SNECMA COUNTER ROTATING FAN AERODYNAMIC DESIGN LOGIC & TESTS RESULTS

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Abstract

The aim of this paper is to present the design logic that has driven the Counter-Rotating Turbo Fan (CRTF) baseline, and how experimental results meet VITAL objectives and match the preliminary CFD analysis that was performed before the manufacturing of CRTF blades.

First of all, we propose to conduct a global survey dealing with the main advantages of the CRTF concept and with some particularities linked to its aerodynamic behavior. We will highlight to some extent the major differences with conventional fans.

Key design parameters contributing to major aerodynamic and acoustic advances will then be presented in order to introduce the CRTF baseline design as developed by Snecma. We will also see to what extent other alternative designs developed within the VITAL program are affiliated to this baseline.

A third part will detail numerical analysis tools (mainly 3D RANS steady code) developed and used by the aerodynamic design team to fulfill performances objectives.

Lastly, a description of the experimental approach used to validate the CRTF aerodynamic behavior will then take place, detailing instrumentation, global performances results, and radial evolutions of major aerodynamic parameters. A comparison of these experimental data with some CFD results will also be provided.

Introduction

In order to meet ACARE 2020 objectives by reducing both the perceived noise and the fuel burn (and therefore NOx and CO_2 emissions), Snecma – within the framework of the VITAL program- has studied the CRTF concept in which the fan pressure ratio is obtained from two fans which rotate in opposite directions. The energy to be produced is distributed between the two fans, thus reducing the fan tip speeds which results in lowering the fan noise emission. Basically, VITAL CRTF targets a 6 EPNdB noise reduction per certification point (leading to a 15 to 18 EPNdB cumulated noise reduction) and an increase in fan efficiency of 2% compared with a year 2000 reference engine.

Snecma led the VITAL program, and in particular the WP2.4 dedicated to CRTF. Snecma coordinated the design, manufacture, instrumentation, testing and analysis involving various partners, including CIAM, DLR, Cenaero, Comoti, NLR, Onera and UPMC [1]. The designs performed in VITAL were much improved by the contributions from these academic partners and research laboratories.

A Counter-rotating fan baseline was designed by Snecma and tested at the C-3A test facility of CIAM [2](Turajevo, Russia) in order to provide the first building block of a whole aero-acoustic validation program. Following this first design, Snecma wrote detailed specifications for two new configurations that have been evaluated with the help of CIAM and DLR (Germany) for aero-mechanical design, and are being tested at the C-3A test rig. The purpose of these alternative designs is to identify effects of axial spacing, blade numbers and loading radial distribution while meeting requirements related to composite blade airfoils thickness. To a certain extent, the last design performed by DLR is meeting real engine specifications in terms of blade count (economic constraint) and axial length of this module (PPS weight constraint). In parallel with these CRTF tests, an existing conventional fan (SRF) was tested for test rig aero-acoustic calibration purposes.

Nomenclature

ACARE: Advisory Council for Aeronautics Research in Europe
ADP: aerodynamic design point
BPR: by-pas ratio
BPDV: by-pass duct valve
CDV: core duct valve
CFD: computational fluid dynamics
CIAM: Central Institute for Aviation Motors
CRTF: counter-rotating turbo fan
DLR: German Aerospace Center
E13D12: fan by-pass adiabatic efficiency
LPC: low speed compressor or booster
Ni: fan i rotational speed (rpm); i=1or2
Nr: fan reduced speed
PCNR: average percentage of nominal reduced speed, i.e. 0.5*(N1r+N2r)
PPS: power plant system
P13Q12: fan by-pass pressure ratio
RANS: Reynolds averaged Navier-Stokes
SLS: sea level static
SOA: state of the art
SRF: Single-stage Reference Fan
s/C: pitch to chord ratio (inverse of solidity)
URANS: unsteady Reynolds averaged Navier-Stokes
VITAL: en**vi**ronmen**tal**ly friendly aeroengine
W2AR: fan corrected mass flow
η: adiabatic efficiency
π: total pressure ratio

CRTF design: main differences compared with classical fan design

General remarks

The initial assumption with regard to the CRTF is to achieve the same pressure ratio as a conventional fan with 2 counter-rotating stages rotating significantly slower, which theoretically results in improved performance (aerodynamic and acoustic). Therefore, for propulsive performances equivalent to those of a conventional fan, this technology offers a potentially advantageous solution for reducing fan noise.
N. Tantot [3] highlights that replacing the conventional fan by a dual stage counter-rotating fan is also a good solution to reduce the outer diameter constraint : indeed, overall secondary pressure ratio can be kept at a rather high value (~ 1.4 to 1.6) which allows for a reduced fan diameter, and therefore a benefit in weight and fuel burn.
The challenges of the CRTF concept can be summed up as follows: reduce the noise level (by decreasing fan rotation speed), be competitive in terms of weight and cost (by limiting fan blade count and diameter increase), and improve specific consumption (by improving fan efficiency).

CRTF aerodynamics

The front fan ("fan1") acts as a conventional axial-flow fan: the flow deviated into the relative reference frame of fan1 produces the first compression. The rear fan ("fan2"), which benefits from the pre-rotation of fan1, creates a second flow deviation in its relative reference frame (2nd compression) and delivers at outlet a flow in a direction close to the engine axis, which avoids the need for an outlet guide vane (OGV). The successive flow deviations inside the two fans are illustrated in *Fig. 1*.

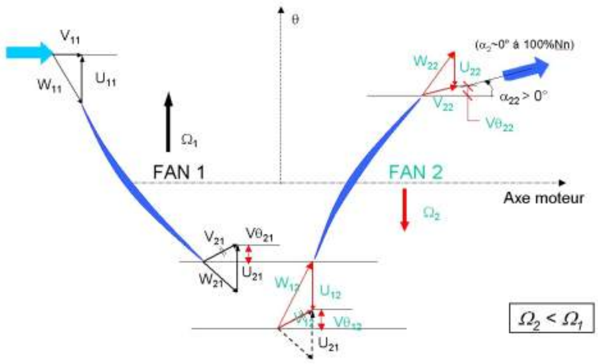

Fig. 1 –CRTF vectors diagram

Design peculiarities

While the design of the fan1 is similar to that of a conventional fan with low tip speed, the profiles and shape of the fan2 are difficult to design. One of the challenges to be met from an aerodynamic design standpoint is to obtain a high enough isentropic efficiency on fan2 to ensure good overall efficiency without impairing the stability of this counter-rotating stage. This difficulty is tied to the supersonic nature of the flow over the entire height of fan2, to the interaction of the detached shock on the leading edge of fan2 with fan1 (*Fig. 2*), to the interaction of fan2 with tip vortex produced by fan1, and lastly to the low aerodynamic load generally found on this second fan.

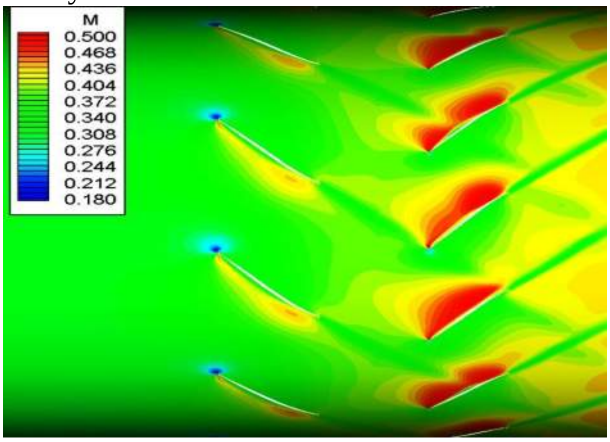

Fig. 2 - Unsteady Mach number field at mid-span height (CIAM calculation)

The reference design (CRTF1) produced by Snecma is quite ambitious, due to the low blade count per fan (in order to obtain a total blade count equal to or lower than that of single-stage fans in service) and to its high pressure ratio at a given tip speed.

A few key parameters of CRTF design, focusing on the differences relative to a conventional fan are detailed below:

- **average speed and N2/N1 speed ratio:**

The choice of the average speed and N2/N1 ratio is a compromise between aerodynamic efficiency, noise sources reduction and operability. They are also directly linked to LPC aerodynamic load and impact the torque ratio (C2/C1) of the LP turbine, and therefore its efficiency.

The final choices of N2/N1 and average speed made by Snecma in VITAL are a general compromise verifying the following rules:

- the **fan 1** rotation speed is chosen as low as possible, within the feasibility limits of this fan, in order to maximize its efficiency and favor the acoustics (reasonable aerodynamic loading to mitigate fan1 wakes and their interaction on fan2)
- the **fan2** rotation speed must be high enough to generate an acceptable booster load and to guarantee a fan2 choked configuration close to nominal design speed …but the **N2/N1 ratio** is preferably adjusted as less than 1, in order to favor fan2 configurations that are the least supersonic possible, and therefore to limit shock induced losses in the CRTF overall efficiency. The final N2/N1 value was fixed equal to **0.75**.

- **fan1-fan2 relative spacing:**

The axial spacing between the two fans is the result of a compromise to be found between the compressor module overall weight, the dynamics of the engine as a whole, the acoustics (fan1/fan2 interaction noise) and the aerodynamic efficiency of the CRTF system. On this last point, the interaction between fan1 wake and fan2 leading edge detached shock contributes to the overall efficiency of the stage.

- **solidity –blade count:**

The key factor that determined the number of blades used on VITAL was economic (total cost of ownership): the total CRTF blade count must be less than or equal to the blade count of a conventional fan. Therefore, the VITAL CRTF1 model was given **24 blades** in all (10 blades on fan1 and 14 blades on fan2), *Fig. 3*. The alternative design CRTF2.b, which has 20 blades (9 + 11), is even closer to the current target for an engine application.

Fig. 3 - Blade count 10x14 (Snecma- CRTF1)

The reduction in rotation speeds compared to a conventional fan allows some leeway for the s/C values while maintaining acceptable performance levels. Therefore, for the designs made in VITAL, we achieve pitch to chord ratios that are on average greater by a factor of 2 for hub cross sections, and 50% for the blade tip sections, compared with the 2000 state of the art.

Unlike a conventional fan, fan1 at design point operates in un-throttled configuration with the presence of a detached oblique shock, and fan2 is just barely choked – presence of a strong shock in the blade passage (*Fig. 4*), which directly influences CRTF speed line shape and makes it even more complex to achieve the stall margin objective at high-speed.

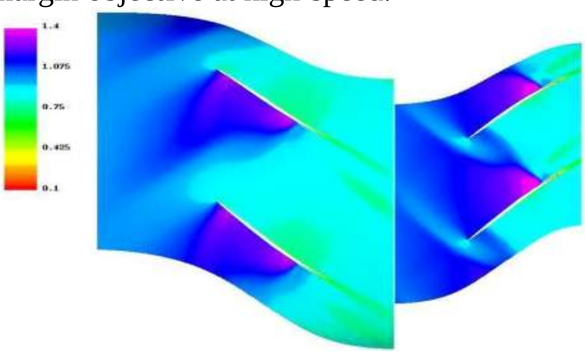

Fig. 4 - Mw1 field at 95%span height (CRTF1)

Lastly, for the CRTF1 baseline design, the main characteristics values generally used in aerodynamic design are compared to that of a baseline fan (2000 state of the art) as follows:

CRTF1 characteristics (ADP)	CRTF1 (fan1 /fan2) compared with reference fan (2000 SOA)
Specific flow	+4%
Tip speed	-35% / -51%
Speed ratio (N2/N1)	0.75
Blade count	10 / 14
Tip s/C	+64%/ +51%
Hub s/C	+101%/+119%
Aspect ratio (H/C)	-14%/ -25%
Chord ratio (C_{tip}/C_{hub})	+14%/+5%

VITAL WP2.4: design logic

The logic of the work driving the VITAL WP2.4 activities was to design a reference fan (SRF) and 3 configurations for the CRTF model fan rig, then to manufacture these new models at fan rig scale (scale factor 1:3) and finally to test the 4 model configurations in the rig for aero and noise performance evaluation. Optimizations and successive validations were carried out according to the following scheme:

- **SRF** fan design (22" diameter) based on 2000 engine cycle (acoustic reference)
- **CRTF1** fan design (22" diameter) based on CRTF engine cycle: considered to be the baseline design for preliminary assessment and characterized by a 10x14 blade count and an average tip speed reduced by roughly 40% compared with the SRF design
- A phase of detailed parametric studies was then launched in order to identify relevant parameters improving aerodynamic and noise performances (blade count, profile shape, 3D stacking, hub contouring, speed ratio, fan load split, etc) [4]. Based on the lessons learned during this parametric study phase, and according to the Snecma specifications and requirements update, 2 alternative concepts were then generated:
- **CRTF2.a** design (22" diameter) consists in CRTF1 blade aero-acoustic

optimization, as well as mechanical justification at rig scale, using the CIAM 3D-inverse optimization method [5] and matching new constraints relative to blade thickness (composite blade design constraints). Blade count, profiles stacking and axial spacing were kept unchanged compared with the CRTF1. Final evaluation based on Snecma CFD results indicated that despite increased profile thickness, optimization performed by CIAM made it possible to protect the efficiency level around cruise speed (*Fig. 5*).

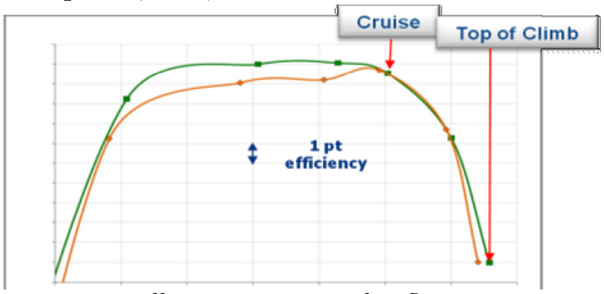

Fig. 5 – Efficiency vs. specific flow on cruise operating line: CRTF2.a (orange) – CRTF1 (green) from Snecma CFD results

- **CRTF2.b** (22” diameter) is a second variant entirely devoted to match economic constraints (low blade count – 20 blades maximum for both rotor1 and rotor2) and to be representative of a rotor module length consistent with realistic engine integration. Furthermore, this new design was intended to keep –as far as possible – aerodynamic and acoustic performances equivalent to those demonstrated on the CRTF1 baseline. DLR, based on a preliminary geometry already adapted to new specifications, and provided by Snecma, performed the whole aerodynamic and mechanic design at rig scale [6]. As for CRTF2.a, Snecma performed the final performance evaluation of CRTF2.b, and it appeared that despite strong design constraints, a benefit in efficiency was highlighted at high speed, with no penalty around cruise speed (*Fig. 6*).

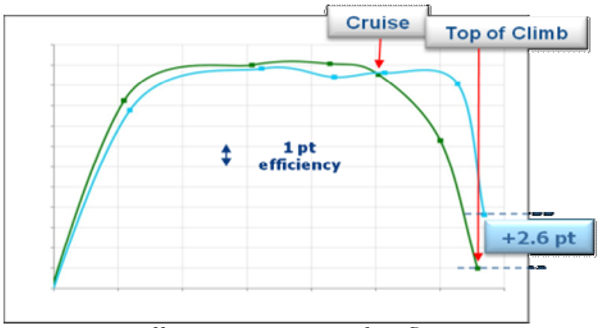

Fig. 6 – Efficiency vs. specific flow on cruise operating line: CRTF2.b (blue) – CRTF1 (green) from Snecma CFD results

Experimental set-up: CRTF1 – CRTF2.a

Model constitution

The CRTF1 model (outer diameter: 22 inches) is depicted in *Fig. 7*. A first module comprises a cylindrical performance bellmouth at fan inlet, and a removable turbulence control system (TCS) made of metallic spherical honeycomb mesh. The CRTF module is composed of fan1 (10 blades) and fan2 (14 blades). In the by-pass flow are located 10 radial struts at CRTF exit (no flow turning), a set of different fixed nozzles to perform acoustic tests and simulate several operating lines positions in the fan map, and one variable fan nozzle (BPDV) installed to perform aerodynamic fan mapping. Finally, the core duct includes a single-stage booster (IGV, rotor, OGV) whose main function is to extract air in core duct, and thus contributes to by-pass ratio control. Downstream, a system used to throttle the core flow (CDV) ensures a proper adjustment of the required BPR.
The same experimental set-up is of course available for the CRTF2.a and CRTF2.b test campaigns, including some additional improvements inherited from CRTF1 lessons learned (e.g. BPR adjustment).

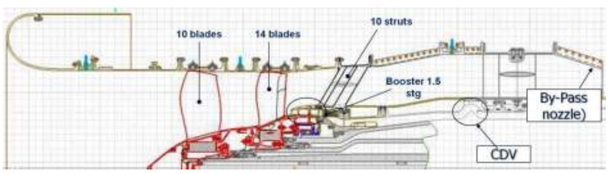

Fig. 7 – CRTF1 fan model as tested at the C-3A tests facility

Aerodynamic instrumentation

The aerodynamic instrumentation volume and characteristics remain rather conventional in terms of pressure and temperature characterizations: several measurement planes located in front, between and downstream from the fan blades are equipped with different radial rakes to build up Pt, Tt and flow angles profiles. Boundary layer rakes are used to provide accurate values of Pt profiles near walls and to detect potential flow separation zones (fan1 inlet, between fan1-fan2, and downstream from fan2). Core flow inlet and outlet planes were instrumented as well to verify the proper behavior of the single-stage booster. Static pressure taps (meridian lines) were implemented around core/by-pass flow splitter to characterize and track possible flow separation at off-design speeds.

Moreover, a dedicated test phase was equipped with 2 radial traversing probes to identify (Pt, Tt, flow angle) radial distributions behind the front and rear fans, thus making it possible to calculate separate performances for each fan. Lastly, strain gauges glued on several blades helped monitoring mechanical and aero-elastic phenomena such as flutter onset or classical dynamic responses. Tip clearances measurements were monitored and acquired in running conditions to avoid any unexpected contact between blades and casing and to contribute to a more accurate performances assessment.

In short, the basic aerodynamic parameters were calculated and monitored in real time during all test phases using the following measurements:

- The total corrected fan mass flow was calculated based on 4x4 (Pt, Tt) rakes and 16 Ps ring located in bellmouth
- The overall fan pressure ratio and isentropic efficiency was based on inlet rakes (4x4 Pt) and fan 2 outlet rakes (8x7 Pt) measurements (*Fig. 8*)
- The core flow was characterized thanks to a venturi meter installed in core duct, far downstream from the single-stage booster
- The booster pressure ratio and efficiency were built using 4x4 (Pt, Tt) rakes at booster outlet and instrumented IGV (welded Pt, Tt sensors on leading edge)

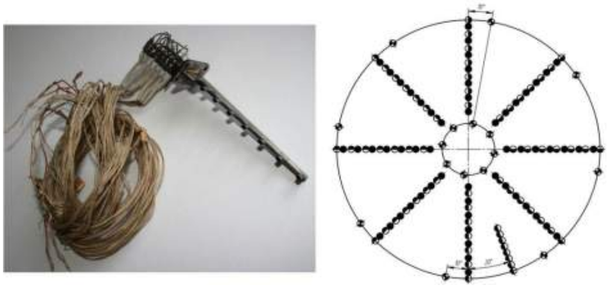

Fig. 8 – CRTF1 instrumentation: 7 immersions radial rake at fan2 outlet (Pt-Tt measurements)

All sensors were calibrated within the CIAM facility, and static/dynamic corrections were provided to correct raw measurements of temperature values. A resulting dispersion lower than 0.4% was observed for all Tt and Pt profiles (CRTF inlet and outlet), therefore ensuring an acceptable accuracy for efficiency calculation over a wide range of rotating speeds.

Test matrix

CRTF1 aerodynamic tests took place from June 2008 to March 2009, involving test rig mechanical check-out (67 test points) and flow correlation (85 test points) using fixed nozzles characterization before acoustic tests. The overall aero test campaign, including fan mapping (178 test points) was completed on March 4th, 2009. It is to be highlighted that from Snecma aero team, a satisfactory test management and test rig behavior in CIAM C-3A facility has been pointed out.

Experimental Results: CRTF1

CRTF1 Aero fan Mapping – Main Results

Three different fan maps were made (without instability identification) from 40% to 107%Nr with fan inlet rakes mounted. Each fan map corresponds to a specific speed ratio evolution as mentioned below:

-Nominal speed ratio evolution (N2/N1=0.75 @ 100%Nr); as illustrated in *Fig. 9*.

- Rotor 1 speed increased by 5% and rotor 2 speed kept unchanged (N2/N1=0.71)

- Rotor 1 speed decreased by 5% and rotor 2 speed kept unchanged (N2/N1=0.79)

These 2 last fan maps were devoted to test CRTF1 robustness in terms of speed mis-adaptation, and also to provide speed derivatives for engine cycle purposes. The lowest position for each speed line corresponds to a full open BPDV configuration.

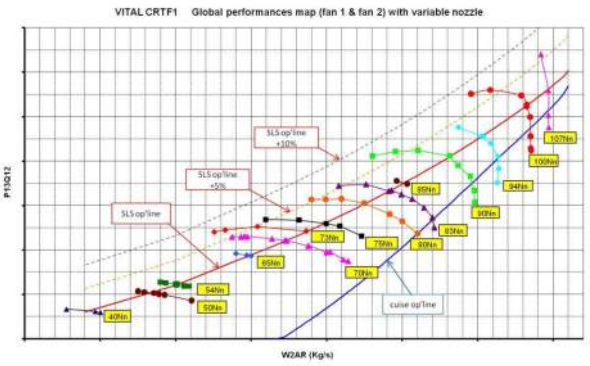

Fig. 9 – CRTF1 experimental fan map

An alternate test was carried out as well to characterize CRTF performances with a torque ratio (C2/C1) kept constant while describing the SLS operating line already explored in fixed nozzle configuration; the N2/N1 evolution relating to this test was then quite different from the nominal speed ratio schedule (*Fig. 10*).

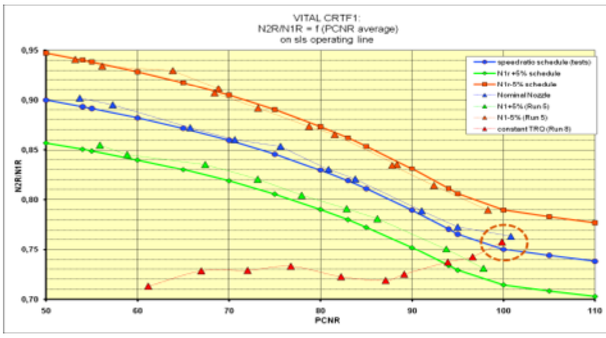

Fig. 10 – CRTF1 speed ratio evolution on SLS operating line

From an operability standpoint, a subsonic flutter margin greater than 5% was demonstrated during the final runs, and a minimum stall margin demonstration at high speed was achieved (*Fig. 9*). Test rig safety and integrity being a major management constraint, no explicit stall was searched for during this test campaign and a stall margin greater or equal to 7% within 90%-100%Nr range was demonstrated.

In a second test configuration, the performances of each fan were characterized by means of radial traversing probes (5 iso-speed lines tested) from 54 to 100%Nn. A total amount of 20 test points with 8 immersions each were recorded.
The main results from an aerodynamic standpoint are described below:

- The flow versus speed evolution shows a shortage of 2% at high speed compared with the VITAL specification on cruise and SLS operating lines. This gap seems to be mainly linked to manufacturing deviations vs. theoretical shapes at leading edge (-0.5%), a fan1 tip clearance more open than expected (-0.1%), and CFD code calibration specific to CRTF not taken into account (-1.4% maximum).

- Efficiency-tested levels are close to VITAL specification on cruise point (-0.2pt).

  Based on CRTF1 baseline aero test results, a transposition to engine scale reveals a net benefit of 2 points in fan efficiency in cruise conditions compared with the reference engine (2000 SOA) as illustrated in *Fig. 11*.

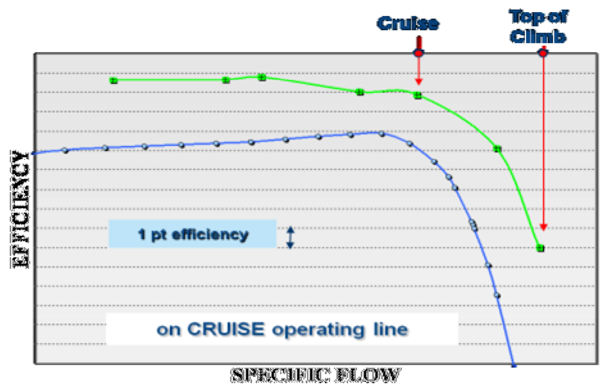

Fig. 11 – CRTF1 (green) vs. 2000 engine (blue) efficiency evolution on cruise operating line

Therefore, this assessment confirms the advantages of the CRTF concept from an aerodynamic standpoint and the quite good agreement with the VITAL initial target.

Comparison of experimental and CFD results

General remarks on Snecma CFD analysis

Let us examine some main features about steady-state RANS calculations that were carried out throughout the design phase, before and after tests. These computations are meant to evaluate global performances, to focus on flow field detailed characteristics and thus to drive design choices during aero-mechanical-acoustical design loops. The calculation domain typically includes fan1, fan2, and the flow splitter (*Fig. 12*).

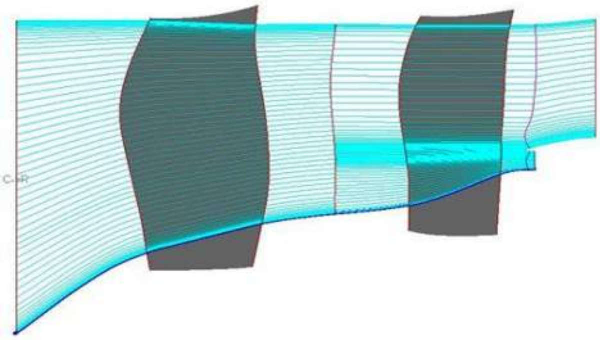

Fig. 12 – CRTF1 aerodynamic mesh used for RANS calculation

Turbulence models (2 equations, Launder-Sharma k-ε model) associated with the *elsA* solver are used; the multi-stage environment being taken into account through the mixing plane approach. Boundary conditions imposed are those normally used for turbofan analysis: uniform Pt, Tt, and flow angle conditions at inlet, mass flow imposed at core duct outlet and compatibility equations (throttle) at by-pass duct outlet.

During the design phase, the same geometry – profiles at ADP - is meshed while describing the whole range of speed lines, as well as an average nominal radial tip clearance for each fan. Nevertheless, performance assessments made on the final CRTF designs use more accurate geometries based on cold to hot recalculated geometries, to take profile deformations due to centrifugal and aero pressure loads into account.

It also appeared that the assumption of a constant relative radial tip clearance (j/h=0.34% for fan1 and 0.21% for fan2) for the overall CRTF map was leading to results quite close to those obtained with variable clearances when changing the rotation speed.

Lastly, for information, complex computations, most of them based on URANS calculations and including more sophisticated turbulence models, were performed by academic partners [7], [8] to evaluate far field noise propagation of CRTF.

Global performances (experiment - CFD)

CFD results without any calibration were compared with the test results (*Fig. 13*) and showed that speed line shapes are well predicted on a wide range of rotation speeds. Flow capacity at high speed is nevertheless over-estimated (roughly +2% mass flow at 100% design speed) by the elsA solver, even though this extra amount of flow is partly due to tip clearances more open than expected on fan1 and manufacturing deviations affecting the leading edge shape. It is to be noted that the location of maximum efficiency on the fan map (green doted and solid lines *Fig. 13*), is fairly well assessed by CFD, this being essential in design processes to match performances objectives on a cruise operating line and ensuring a sufficient stability margin.

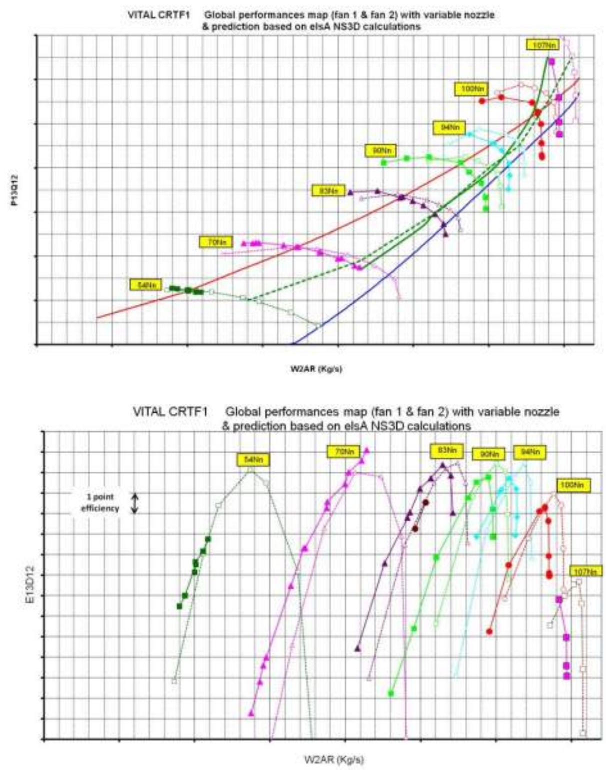

Fig. 13 – CRTF1: experimental fan map (solid lines) and prediction based on elsA calculations (dotted lines)

Main values extracted from both CFD and experimental fan maps are used to compare flow and efficiency evolutions on both cruise and

SLS operating lines (*Fig. 14*, *Fig. 15*). Once again, based on CFD maps produced before tests, the mass flow is predicted with good accuracy (lower than 0.5% up to 80%Nn) on the SLS operating line.

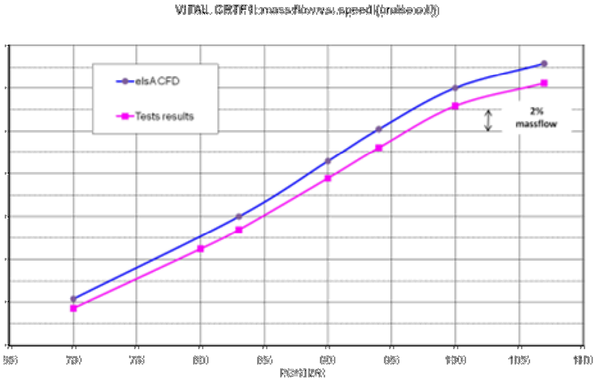

Fig. 14 – CRTF1: flow speed capacity on cruise operating line: experiment – calculation comparison

As for efficiency evaluation, CFD would seem to under-evaluate tests values lower than 90% design speed and matches test results within 0.5 point on the SLS operating line. On the cruise operating line, a good agreement is found between 70% and 95% of design speed, and CFD under-evaluates the efficiency, probably due to discrepancies in shock patterns (fan2 operates in choked configuration in this area).

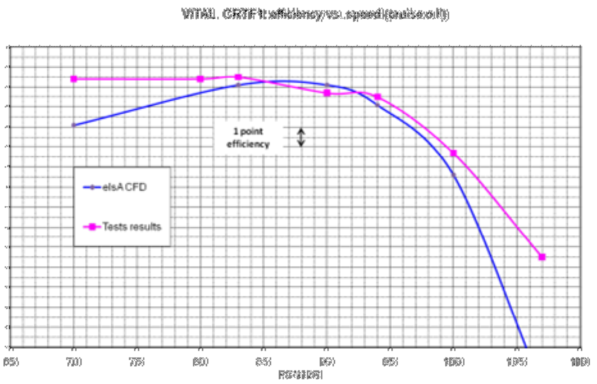

Fig. 15 – CRTF1: efficiency speed capacity on cruise operating line: experiment – calculations comparison

Radial evolutions (experiment - CFD)

When comparing tests vs. CFD-based predictions at 100% design speed – near peak efficiency, we observe once again a quite good match in gradient shape (*Fig. 16*, *Fig. 17*) and a flow turning at fan 1 outlet overestimated by CFD. In the fan 2 exit plane, Pt and Tt gradients are well predicted by CFD, leaving aside a 2% average shift to match test result global performances. This means that the fan2 aerodynamic work is rather well modeled. A slight discrepancy noticed on the Tt and Pt gradient near the outer wall shows that CFD under-estimates pressure losses, and this seems to be linked to different secondary flow effects in the CFD calculations, since tip clearances during tests did not exactly match the theoretical values.

Lastly, the flow angles calculated at the fan 2 outlet well match the experimental data, showing a maximum deviation of around 1°. This low value of swirl angle reflects a good balance between the rotor1 and rotor 2 torque values, the experimental ratio near ADP being close to 1.05.

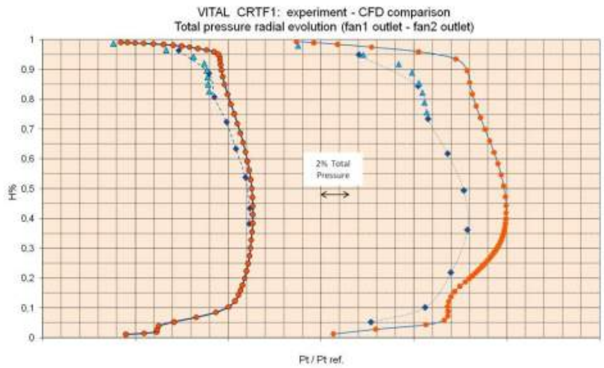

Fig. 16 – CRTF1 Total pressure radial evolution (experiment- calculated) near peak efficiency

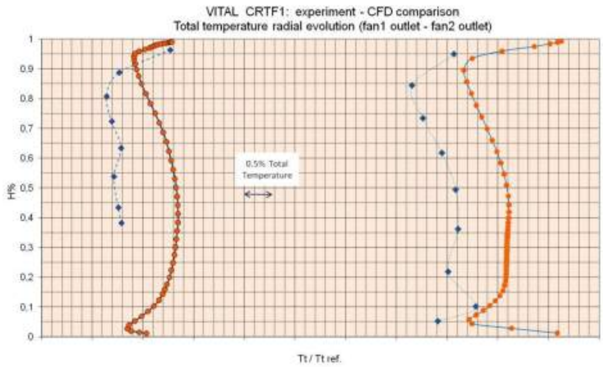

Fig. 17 – CRTF1 Total temperature radial evolution (experiment- calculated) near peak efficiency

Relevance of numerical approach used in design phase

From these comparisons of experimental calculations/results, we find that for configurations close to CRTF1 (with similar blade count and relative spacing for fan1-fan2), the RANS calculation method with mixing plane and modeling of radial tip clearance of blades is sufficient to provide aerodynamic sizing that satisfies the specifications sought in the VITAL program. The flow level and efficiency predictions and the maximum efficiency position are precise enough to properly guide the various designs implemented (CRTF1, CRTF2.a and CRTF2.b).

Conclusions

Snecma successfully conducted collaborative work that benefited from the expertise of each partner in design, testing and test analysis. The basic rules for CRTF aerodynamic design and the key differences relative to the design of a conventional fan were determined. The experimental results found during the first test campaign (CRTF1) are reassuring with regard to the performances obtained relative to the VITAL objective, and confirm the suitability of the CFD approach, identical to that conducted in the design phase, for predicting the reality observed during testing with a sufficient level of precision. The same methodology applied to alternative designs CRTF2.a and CRTF2.b confirms the advantages of these two versions. Promising performance level was demonstrated in March 2010 for CRTF2.a (detailed analysis in progress) and similar conclusions should be verified before end of this year during the forthcoming CRTF2.b test campaign.

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