Decreasing the Mass of Turbomachinery Subansamblies Using Advanced Polymer Composites

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The extension of use of light advanced polymer composites from structural parts of an aircraft to all kinds of components of the engine is presently very limited by the knowledge of both technological development process and materials behaviour during service. The paper comes to meet an area of interest for many researchers and large integrators and manufacturers, by presenting the first steps made into the manufacturing of a carbon fiber reinforced composite blades for a centrifugal compressor impeller. An existing metallic reference impeller was redesigned, air flow studies were achieved to establish new design performances, precursors (type, volume fraction, architecture, distribution) were defined for the CFRP (Carbon Fiber Reinforced Polymer), stress analyses were performed on proposed structural materials configurations. Furthermore, the paper award an important section to manufacturing process stages, the manufacturing technology used and first developed trials. It was concluded that an entire impeller CFRP (Carbon Fiber Reinforced Polymer) manufacturing can and shall be the next step of the study, using autoclave technology.

Keywords: Impeller, design, CFRP composite, stress analyses, autoclave technology

The current tendency for aviation, energy and many other fields is to reduce fuel consumption and polluting emissions, in order to reduce the environmental impact. These reductions can be accomplished through a better use of the fuel by better combustion processes into energy production systems like gas-turbines or through weight reduction of overall assembly, for aviation, or rotary sub-assembly for industrial machines. Since the combustion process has been highly developed with efficiencies of up to 99%, the second option is the remaining demanding one, namely that of reducing the weight of the machines. In the last two decades, there has been a marked increase in the use of composite materials for the structural parts of aircrafts (such as the wings, control surfaces, tail planes, fins and fuselage), random, skins and fuselages, pressure vessels and tubes for satellites [1]. The next logical frontier in the use of composite materials in aircraft systems is the application of composite materials to engine components. In the last years a great concern for the material science and aerospace engineers represented the increasing demand for composite rotating components that can reduce the noise in jet engines. Studies were conducted to design and test composite axial compressor blades with focus on vibration behavior and it was observed that composite materials can contribute to a reduction of vibration amplitudes due to their inherent advantageous damping behavior and their high specific stiffness [2]. Most of research studies regarding rotary blade components were conducted on helicopter rotors or wind turbine rotors [3-6, 9] especially due to the fact that the composites materials for this type of structures shall meet lower level requirements compared with heavy duty components like fan blades, axial/centrifugal blades or turbine blades. However, even if high demands are imposed for this type of high speed rotors, researches were made to integrate composite materials in such applications [4,7,8]. For example, the LEAP engine's fan blades are manufactured of 3D woven carbon fiber reinforced composites and they are currently used to fly commercial planes like Airbus A320neo, Boeing 737 MAX or COMAC C919. Also, a modern airplane, like Boeing 787 Dreamliner, consists of 50 percent polymer composites, a fighter aircraft like the Eurofighter consists of 70 percent polymer composites. For instance, a wing made of polymer composites is assembled by the junction of 10 elements and a metal wing made of 100 elements. This means that construction of a metal wing costs more. Moreover, CFRP exhibits six to eight times higher strength than aluminum, being 1.5 times lighter. Air-transport currently relies almost entirely on gas-turbine engines for power, propulsion or thrust. One indispensable component of such an engine is the compressor which provides a mass flow rate with a certain pressure ratio. Since the pressure ratio increase of the compressor is commonly achieved by adding supplementary compressor stages the overall weight of the compressor has increased, consequently demanding more and more novel light weight high temperature resistant materials.

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With this background, this paper reports the results of a preparatory study on new design, Computational fluid dynamics **(**CFD**)** results, materials, stress analysis and manufacturing of a carbon fiber reinforced composite blades for a centrifugal compressor impeller. In particular, the study shows that both selected structural materials and development technology are adapted to reach the goal. Likewise, conclusion is that an entire impeller CFRP (Carbon Fiber Reinforced Polymer) manufacturing can and shall be the next step of the study, using autoclave technology.

Experimental part

New centrifugal compressor impeller design

The study started having as a reference the metallic (17-4 PH) centrifugal rotor of the CCAE 9-125 air compressor produced by Romanian Research and Development Institute for Gas Turbines COMOTI (Figure 1). This was remodel using 3D modelling Solid Edge and CATIA software's, applying optimization iterations, and finally passing from 17 blades (3 mm blade thickness) to 7 blades (6 mm blade thickness-3 mm wall thickness and 3 mm inner clearance). The centrifugal rotor (impeller) has a 17050 rot./min. Rotational speed, 1 atm entrance pressure, temperature functioning range of [20-100˚C], flow of 4.25 kg/s, compression rate of 1,8 compared to the metallic refence of 2,1.

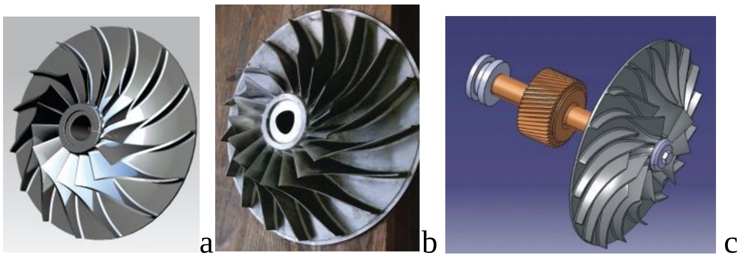
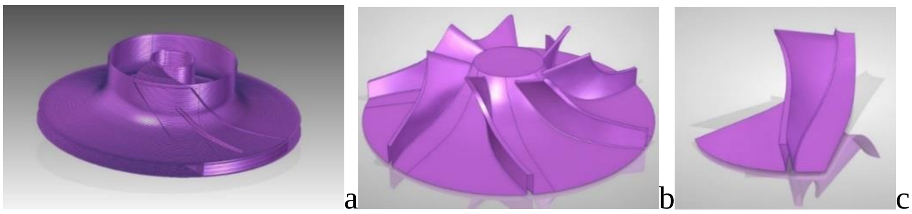


Fig. 1. CCAE 9-125 centrifugal compressor rotor: a) rotor – CAD design; b) 17-4PH metallic rotor; c) rotor assembly stage I – CAD design

Figure 2 presents the new impeller design, obtained following a numerical simulations campaign aimed to define an optimum geometrical configuration taking into account both manufacturing technological issues as well as aerodynamic considerations.



Fi. 2. 3 steps configurator: a) Remodeling Rotor surfaces; b) New version of centrifugal rotor surface; c) One blade surface

*Computational fluid dynamics (**CFD**) analysis*

Furthermore overall aerodynamic performances were investigated using Computational fluid dynamics (CFD) analysis. Simulations were performed using Numeca Fine/Turbo solver and Spalart Allmaras turbulence model (upwind 2 discretization scheme). Convergence criterion were related to the residual value and minimizing input and output flow imbalance (under 0.01%). Four configurations were investigated with tip blade ratio variations at the entrance and exit: 0.5/0.5; 0.2/0.2; 0.2/0.5; 0.5/0.2. Since the turbulence model employed resolves the boundary layer, a y+ distribution lower than one unit was imposed to all walls. In addition to the baseline case - the classical rotor made from metal - four more geometries were tested representing the carbon fiber impeller. Since metalic parts have greater defformation during operation (due to temperature changes and centrifugal loads), for the carbon fiber rotor smaller tip gaps were tested. This was envisioned to compensate the lower number of blades technologically feasable. The four carbon fiber variations had 7 main blades (replacing the original 17) with tip gaps of 0.5 mm and 0.2 mm at inlet and outlet and combinations of those values. Global parameters were sought, such as total pressure ratio, isentropic efficiency and torque (which is a measure of overall mechanical work delivered by the impeller to the fluid). Figure 3 presents the total pressure distribution for two representative cases (constant tip at tip blade 0.5mm).

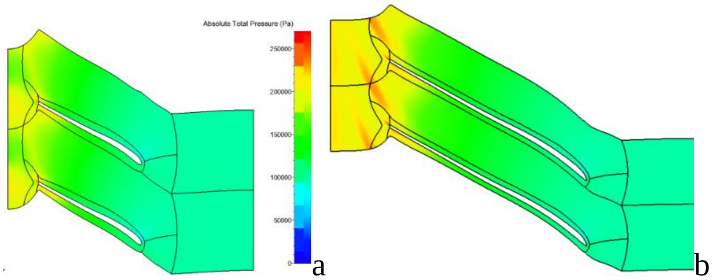


Fig. 3. a) Total pressure distribution for two representative cases (constant tip at tip blade 0.5mm)

Figure 4 shows histograms of the important parameters which were compared for this case

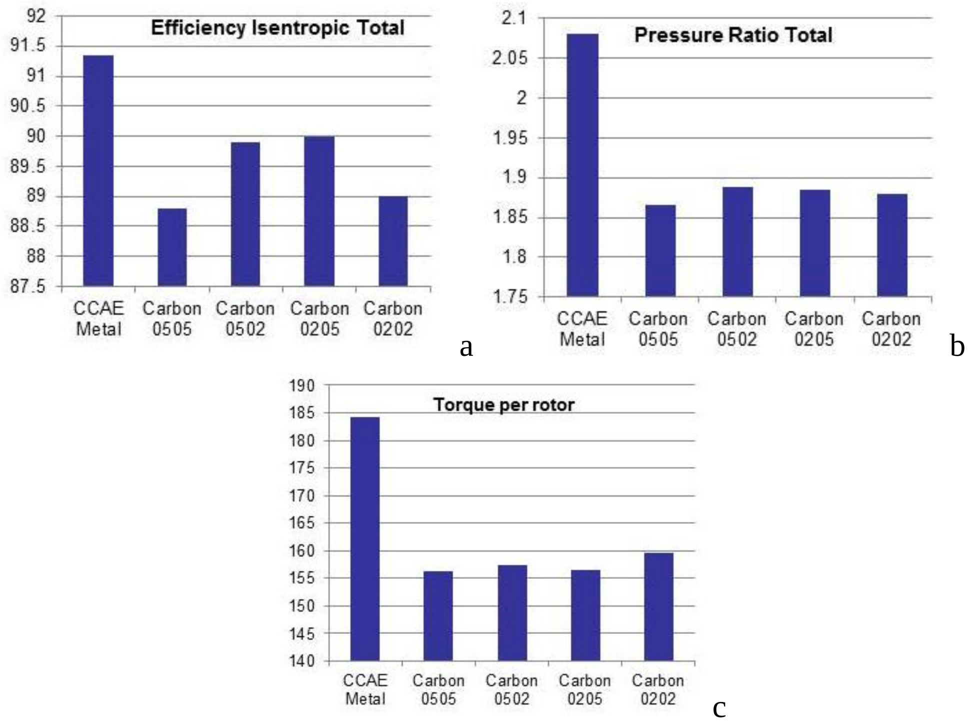


Fig. 4. Comparative graphic for all analysed configurations metallic reference- composite regarding the total efficiency, compression ratio and respectively torque

Computational fluid dynamics (CFD) results presented above in figure 3 and respectively 4, showed changes in all tested parameters but the performance most affected by the design changes is the overall pressure ratio. This is the case for rotors with fewer blades since the maximal loading per blade was reached meaning no further work could be delivered. This is in spite of having no flow separation but the overall loading is less than the one obtained with 17 blades. Furthermore, differences between the carbon fiber cases are small and may fall within the assumed numerical error of the method. Therefore it is the conclusion of this stage that the restrictions generated by the TRL are quantifiable but not particularly significant, considering the added benefits of weight and manufacturing time/cost.

Design and manufacturing of the mould

Given the complexity of the centrifugal compressor impeller, a multi-component mould was designed and manufactured. Starting from the new impeller design, a first version technological mould was designed (figure 5-a). 7 segments sections were modelled using as revolution surface the tip blade, two segment section and one spacer shall be used to obtain one impeller blade (figure 5c).

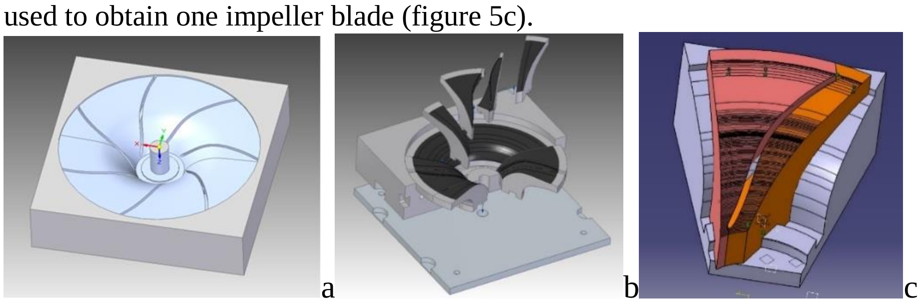


Fig. 5. a) 7 blade negative impeller; b) CAD animation blade extraction; c) configuration of segment and spacer used to manfacture one blade

Both space and segment sections components exhibit one plane surface for enabling easy composite parts mould extraction. Thus, 21 components consisting in 7 separators, 7 type 1 (pressure side) pieces and 7 type 2 pieces (suction side) were designed in order to manufacture the full impeller. Moulds was performed in Al 2024–T351, figure 6 presenting some intermediary machining steps as well as the preliminary manufactured mould version including pars for manufacturing one blade impeller (figure 6d)

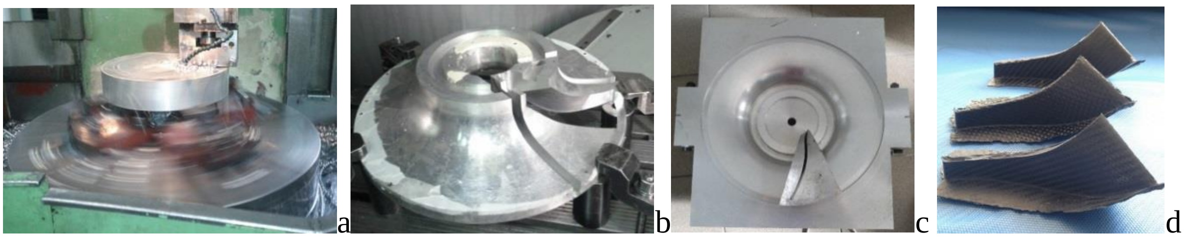


Fig. 6. a) b) intermediary machining steps of the Al 2024 – T351 block; c) preliminary manufactured mould version; d) first impeller blades 1:1 scale first technological trials

Material selection and one rotor blade manufacturing

Several materials precursor were investigated, nevertheless, in the present study only one of them is presented as optimum candidate, taken also as input within the stress campaign analysis. M49/ 42%/200T2X2/CHS-3K is a Hexply product. Material include a 42wt% high toughened epoxy blend (1,18 g/cm^3 density) with excellent tack and drap, reinforced by a fabric bidirectional network (twill2x2 type) of high strength carbon 3K. An areal geometrical pattern (extracted from CAD design) was used for the first technological impeller blade manufacturing. This was used to cut the 7 plies of preimpregnated carbon tow in order to obtain the final 3mm thickness of the blade wall. The 3 mm inner clearance was obtained applying the autoclave technological related stage by using un internal vacuum bag. After material layed-up within the mould, the inner and external bags was connected to the vacuum lines and the assembly was cured in the autoclave at 130°C (heating rate of 2°C/min.), for 60min. at 5 bars. A 120°C Tg was determined using DSC analyser. Using autoclave technology and assessing a proper set of working parameters, void free complex structures can be obtained by applying external pressure during thermal activation of the polymer curing process, resulting in high performance components. During exploitation compressor impeller blades are exposed to temperature range [20-100°C], thus composite material selected answer thermal resistance requirements. With respect to work environment, M49 epoxy blend exhibit good impact and abrasion resistance, good stability under UV. Regarding mechanical strength, a stress analysis campaign was performed before full 7 blade impeller manufacturing and test bench experimentation.

Stress analysis

Boundary conditions, loads and finite element model are presented below in figure 7.

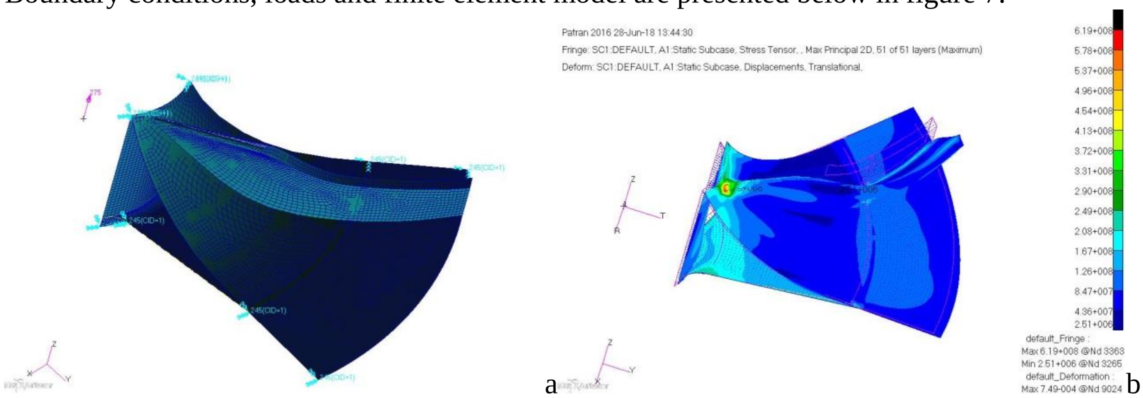


Fig. 7. a) The finite element model of the impeller blade; b) Maximum stress [Pa] distribution on all plies

Laminate mechanical properties predetermined on the selected M49-42%/200T2X2/CHS-3K material and used as input are: $E_{11}=E_{22}=6.23E10$; ν = 0.28; density 1472 kg/m.c.; UTS (ultimate tensile stress) 875 MPa; UCS (ultimate compression stress) 675 MPa. The centrifugal force distribution induced by rotational mouvement is presented in figure 7b above. Maximum stress is 619 MPa localized in the leading edge blade region, whereas minimum stress is 248 MPa localized in the same region.

The first analyzed configuration considers a laminate from 22 plies in the disc area and 7 plies on the blade (related to the 3mm thickness of the wall). The second configuration considers a laminate from 22 plies in the disc area, 7 plies on 2/3 of the blade and 5 plies on 1/3 from the tip (variable blade wall thickness). The third configuration considers a laminate from 44 plies in the disc area and 7 plies on the blade (3mm thickness of the wall). Stress analysis results for all three configurations are presented in figure 8. Strength evaluation is based on Yamada-Sun failure criterion [10], work of Chang and other [11] and experimental test performed in COMOTI [12].

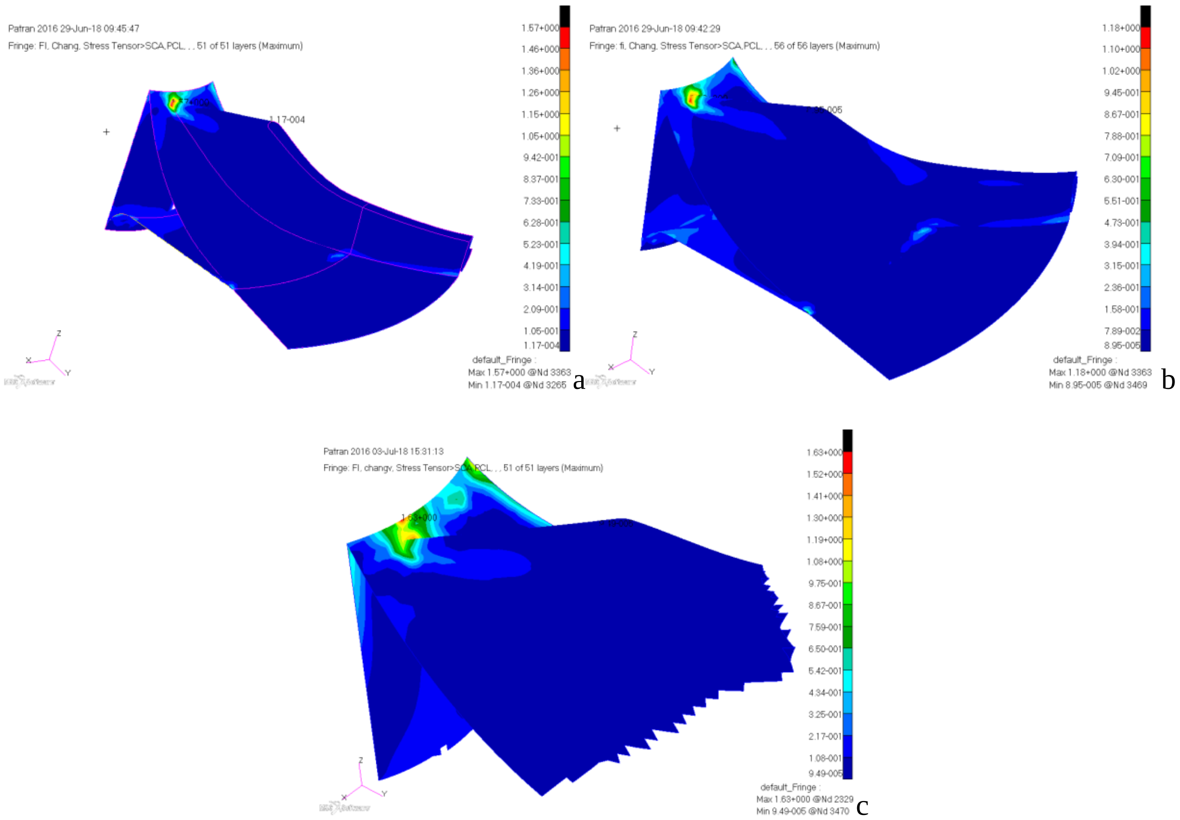


Fig. 8. Yamada-Sun failure criterion indices a) 22 plies disc and 7 plies blade areas; b) 22 plies in the disc area, 7 plies on 2/3 of the blade and 5 plies on 1/3 from the tip; c) 44 plies disc and 7 plies blade areas

Results and discussions

Succeeding a numerical simulations campaign, an optimum geometrical configuration was defined taking into account both manufacturing technological issues as well as aerodynamic considerations.

Computational fluid dynamics (CFD) analysis showed small differences between the carbon fiber cases that may fall within the assumed numerical error of the method. Therefore it is the conclusion of this stage that the restrictions generated by the TRL are quantifiable but not particularly significant, considering the added benefits of weight and manufacturing time/cost. Starting from the selected advanced composite material precursors, an optimum structural configuration was defined. The final CFRP (Carbon Fiber Reinforced Polymer) composite exhibits a 120°C Tg assuring thermal requirements resistance since during exploitation compressor impeller blades are exposed to temperature range [20-100°C]. Likewise with respect to functioning environment, selected epoxy blend exhibit good impact and abrasion resistance, good stability under UV. Compact, void free complex structures (i.e. blade impeller) were obtained on first trials by applying vacuum for air extraction and external pressure during thermal activation of the polymer curing process (high performance technology-autoclave). Regarding mechanical strength, stress analysis campaign shows that according to Yamada-Sun criterion a failure region appears under blade bending regime, due to compliance difference between the disc and the blade region (22 plies to 7 plies) but also due to the uniform distribution of the mass on the blade, which increase the value of inertial forces which are applied and implicitly the loading caused by the bending solicitation. Previous study experimental mechanical tests showed that for a 2 mm constant section the composite material presently under investigation exhibits a 940 MPa maximum bending strength. Thus the main issue is not mechanical strength resistance of the composite material but choosing the proper compliance difference ratio between the disc and the blade region. Thus, two other structural configurations with respect to these issues were investigated showing that failure criterion indices decreased, leading to migration of the failure region to the disc hub, when stiffening the disc region by adding supplementary plies of composite. This inconvenient shall be eliminated afterwords by the integration of the metallic sleeve, which assures also the impeller drive.

Conclusions

By reduction the total weight of the rotary assembly, better performances can be achieved related to fuel consumption and polluting emissions reduction, in order to reduce the environmental impact. Likewise higher payloads can be obtained for used in other compressor/engine components. The paper presents results related to a complete technological cycle for the development of a full CFRP (Carbon Fiber Reinforced Polymer) centrifugal compressor impeller, starting from geometric design, aerodynamic air flow studies done to establish new design performances, selecting the advanced composite material precursors, performing stress analyses validation of mechanical strength, defining the manufacturing technological stages, developing the first trials for technological cycle validation. Numerical simulations, both CFD and stress analysis, showed that equally high strength and aerodynamic performances can be obtained on the new designed CFRP composite impeller.

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