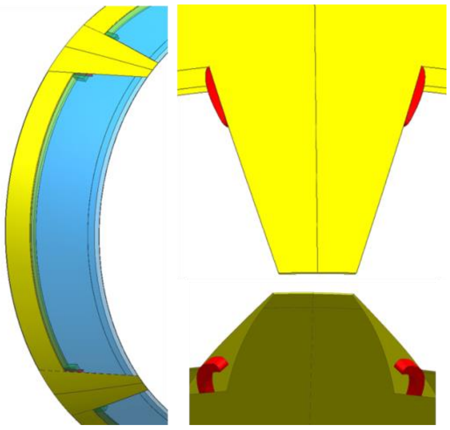

Figure 3: Nozzle flap segment fixed between inclined fixture segments. Top view of inclined fixture segment with rails (right-up), view from inside (right-bottom)

Both concepts require a linear actuation system for the translation.

A throat section study of both concepts showed that they are able to deliver the required range of change in the throat section area. The design space for these concepts is limited upstream by the dimension of the blocker doors of the TRU (how far the TE of the blocker doors is placed) and the internal design space in the nacelle including the dimensions of acoustic liner and sealing segments.

Preliminary VAFN concepts at the inner fixed structure, IFS

The second configuration, i.e. the change in throat section through modifying the inner fairing structure, can also be realized by different VAFN kinematics. Three different types of designs were accessed and their kinematic were studied (see Figure 4 with all three designs).

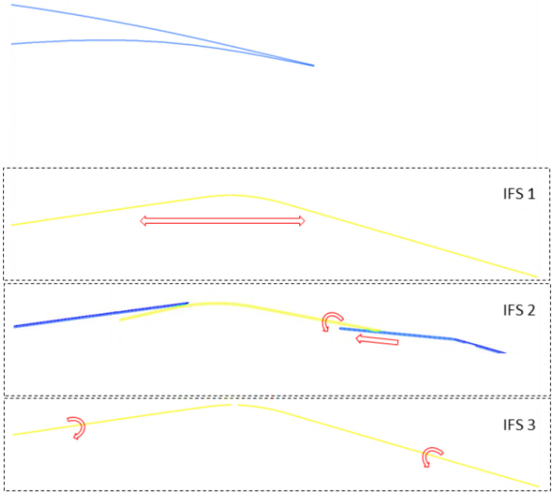

Figure 4: Preliminary VAFN concepts at IFS.

The first concept, IFS 1 in Fig. 4 ,works with linear translation of the inner structure in axial direction. The geometric analysis of the throat section area has shown that a linear translation of the IFS in axial direction requires a large design space to produce the required maximum change in nozzle throat area. The linear movement of this design opens a large surface area of the internal structures, which needs to be covered with extra sheet metal (weight penalty) to produce a clean air flow in the BPD.

The second concept, IFS 2 in Fig. 4, has a dual kinematic which consists of an angular and linear translation of the rear IFS segment. With this modification it was able to achieve high values of the over-area change. The kinematics of IFS 2 consists of a linear translation of the rear IFS segment along an inclined railing fixture and simultaneously its angular movement folding it inwards under the fixed fairing structure upstream. This configuration was able to result in the maximum required variation in the throat section area but also resulted in a kink in the rear part of the IFS, which could result in an extra aerodynamic drag and loss in overall performance.

The third design IFS 3 in Fig. 4 was developed consisting of many segmented structures. The whole IFS was divided into two portions, a forward IFS upstream in the BPD and a rear portion up to the vent nozzle. Each of them was subdivided into segments, which were rotationally fixed with the rigid stationary structure at one end. These segments can be folded inwards resulting in a throat area change of a given range. An under-area can be produced through opening (folding out) those segments outwards in radial direction. The kinematic study of this concept has shown overlapping surfaces between the segments in axial and rotational direction around the engine axis. This concept can be actuated through different actuation arrangements depending on the design space available under the IFS. In comparison with the first two IFS designs, this concept will deliver better aerodynamic results as there are no sharp kink and steps in the structure if the full length of the BPD inner structure is used. It also offers weight benefits compared with the outer nacelle concepts as the VAFN mechanism is placed at a smaller radius requiring less material.

On the contrary, in comparison with concepts at the outer nacelle radius, concepts at the IFS with a smaller radius need to cover larger displacements. A ultra-high by-pass ratio engine provides a large design space under the IFS that can be used ideally for large translation paths.

The aerodynamic effects of both the VAFN concepts, IFS 3 and flaps at outer nacelle, have to be studied for few defined flight cases which require the maximum variation in the throat area change. The parameters that can be influenced by the IFS concept are the after-body drag and flow interaction with the wing and aircraft body. This may be enforced due to the change in the after body inclination angle with respect to the engine axis. Another aspect that can be traded against the VAFN benefits is the noise signature produced by the IFS concepts, only during the over-area variation at take-off. The kinematic of the IFS segments results in a decrement in the wetted area, where noise absorbing liner segments are placed.

VAFN Design assessment

The technological targets for the VAFN are mostly defined through the requirements derived with system engineering methods. For an early design assessment of a concept only a few requirements were considered. These were covered by mainly the range of the throat section over-area and under-area for the BPD nozzle. The movement of the throat section plane upstream, which could produce a convergent-divergent nozzle, was also an important parameter to be studied during the design assessment.

For the design assessment during the preliminary phase, two VAFN concepts, concept IFS 3 (Fig. 4) and the concept nozzle with flaps on rails (Fig. 2), were selected. A range from a slight closure (throat area change) up to a significant opening of the throat area change was studied. The throat area calculation was done by considering the so called “rolling ball method” on the 2D geometry.

Concept folding IFS segments

This type of VAFN can be specified through the major design features such as the position of the section plane, which divides the IFS into two major parts. This dimension depends strongly on the arrangement of the IFS aero lines for maximum over-area position. The over-area is created through folding the IFS aero lines inwards, in other words, the IFS structure will be shifted from a larger radius (upper position) towards the lower radius (lower position, maximum over-area). If the section, which divides the IFS into two parts, is chosen too far in downstream (at after-body) then the VAFN will create a hump during over-area generation and will result in a flow distortion at the after-body, increasing the after-body-drag. The same applies if the section is chosen at too far at upstream position into the BPD, which can result in a flow disturbance, decreasing the nozzle performance. Both IFS sections (upstream and downstream portions) were subdivided into many sector segments.

The second major design parameter is the location of the rotational axis of the IFS segments. During the maximum over-area constellation, a kink occur near the rotational axis area (see Fig.5) which can disturb the air flow. For the following throat section study, a configuration was selected with the interface between rear and front IFS at an position upstream of the highest IFS location.

2D axis-symmetry geometry was considered and the nozzle throat area was defined by the 360° rotational surface, without considering the cross-section areas of the pylon and the supporting struts. A thickness of 40 mm for the liner acoustic segment at the IFS was taken into account. This thickness is an important measure to design the overlapping surfaces in axial direction between the front and rear IFS segments (see Figure 6 below). To determine the type of the nozzle (whether convergent or convergent-divergent nozzle), the rolling ball method was used at three locations. Figure 5 shows their positions and a detailed view of the gap and step between the segments. The *plane IFS front* is fixed at the highest point (edge) of the IFS front segment, the *plane IFS rear* is placed floating at the hump area of the IFS without any fixed point constrain and the *plane TE* with a fixed point constrain at the trailing edge of the nozzle (see Figure 5). The kinematic of this concept is realized in which the IFS front and the rear segments were pivoted at their rotational axis (see Figure 5 at bottom corners). The throat section was defined simply by a connecting line between the intersection points of a bi-tangential circle between the inner nacelle surface and IFS surface. The geometry of the IFS front segment was constrained to slide over the IFS rear segments. For the under-area movement, the rear segments were extended to result in a relatively smooth stream flow over the IFS. A range of pivot angles at the rotational axis was studied to produce the required range of throat area change. The position of the rotational axis, which are also the fixture location of the segments, was selected largely apart from each other (LE of IFS near guide vane and TE of IFS near vent nozzle). The 2D throat section study was done by pivoting the IFS rear segments. During the study, the lengths of the three defined planes (Figure 5) and the area created by them were measured. The change in the axial position of the planes were also noticed. The range of angle change at the IFS front panel was determined after the IFS front segments followed the rear segments along the defined sliding constraints.

Over-area movement of folding IFS segments

The over-area movement was realized by folding the IFS segment inside the inner design space. During the motion, the IFS front segments do slide over the rear segments. This constellation resulted in a constant step of 0.5 mm (assuming that a sharp edged sealing will be used at the edges of IFS front segments). During the whole pivot range, the smallest throat area was produced by the *plane TE* at the trailing edge of the BPD. This result ensures that, for the given range, no convergent-divergent nozzle was produced as the smallest throat area laid at nozzle TE.

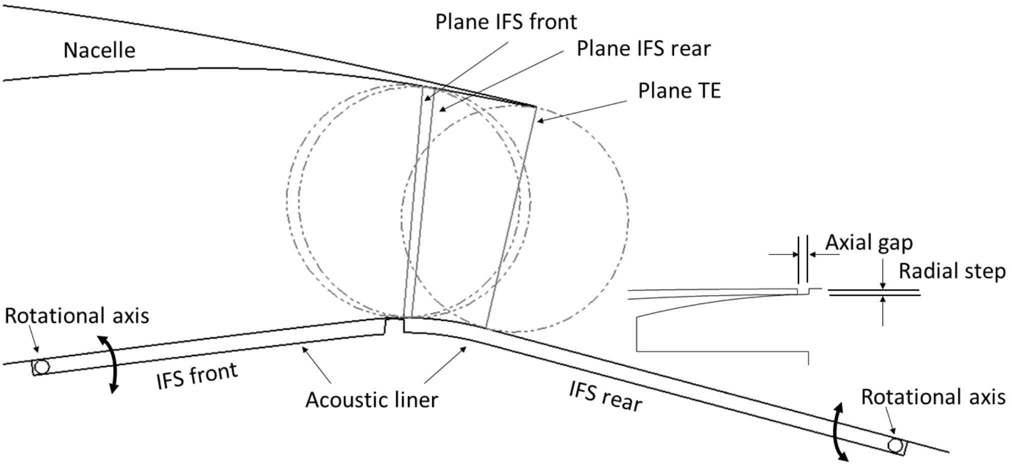

Figure 5: 2D geometry for throat section study (left) and overlapping area (right)

Under-area movement of folding IFS segments

During the under-area motion, the IFS segments move upwards in the BPD flow. A structure extension at the LE of the IFS rear segments helped to prevent the leakage into the IFS inner space. The segments of the rear IFS were extended along a curve in such a way that the front IFS segments slide over the extended surface and does not create big steps downstream.

From this configuration, the 2D study revealed that the design space for the maximum over-area was almost five times more than the space for under-area variation. The following Figure 6 shows a 3D side view of a section and a top view at the IFS segments (up-right). The overlapping area in tangential direction is placed in the flow direction. The two other pictures in Figure 6 (below) are showing a possible configuration of the actuation module. Each IFS segment is connected through the drag links with the actuation module which uses a sliding mechanism to pivot the VAFN. That actuation module contains many rail segments which are fixed at a C-structure (half-ring). Each side of the engine (D-duct configuration) has such a C-structure which is fixed at the internal vertical walls of the D-duct in such manner that the whole ring follows the opening mechanism (for maintenance) of the duct. Those C-structures, together with the fixture of the IFS segments at their rotation axis, are designed to hold and to transmit the loads of the VAFN to the load carrying static structure.

Concept flap-nozzle

The study of design parameters resulted in the following major conclusions. The size of the flap was mostly constrained by the axial position of the blocker doors and the position of the rotational axis (see Figure 7). For the required range of throat area change, the range of the rotational angle was calculated. The magnitudes of the angle were strongly dependent on the axial position of the rotational axis (Figure 7). During the over-area movement, it was found that the collision between the flap leading edge and the trailing edge of the stationary nacelle was not avoidable. Due to the presence of the blocker doors at the inner surface of the nacelle, the overlapping at the outer surface was taken into account.

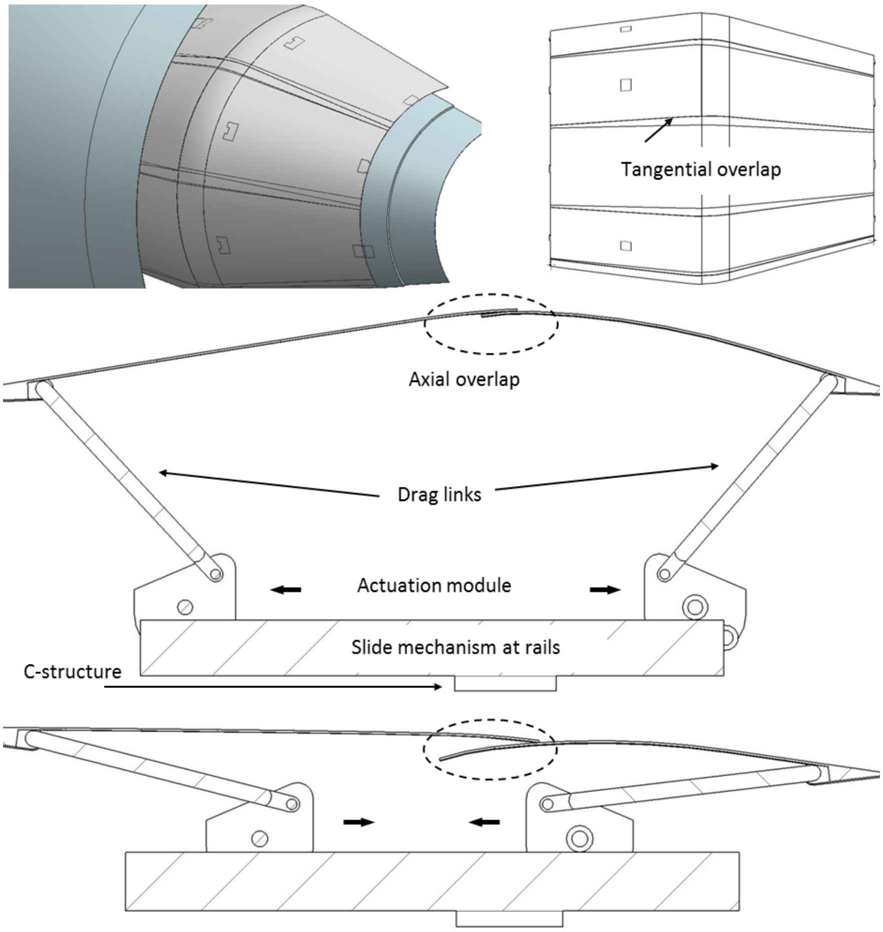

Figure 6: 3D view of the IFS segments (top left), area of tangential overlap (top right) and the possible actuation module with the axial overlapping between the segments

The part of the outer nacelle can be replaced with the flexible sealing segments, allowing the flaps to over run the trailing edge of the nacelle. The following conclusions were drawn from the study for under-area and over-area movements. The location of the rotational axis resulted from the design of the rail segments, which were fixed at an inclined surface (see Figure 3), resulting their center points be located in the BPD.

Under-area movement of concept flap-nozzle

To produce the given range of under-area change was not a problem with this concept. The 2D throat assessment showed that the required rotation to produce the under-area was sensitive to the axial position of the rotational axis. By shifting the rotational axis upstream resulted in a larger distance between the axis and LEs of the flaps. With the large radius a reduced magnitude of rotational angle was required to produce the same amount of variation in throat area. During under-area motion, the gaps at the outer surface and the steps at the inner surface of the flaps were noticed. The gaps can be covered by introducing the flexible sealing, fixed at the trailing edge of the stationary nacelle structure, stretching over the gap between the nacelle trailing edge and the flaps leading edges. The steps at the inner surfaces can be solved by using a rounded leading edge and, if required, also using a sealing. During the whole under-area movement the nozzle remained convergent.

Over-area movement of concept flap-nozzle

Due to the requirement that the VAFN should not produce any convergent-divergent nozzle, many iterations of the design parameter changes were necessary. This design assessment used the plane between the flap inner surface and the top point of the IFS. This divergence behavior of the VAFN was solved by moving the axial position of the rotational axis upstream in the BPD (see Figure 7). Due to this change, the inner surface could be moved with a larger rotational radius, avoiding a convergent-divergent nozzle. But this change also required the flaps to be longer, consuming more design space which could come in conflict with the blocker doors of TRU. On the other hand, the large rotation radius of the outer surface will generate a large overlapping area at the outer surface. That results in a need of large sealing segments to produce aerodynamic smooth flow at the outer nacelle surface.

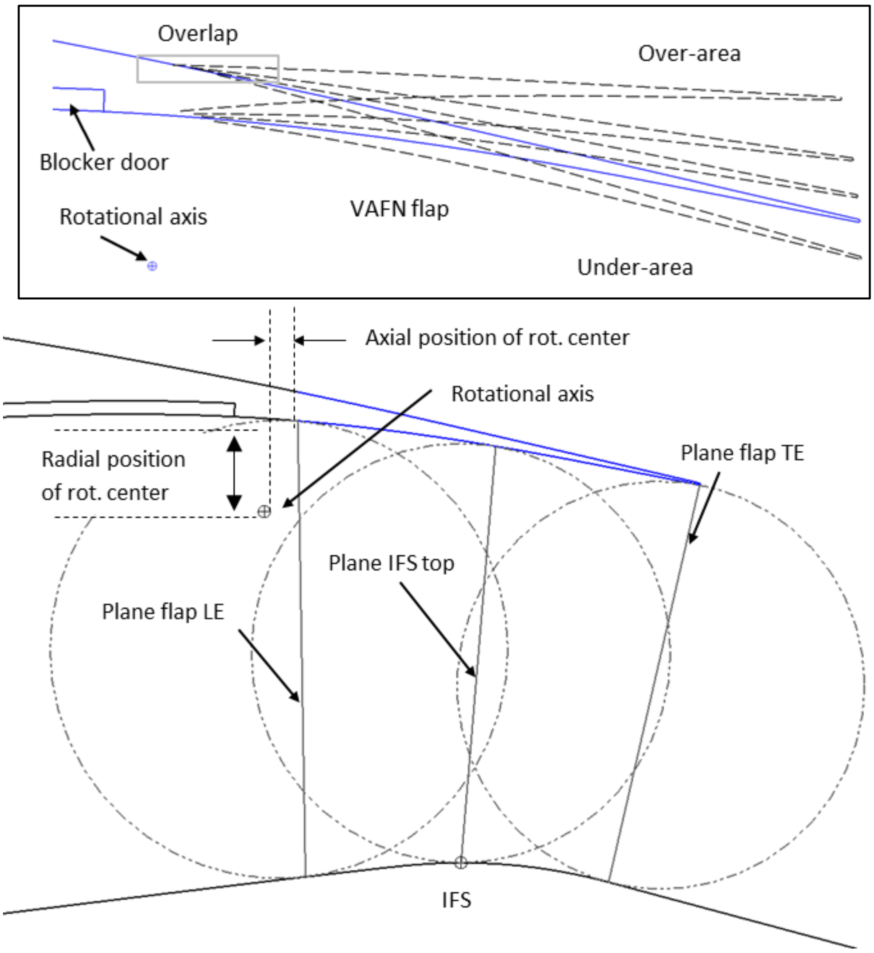

Figure 7: 2D view of the under- and over-area flaps (up) and the geometry for the throat section study (below)

Conclusion

This study showed different ways to derive the design space for a VAFN system for an UHBPR turbofan engine. Some few different VAFN concepts were studied for a range of nozzle area change relative to the nominal nozzle area. This comparative study showed that the creation of a large over-area faced many constrains in the design space at the outer nacelle. To avoid a convergent-divergent nozzle, the VAFN concept at the nacelle required a large design space (length in upstream), which came into collision with the blocker doors of the TRU. The other concept, at the IFS contour, proved more promising in resulting in a convergent nozzle during the whole required range of area change. It was found that this concept offers more design space than a VAFN at the nacelle. Due to that fact that VAFN at the IFS is completely covered by the BPD flow (which is not the case with VAFN with flaps at the nacelle), it may produce comparatively less aerodynamic losses and noise emission (caused due to interaction with outer flow).

A detailed aerodynamic assessment study on both the concepts is required to derive the absolute performance of both VAFN concepts and to optimize the 3D design features like steps and gaps.

Acknowledgement

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