The preliminary design of a scaled Composite UHBR Fan for a wind tunnel test campaign

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Abstract

The ambition of the CA3ViAR project is to design an open test case fan that experiences instability mechanisms, which are representative for ultra-high bypass ratio (UHBR) fans of civil aircrafts, and to perform a comprehensive experimental investigation to measure aerodynamic, aeroelastic and aeroacoustic performance in a wide range of operational conditions. Experimental tests will be performed in the Propulsion-Test-Facility (PTF) of the Institute of Jet Propulsion and Turbomachinery (IFAS) of Technische Universität Braunschweig, Germany. The final objective of the project is to provide an open test case for the entire research community, with geometries, numerical and experimental results to establish a new reference for composite UHBR fan design. This will support the development of new methods and tools for the development of safer, lighter and more efficient composite fans for greener UHBR engines. In this work the preliminary design of the low transonic fan (LTF) to be used as test article, whose main requirement is to be operated in a safe and controlled way in conditions of aerodynamic and/ or aeroelastic instability during wind tunnel operations, is presented. More in particular, consolidated aerodynamic design, strategy adopted to drive the structural design, flutter analysis taking into account acoustic reflection at the intake, dynamic and stress analyses, as well as aeroacoustic measurement optimization are presented and discussed. The preliminary mechanical design of composite blades and the rotor hub, together with the rotor instrumentation and related studies to embed sensors in the composite blades, are also part of this article, and complemented by manufacturing trials and demonstration tests give the full picture of all the project activities up to the preliminary design review.

Keywords: UHBR fan, composite material, fan aerodynamics, aeroelasticity, flutter, aeroacoustics, WT testing

1. Introduction and Motivation

Following national and international laws and agreements between countries [1], [2], in the last decades, airplane operators and manufacturers have been continuously investing in new technologies for more efficient and less polluting aircraft, aiming for positive economic and ecological impacts. For this purpose, advanced conventional designs for airplanes as well as for engines have been developed over the last years. For engines, the two general fields for further improvement are the increase of thermodynamic efficiency as well as the increase of propulsive efficiency [3].

Recent advances in ultra-high bypass ratio (UHBR) engines are the result of considerable efforts in the development of more efficient turbofan engines as a response to the need to increase propulsive efficiency. One of the major contributors to the reduction of fuel consumption and emissions has come through diminishing the difference between flight and engine outlet velocities [4].

UHBR propulsors require larger fans, posing significant challenges from aerodynamic and structural points of view. The higher engine-BPR does increase the required operating range of the fan by moving take-off and approach closer to the part power limit of the fan and therefore reducing its stall-margin and increasing the flutter risk. In parallel, the increased fan diameter is driving the intake design, with significant implications on drag and airflow inlet distortion at the Aerodynamic Interface Plane (AIP) during off-design and crosswind. Beside these increased aerodynamic requirements, the fan itself has to be reduced in weight, thus requiring the application of lighter and stiffer materials, such as Carbon Fibre Reinforced Polymers (CFRP) instead of more conventional titanium alloys, providing more design degrees of freedom in terms of "customized" stiffness distributions with consequent capability of driving the deformed blade shape. This implies the need of developing more reliable and accurate methods for aerodynamic, aeroacoustic and aeroelastic design of engine fans.

The ambition of the CA3ViAR project is to design an open-test-case fan that experiences instability mechanisms, which are representative for UHBR fans of civil aircrafts, and to perform a comprehensive experimental investigation to measure aerodynamic, aeroelastic and aeroacoustic performance in a wide range of operational conditions. Experimental tests will be performed in the Propulsion-Test-Facility (PTF) of the Institute of Jet Propulsion and Turbomachinery (IFAS) of Technische Universität Braunschweig, Germany.

The purpose of this work is to present the preliminary design of the low transonic fan (LTF) to be used as test article, whose main requirement is to be operated in conditions of aerodynamic and/or aeroelastic instability during wind tunnel operations, in a safe and controlled way.

More in particular, the consolidated aerodynamic design of hub profile, fan and stator blades is presented along with trade-off analysis on blade-tip gap. The strategy adopted to drive the structural design is presented and discussed. One of the aims is to target an optimal stability map of the fan rotor enabling tests close to the instability and at the same time ensuring a sufficient level of safety inside the wind tunnel. This is evaluated by means of high-fidelity flutter analysis taking into account acoustic reflection at the intake for different intake length, aerodynamic viscosity and compressibility effects. On the other hand, dynamic and stress analyses complement the structural design to comply with strength requirements and define a Campbell diagram, which is compatible with design conditions and desired testing points.

The preliminary mechanical design of composite blades and rotor hub has been completed, complying with the main requirement of ensuring the proper stiffness and strength according to structural and aeroelastic analysis, and implementing all the design features to lower the mechanical damping as much as possible. Indeed, further aeroelastic analysis aimed at assessing the impact of the rotor mistuning in terms of deviations in the natural frequencies of the blades on the aeroelastic performance demonstrated that a very low structural damping is required to enable reaching unstable conditions in the wind tunnel.

The rotor instrumentation is also presented, together with the studies to embed sensors in the composite blades, complemented by manufacturing trials and demonstration tests. A preliminary design of acoustic rakes to measure and decompose acoustic modes induced by rotor-stator interactions with the aim of characterizing the aeroacoustic performance complete the overview on the LTF preliminary design.

2. Aerodynamic Design

The fan stage design is an interdisciplinary and iterative process, in which aerodynamics, aeroelasticity, and aeroacoustics need to be considered. The scaled fan stage with a ratio of 1:3.3 represents a geared turbofan engine fan with a bypass ratio of 17. Details of the design process and the numerical setup are described in [5], where also the reference fan stage is presented. In Figure 2 (left), the fan stage consisting of 18 rotor blades and 40 stator vanes is shown, outlining the numerical domain. In order to predict the influence of blade elongation under loads, a tip gap sensitivity study is performed. Therefore, simulations of the throttle lines for 0.5 mm, 0.75 mm and 1 mm at design speed (8667 rpm) as well as take-off speed (8095 rpm) were conducted. The results are depicted in Figure 1 (left), showing that the total pressure ratio and the polytropic efficiency decrease linearly with increasing tip gap size. An increase in tip gap of 1% leads to an efficiency reduction of approximately 1.5%. The best compromise with mechanical design requirements is established with a tip gap size of 0.75 mm.

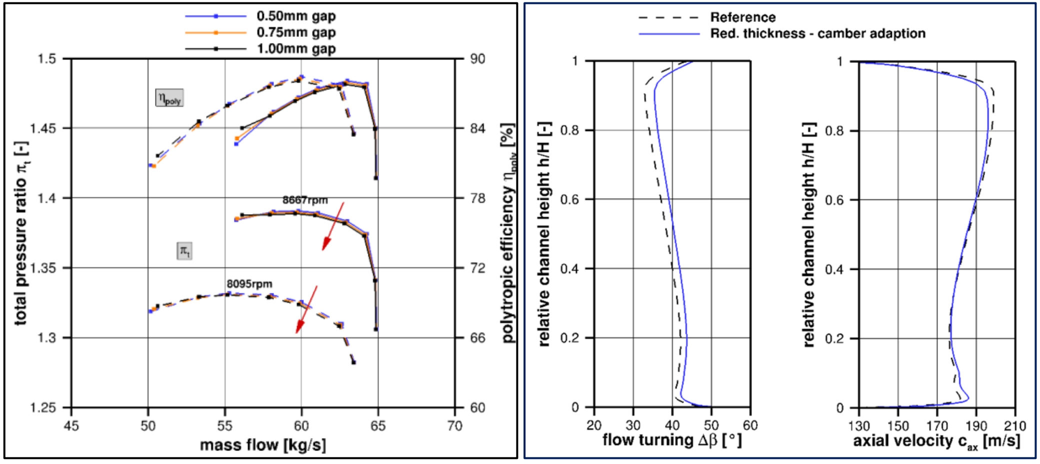

Figure 1 – Influence of tip gap size on the speed lines (left) and Effect of thickness reduction on the fan blade (right)

To meet aeroelastic and structural requirements the fan blade is reduced in thickness by 25% compared to the reference design in [5]. Due to an additional camber adaption to compensate for the thickness-induced camber, the radial flow distribution along the fan blade is affected as shown in Figure 1 (right). Accordingly, the flow turning increases over the full channel height. As the thickness is reduced, the flow is radially redistributed, leading to a higher flow capacity in the hub area.

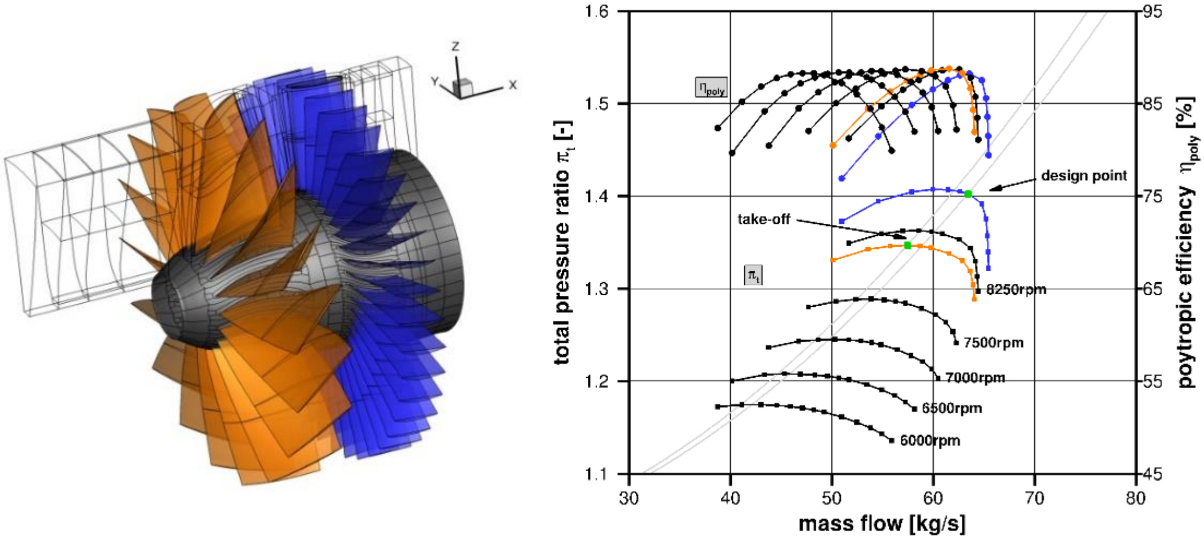

Figure 2 – Fan stage design (left) and Fan performance map (right)

As a result, the speed lines are shifted to higher total pressure ratios and slightly higher mass flows. The fan map is shown in Figure 2 (right). At design point, the fan stage achieves a total pressure ratio of 1.4 with a polytropic efficiency of 88.2%. For design speed, the surge margin is 17.8%.

3. Structural design, dynamics, stress analysis and fatigue

While aiming for a blade with a low stiffness and high twist-to-plunge ratio to analyse aeroelastic instabilities, the structural integrity needs to be guaranteed. For a typical CFRP fan blade the typical ply lay-up usually consists of a certain number of ±45° layers on the outside, giving torsional stiffness and toughness, and 0° (spanwise) for the rest of the blade giving longitudinal and bending stiffness, leading to a very stiff blade and therefore low deformations of the loaded structure. For the CA3ViAR design, the outside layers are reduced to a single combination of ±60° layers to increase the twist under load and 90° layers to reduce the bending stiffness replace some of the 0° layers. These changes lead to an increase of blade deformations under loads and therefore to a reduced margin regarding the material allowables especially for the 90° tension loading.

To analyse the blade regarding the dynamic behaviour as well as the structural integrity, a FE model of the blade is created in MSC.Patran. It consists of ~15000 shell elements and is shown in Figure 3 (up). It is constrained with a rigid RBE2 multi-point-constraint (MPC) at the blade root to simulate the clamped connection of the blade to the hub and loaded with a rotational force. The convention on the direction of the layers and the thickness distribution are also presented.

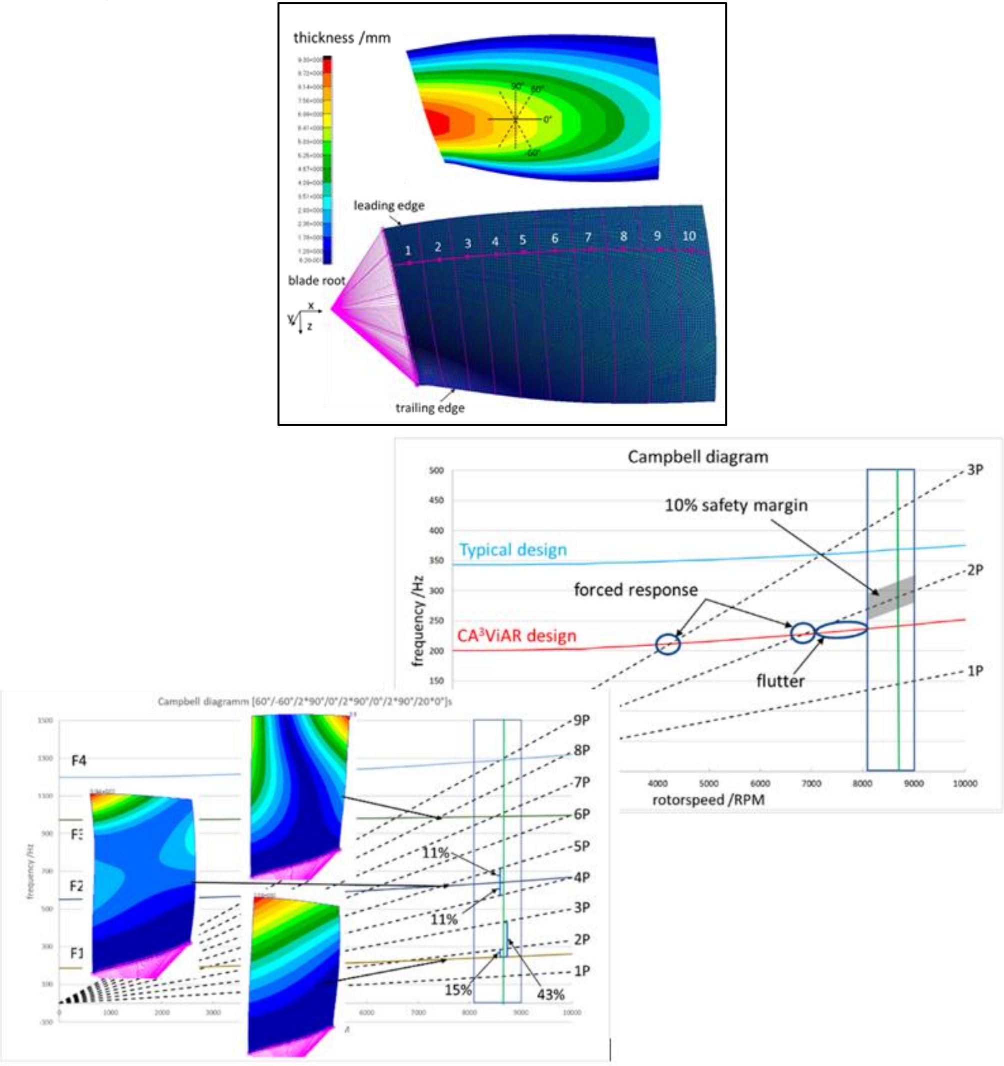

Figure 3 - FE model of the blade (up) and Campbell diagram (down)

For the modal analysis, the Lanczos method from Nastran SOL 103 is applied to draw the Campbell diagram checking compliance with safety requirements [6].

The top of Figure 3 (down) highlights the special behaviour of the CA3ViAR blade compared to a typical design and identifies the regions to analyse aeroelastic instabilities. The bottom of Figure 6 shows the Campbell diagram for the current blade design and the first three eigenmodes. In addition to that, the safety margins to the blade excitation frequencies are given.

For the stress analysis, aerodynamic loads are applied stripewise along the span using RBE3 MPCs connected to the 10 depicted load application points. Due to the large deformations, the stress analysis is performed geometric non-linearly using Nastran solution 106. To provide sufficient safety, a load factor LF=2.5 is employed (LF=1 for fatigue) and a knockdown factor of 1.3 is used on the material allowables to account for possible low-energy impacts during manufacturing and handling.

The Tsai-Wu criterion is used to analyse the strength of the blade. Figure 4 (right, a) shows the resulting failure indices for the stress analysis. A failure index ≤ 1 means the structure is able to withstand the loads. For fatigue, a modified Goodman approach (Figure 4, left) is used to calculate static equivalent loads using the max. and min. forces working on the blade and the performance of the material after the estimated amount of load cycles. The results of the fatigue loads are given in Figure 4 (right, b).

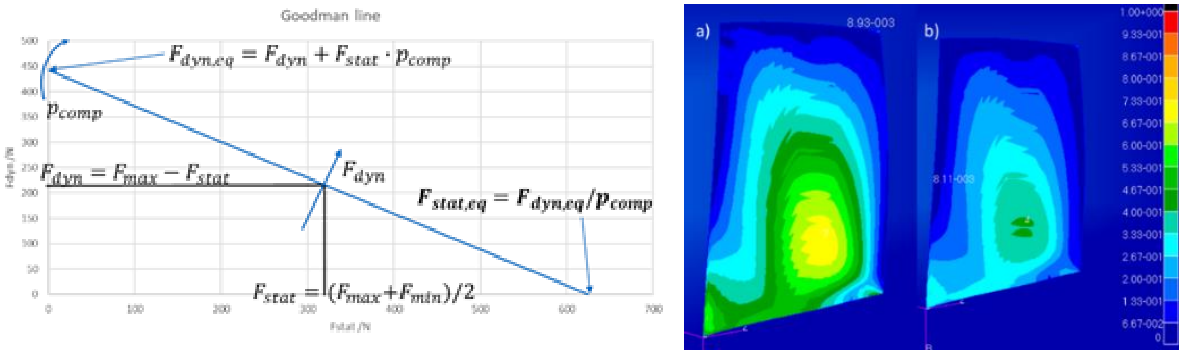

Figure 4 - Calculation of fatigue loads (left) and Results stress analysis - a) static b) fatigue (right)

4. Flutter analysis and stability map

The CA3ViAR fan rotor is designed to be stable at the working line of the fan and, at the same time, able to generate aeroelastic instabilities (flutter) at specific throttled conditions. Due to the short intake design and the increased coupling of intake and rotor for UHBR fans, the intake is influencing the aerodynamic damping of the rotor and therefore must be taken into account in flutter analysis.

The influence of the intake on the aerodynamic damping occurs due to acoustic reflections at the intake highlight. The acoustic modes induced by blade vibrations propagate upstream and are reflected at the intake highlight due to the impedance discontinuity. The reflected, downstream traveling acoustic mode is superposed with the pressure field induced by the blade vibration. Thus, the reflected mode directly influences the modal work and therefore the aerodynamic damping. This effect can be either stabilising or destabilising, depending on the phase difference between vibration and reflected wave. Several studies describe these effects and present analytic [7] and numerical methods [8], [9] to address the coupled aerodynamic damping.

Since CA3ViAR is aiming at generating flutter conditions, the coupling of intake and rotor must be resolved and quantified during the design process. These fully coupled, high-fidelity, and efficient simulations are performed in the frequency domain, with the nonlinear research solver TRACE Harmonic Balance (HB) developed by the German Aerospace Centre (DLR). A scheme of the numerical domain with intake, rotor and stator domain is shown in Figure 5 (left).

Despite the iteration with the aerodynamic design, there are two main parameters to control the flutter behaviour of the fan. These are, (1) the structural-dynamic properties (eigenfrequency and twist-to-plunge ratio) of the rotor blade, which are influenced by changing the composite material and the layup of the plies and (2) the influence of the intake reflection, which can be manipulated by adapting the intake length, which changes the phase difference between rotor vibration and reflected wave.

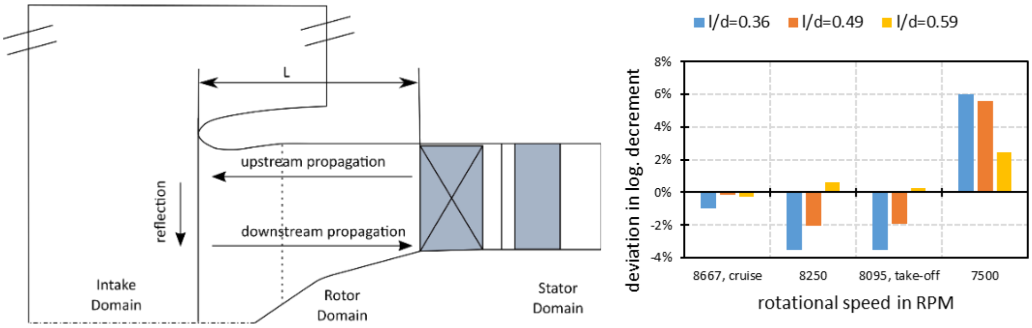

Figure 5 - Schematic of numerical domain to resolve the reflections of acoustic reflections at the intake (left); Influence of the intake length on the aerodynamic damping, ND 2 (right)

Figure 5 (right) shows the influence of the different intake lengths analysed in CA3ViAR at different rotational speeds close to the working line. The short intake (l/d=0.36) is critical at take-off condition and rotor vibration in nodal diameter (ND) 2, reducing the logarithmic decrement by 3.53 percentage points compared to the rotor-only damping. However, lengthening the intake to l/d=0.59 leads to a small stabilisation for the same operating condition. The influence of a ply stackup variation on the eigenfrequency and twist-to-plunge ratio is shown in the top plot in Figure 6 (left, top). By adding further 90° plies, the eigenfrequency reduces with a collateral decrease in twist-to-plunge ratio, both important parameters for the rotor-only damping. The resulting variation of rotor-only damping is shown for ND 1 and ND 2 in Figure 6 (left). For ND 1, the decrease in eigenfrequency is reducing the aerodynamic damping of the fan blade. However, for ND 2, the lower twist-to-plunge ratio predominates the decrease in eigenfrequency resulting into higher aerodynamic damping by adding more 90° plies in the stackup. Therefore, an optimum between twist-to-plunge ratio and eigenfrequency had to be found by changing the ply stackup, resulting into stable condition close to the working line and flutter at throttled fan condition. Iterations between aerodynamic design and several loops within the aeroelastic design led to the preliminary blade design with an eigenfrequency of 245.41 Hz and a twist-to-plunge ratio of 0.67 at 8667 RPM. Figure 6 (right) shows the resulting aerodynamic damping. Both ND 1 and ND 2 are unstable at throttled fan conditions with sufficient margin to the working line.

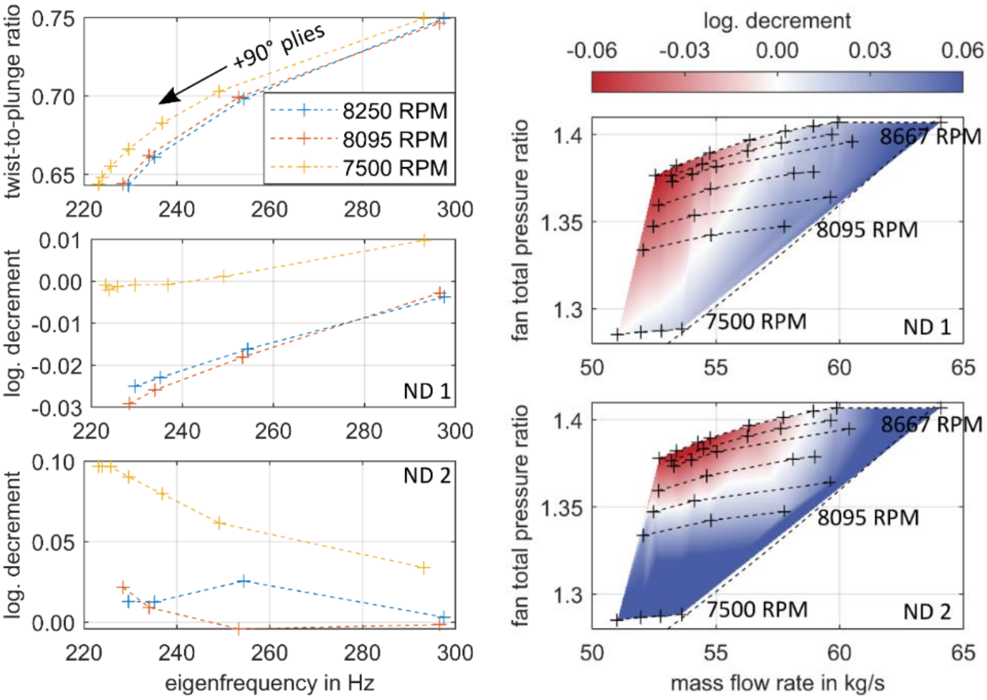

Figure 6 - Variation of ply stack-up with influence on the rotor-only damping (left); Fan performance map with surface plot of allocated aerodynamic damping, Top: 1F & ND 1, Bottom: 1F & ND 2 (right)

5. Aeroacoustic measurements and design of sensors probes

To decompose the superposed acoustic pressure induced by rotor-stator interaction and mode scattering into specific acoustic modes, their sound pressure level and phase relation, an experimental radial mode analysis (RMA) is required. The RMA requires an optimization of the sensor placement to reduce numerical errors during the decomposition. In this case, acoustic rakes placed behind the stator are optimised to decompose acoustic modes up to the 3rd blade passing frequency (BPF) at design rotational speed. This is done by analysing the condition number of a synthetic mode decomposition with varying measurement positions. Based on the number of the maximum cut-on radial mode order, 9 unsteady pressure sensors need to be placed in radial direction. Furthermore, to decompose up- and downstream traveling waves, at least two different measurement positions in axial direction are required. The resulting condition number analysis of two rakes, each equipped with 9 pressure sensors is shown in Figure 7 (left). A design, which is able to decompose the acoustic field up to the 3rd BPF has been found by equally distributing the pressure sensors between 0.185 m and 0.307 m in radial direction. In axial direction, a distance between the two rakes of 0.01 m is a good compromise between available space and condition number. Beside the rake measurement, pressure sensitive paint will be applied on the duct wall of an extended intake. This allows measuring the spatial pressure fluctuations induced by the fan up to 5 kHz by using a high-speed camera. Measurements will be analysed and compared to numerical simulations.

6. Mechanical design

The CA3ViAR stator and rotor stages will be installed on an existing rig developed in the framework of the INFRa project in the Propulsion Test Facility (PTF, [10]) of Braunschweig, and are designed to be able to reuse as many parts and interfaces from the existing test rig as possible. The design of rotor and stator stages is shown in Figure 7 (right). For the stator stage, despite a different aeroshape, the design of the interfaces at shroud and hub are kept unvaried.

Since rotor blades are made up of CFRP, the approach of having a hybrid design using a metallic foot as interface part between blade and hub has been followed. The main reason is to guarantee an intimate blade-hub connection reducing frictions as much as possible, with the aim to minimise the mechanical damping and have a final blade structure more prone to flutter in line with project objectives. The CFRP layers are routed through an opening in the foot and clamped by means of a suitably shaped wedge. Accordingly, the hub is equipped with dovetail-like interface slots able to house the interface feet of the rotor blades. This integrated design also permits the routing of cables coming from the strain gauges installed on the blades, used to both ensure efficient health monitoring during wind tunnel operations and reconstruct the modal participation of the first two natural modes.

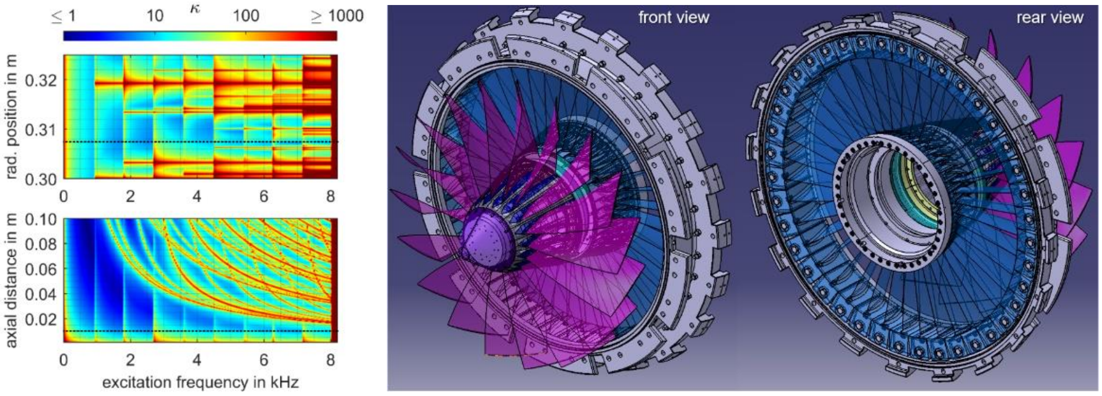

Figure 7 - Condition number analysis for RMA with rakes (left); Preliminary design of rotor and stator stages (right)

Due to the high curvature of the blade airfoil at the rotor hub and the high loads acting on the foot, the surface area of the foot that is in contact with the rotor hub has been maximized and the rotor hub has been slightly extended in the forward direction. This aims to decrease the loads acting on the blade foot.

The tapered rotor foot geometry, increasing in width from front to back, complies with geometrical constraints and enables smooth mounting and dismounting operations. A retaining ring is installed on the back as a safety means to ensure correct positioning during both installation and wind tunnel operations. A large number of headless screws in defined circumferential positions on the front of the rotor hub is foreseen to allow for static and dynamic balancing operations before the final installation on the rig.

7. Analysis of sensor installation and demonstration tests

The basic aim of the sensor installation is the monitoring of the CFRP blade response (max. stress and displacements) under aerodynamic and inertia loads. For these measurements, appropriate stain gauges (SG) are selected following criteria such as: a) size, b) CTE and c) the simplest integration on the blade. For the correct placement of the SG, a special measurement plan was established, using a Laser Tracker for the identification of the (x,y) coordinates (Figure 8, a).

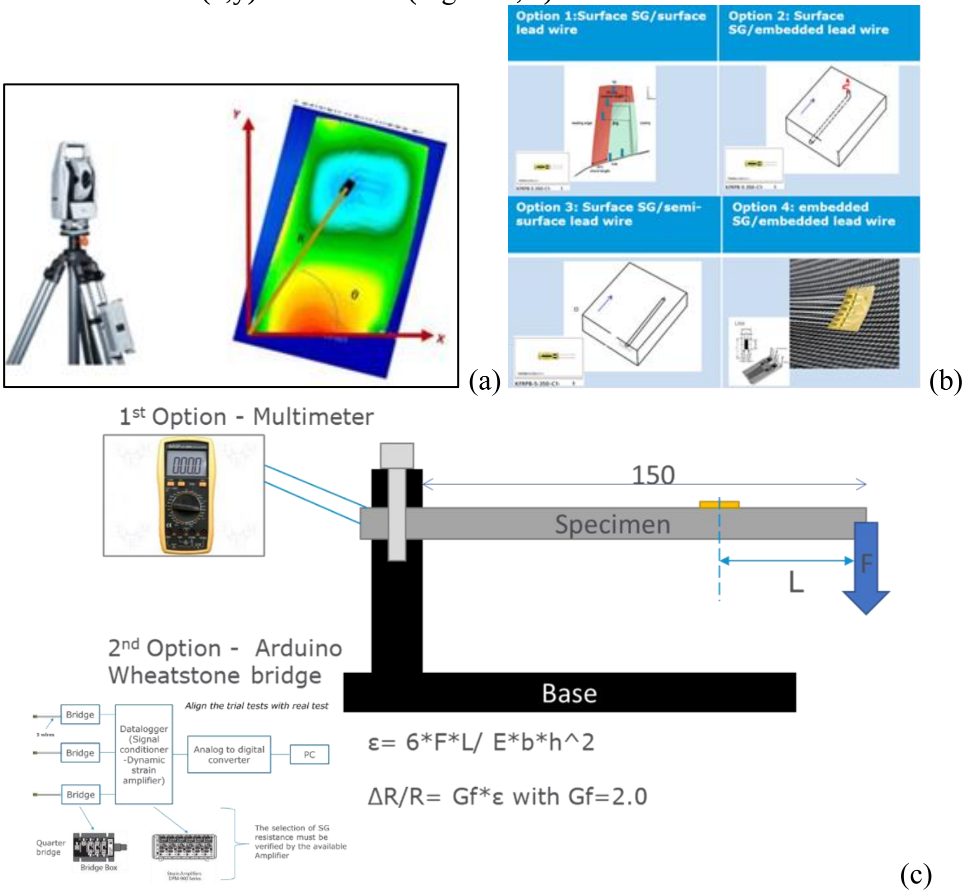

Figure 8 - Local coordinate points measurement for SG correct placement (left); Design options for instrumentation demonstration tests (centre), Metallic frame for CFRP plates support and SG resistance measurement (right)

The 3D geometry of the CFRP blade is a complex structure with a twist and lean angles to succeed specific twist-to-plunge ratio and normal modes (1st eigenfrequency). During the preliminary design review (PDR), 4 demonstration tests were proposed for the integration process between the SG and supplementary equipment (wiring, protection film, adhesives etc.). These tests have differences, affecting a) the blade fabrication process, b) the blade mass and eigenfrequency, c) the installation time and d) the quality between the connecting parts. For this reason, the demonstration tests were applied on plate specimen evaluating the proposed options. These options were: a) surface SG and surface lead wires, b) surface SG and embedded lead wires, c) surface SG and semi-surface lead wires, d) embedded SG and embedded lead wires. The different testing configurations are summarised in Figure 8 (b). A

metallic frame supports the demonstration test set-up where the CFRP plates with the integrated SG equipment is fixed (Figure 8, c). A bending load F is applied and deforms the plate where the SG is installed. The basic operation of the SG/ lead wires connection is checked by using an Ohmmeter. The normal operation of the integrated parts is ensured by a quarter Wheatstone bridge with the necessary telemetry and temperature compensation.
Test results will allow ranking the different solutions based on a trade-off analysis, assigning scores to different criteria with different weight factors. The most important criteria to be assessed are: 1) the accessibility and capability to uninstall the SG integrated component (strain gauge and lead wire) when a malfunction is observed. This criterion directly affects the manufacturing cost of the CFRP blade; 2) From a technical point of view, the blade's surface quality potentially affecting the flow. The combination of these two criteria will lead to the final selection for wind tunnel testing.

8. Conclusions and future work

The preliminary design of the composite fan being developed in the CA3ViAR project has been presented, together with complementing numerical and experimental activities aimed at consolidating the design of test article and test setup to achieve the critical design review (CDR) currently foreseen in November 2021. After the achievement of the CDR, manufacturing-related activities will ramp up, starting from the finalization of the mould design, through the first manufacturing trials, up to final manufacturing, instrumentation and assembly activities, in order to target a wind tunnel test campaign in the second half of 2022.

9. Acknowledgement/ Disclaimer

This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 864256. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.
The present work reflects only the authors' view and the European Commission and Clean Sky 2 JU are not responsible for any use that may be made of the information contained herein.

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