Applications of design and reverse engineering for the development of digital and smart tools for composite additive manufacturing

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Abstract: *This paper presents a study dedicated to the development of Digital and Smart Tools, based on solved applications of design engineering and reverse engineering. This approach is justified by the fact as well as the need for preparations prior to Composite Additive Manufacturing. Future integration of Digital Smart Tools with Composite Additive Manufacturing will significantly contribute to the efficient and effective support of the green economy, the active, responsible, safe and resilient protection of environment, life and climate. The research involved in this paper contributes to develop Digital and Smart Tools Applications, intended for integrated digital design, development, manufacturing and further predictive maintenance and services, based on robotic systems, extended automatic control, Artificial Intelligence and Machine Learning, including Mathematical Modeling and Numerical Simulations for Performance Prediction at Design Regime and Off-Design Regimes for jet engines, with the best capabilities to generate and integrate improvements, optimizations and potential innovative solutions. This paper presents significant applications of design, concept engineering development and reverse engineering design, as: 1/ the design of a transonic axial compressor rotor blade, 2/ the design of a swept axial compressor rotor, 3/ concept design engineering developments in case of a swept fan rotor blade, 4/ concept design developments and reverse engineering in case of a HP axial compressor rotor blade, part of Spey 512-14 DW turbofan engine, 5/ reverse engineering design of a Cessna 182*

Skylane N223IF light aircraft wheel cover. In line with Europe´s vision for sustainable aviation, this research study and INCAS′ TGA Project "Technological Development Platform for "Green" Technologies in Aviation and Ecological Manufacturing with Superior Added Value; TGA - Technologies for Green Aviation" will significantly contribute to the Green Deal, as a production center using "Green" Technologies in aviation and ecological manufacturing, as well as collaborative developer of Digital and Smart Tools for Composite Additive Manufacturing.

Key Words: *Engineering Design, Reverse Engineering, Concept Development, Digital and Smart Tools, Composite Additive Manufacturing*

1. INTRODUCTION

In accordance with the European objective for sustainable aviation [1], the INCAS TGA project aims to establish a “Technology Development Platform for 'Green' Aviation Technologies and Green Manufacturing with superior value-added.” TGA, namely Technologies for Green Aviation, will make a meaningful contribution to the Green Deal. TGA functions as a production center that employs "green" technologies in aviation and green manufacturing. It is also a collaborative developer of digital and smart tools for additive manufacturing of composite materials, which can further enhance the use of such materials in aviation. Manufacturing aircraft and aerospace vehicles from composite materials has the direct consequence of reducing their weight, thus significantly lowering fuel consumption. This reduction ultimately contributes to mitigating the environmental impact, creating a cleaner and greener environment. Composite materials, [27, 34-36, 45-47], are widely used today in aerospace engineering design, [17-21], due to their provided advantages, such as: lighter weight, the ability to tailor the layup for optimum strength and stiffness, improved fatigue life, corrosion resistance, long working life, lower density with respect to steel alloys, high strength to weight ratio, low coefficient of thermal expansion, five times stronger than steel, reduced assembly costs due to fewer detail parts and fasteners in case of mastering good design practice. On the other hand, disadvantages of composites, [4-5, 34-36], must be taken into account and contingency plans must be provided, where applicable or available; disadvantages of composites refer to: high raw material costs and usually high fabrication and assembly costs, adverse effects of both temperature and moisture, poor strength in the out of plane direction where the matrix carries the primary load, susceptibility to impact damage and delimitations or ply separations, greater difficulty in repairing composite parts when compared to metallic structures. Safety, security and resilience are important goals for aviation pillars in Europe´s vision for sustainable aviation, [1]. Effectively achieving the goals of safety, security and resilience requires the implementation and active use of safety risk-based assessment and mitigation at strategic and operational levels [4-5]. This should be done at all phases, including design, development, manufacturing, testing, certification and MRO, which includes digital design, manufacturing, predictive maintenance and services. Risk Management is important for Engineering Design, [17-21], since its feedback can produce a strong impact over the initial solution, thus leading to solution improvements and ultimately optimizations of the solution. The research involved in this paper contributes to develop Digital and Smart Tools Applications, intended for integrated digital design, concept development, reverse engineering, 3D additive manufacturing, [45-47], based on robotic systems, extended automatic control, AI and Machine Learning, including direct link and feedback from Mathematical Modeling and Numerical Simulations on Aerodynamics, Structural Analysis and Performance Prediction at Design Regime and Off-Design Regimes for jet engines, [39-44]. The study presented in this paper refers to applications: # 1/ design of transonic axial rotor blade cascade geometry, [10], from the aerodynamics, kinematics and thermodynamic parameters, determined at Design Regime, for the first stage transonic rotor of a NASA 7 staged axial compressor reference case, NASA CR-54532, [2], NASA CR-54531, [3]; # 2/ design of an axial compressor rotor blade with sweep effect, [10]; # 3/ concept design engineering developments for swept fan blades; # 4/ concept design developments together with reverse engineering in case of an axial compressor rotor blade, a part of intermediate stage of the 12 stage HP compressor of Spey 512-14 DW low-by pass turbofan engine; # 5/ reverse engineering design of a Cessna 182 Skylane N223IF light aircraft wheel cover, [6-7].

2. DESIGN ENGINEERING IN CASE OF TRANSONIC AXIAL COMPRESSOR ROTOR BLADE

The Test Case # 1 is represented by the first stage transonic rotor of a NASA 7 staged axial compressor, NASA CR-54532, [2], NASA CR-54531, [3], where the fluid flow path and radial distributions of energy, stagnation pressure, stagnation temperature and stage velocity diagram or axial velocity ratio have been calculated, [10], based on the Full Radial Equilibrium Theory, [16]. The main stage thermodynamic parameters (specific work on compression, stage pressure ratio, first stage rotor pressure ratio and first stage stator pressure loss), as listed in Table 1, resulted from calculations, [10].

Table 1 – Axial Compressor First Stage - Main Thermodynamic Parameters, Andrei I. C. [10]

No.	Parameter Nomenclature	Notation	Value	Units
1	stage specific work on compression	$l^*_{C\_stage1}$	34.2	$[kJ/kg]$
2	stage pressure ratio	$\pi^*_{C\_stage1}$	1.4243	$[-]$
3	first stage rotor pressure ratio	$\pi^*_{C\_rotor1}$	1.4312	$[-]$
4	first stage stator pressure loss coefficient	$\sigma^*_{stator1}$	0.9952	$[-]$

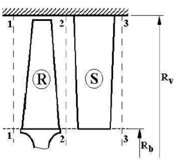


Fig. 1 - Axial Compressor Stage, [10]

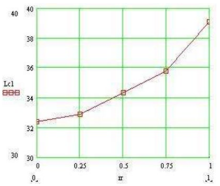
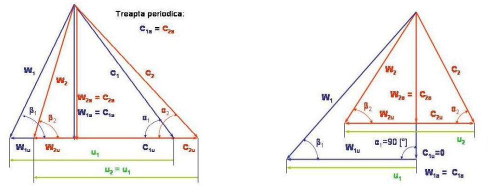


Fig. 2 – Distribution of specific work, [10]



(a) – Periodical Stage (b) – Non-Periodical Stage

Fig. 3 – Velocity Diagram for the Axial Compressor Blade Cascade, [10]

The Kinematics of Axial Compressor Blade Cascade is represented by the Velocity Diagram, Fig. 3. In case of a periodical stage, the axial component of the velocity is constant, Fig. 2.a, while in case of a non-periodical stage, the axial component of the velocity decreases at stage exit, Fig. 2.b.

In case of the first stage, a particular design issue resides in the fact that the flow inlet has only the axial component of the velocity, but no tangent component at first stage inlet, Fig. 2.b. The velocity diagram vectors determine the deflection of the fluid flow and by way of consequence, the twist of the blade airfoil.

The design of the blade airfoil results from the kinematics of the blade cascade. The design of the axial compressor stage using the Full Radial Equilibrium Theory, [16], allows to obtain a solution as close as possible to the real construction case. Other options for the radial design law, which can be used in axial compressor design and consequent calculation of its aerodynamics and blading design of multistage axial compressors, [11-16], are synthetized in Table 2.

Table 2 – Radial Design Laws for the Axial Compressor Stage, [10].

No.	Radial Design Law	Blade spanwise variation of Tangential Velocity $C_u = f(R)$	Blade spanwise variation of stage specific work on compression $l_u^* = f(R)$
1	Solid Body	$C_u = D \cdot R$, where $D = const.$	$l_u^* = f(R)$
2	Constant Vortex	$C_u = B/R$, where $B = const.$	$l_u^* = const. \neq f(R)$
3	Constant Reaction Degree	$C_u = \mp B/R + D \cdot R$, where $B, D = const.$	$l_u^* = const. \neq f(R)$
4	Full Radial Equilibrium Theory	$C_u = \frac{B}{R} + C + D \cdot R + \frac{A}{R^2} + E \cdot R^2$, where $B, C, D, A, E = const.$	$l_u^* = f(R)$

Table 3 – Radial Blade Cross Sections/ Blade Spanwise Sections, [10].

Blade Spanwise Sections	**B** HUB	**BM** Intermed	**M** MID Span	**MV** Intermed	**V** TIP
Ratio $\left(\frac{R-R_B}{R_V-R_B}\right) \equiv [\%] \cdot$ $Blade\ Span$	0 %	25 %	50 %	75 %	100 %

The geometry of the first stage axial compressor transonic rotor blade results [10] completely determined from the cascade aerodynamics, thermodynamic parameters and the velocity diagram of the axial compressor first stage, [11-16, 48-49].

Table 4 contains all the details regarding the determined geometry, for the first stage axial compressor transonic rotor blade, calculated by using the Full Radial Equilibrium Theory, [10].

Table 4 – Calculated Design Parameters for the first stage axial compressor rotor blade, Andrei I. C. [10]

Parameter	Blade Spanwise Sections				
	B Blade HUB	**BM**	**M** MID Span	**MV**	**V** Blade TI
NACA 65 Airfoils	**65(22)12**	**65(21)11**	**65(20)10**	**65(19)09**	**65(18)08**
Airfoil Chord = b $[mm]$	88	73	62	54	48
Cascade Spacing = t $[mm]$	39	42	42	39	37
Relative Spacing = $\bar{t}$, $[-]$	0.439	0.579	0.683	0.724	0.770
Camber angle θ [°]	37.838	23.789	14.665	11.652	8.670
Stagger angle β_f [°]	60.605	50.500	41.901	38.165	33.874
Reynolds number, $[-]$, calculated from relative velocity, airfoil chord	$> 1.10 \cdot 10^6$	$> 1.18 \cdot 10^6$	$> 1.24 \cdot 10^6$	$> 1.19 \cdot 10^6$	$> 1.19 \cdot 10^6$
Inlet flow angle β_1 [°]	43.692	38.710	34.084	31.777	28.972
Exit flow angle β_2 [°]	68.917	54.569	43.861	39.545	34.752
Cascade deflection angle $\Delta\beta$ [°]	25.225	15.859	9.777	7.768	5.780
Diffusion factor D_R, $[-]$	0.3088	0.3588	0.3544	0.3477	0.3474
Inlet Mach number, absolute flow, M_{C1}	0.5320	0.5750	0.6050	0.6120	0.6160
Exit Mach number, absolute flow, M_{C2}	0.6954	0.6497	0.6205	0.6098	0.5949
Inlet Mach number, relative flow, M_{W1}	0.7690	0.9250	1.0800	1.1620	1.2720
Exit Mach number, relative flow, M_{W2}	0.5857	0.6564	0.7620	0.8229	0.8954
Radius at cascade inlet, R_1, $[mm]$	318.00	397.25	476.50	555.75	635.00
Radius at cascade exit, R_2, $[mm]$	378.00	442.25	506.50	570.75	635.00
Ratio of Radii, $\bar{r} = R/R_V$, $[-]$	0.50÷0.60	0.63÷0.70	0.75÷0.80	0.88÷0.90	1.00

Table 5 – Calculated Reaction Degree, Flow Coefficient and Load Coefficient, Andrei I. C. [10]

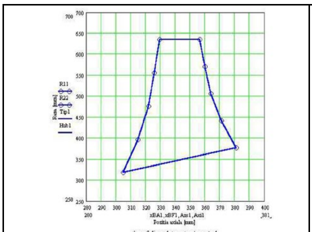
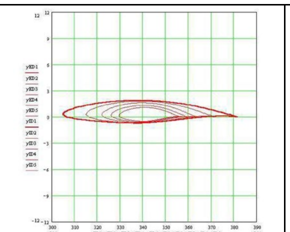
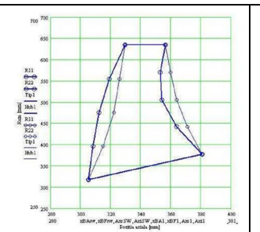
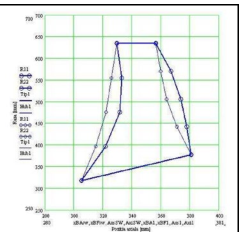
Parameter	Blade Spanwise Sections				
	B Blade HUB	**BM**	**M** MID Span	**MV**	**V** Blade TIP
Reaction Degree, ρ_c, $[-]$	0.730	0.843	0.907	0.931	0.962
Flow Coefficient, $\overline{C_a}$, $[-]$	0.6455	0.6549	0.6063	0.5711	0.5211
Load Coefficient, $\overline{l_u}$, $[-]$	0.6242	0.4660	0.3585	0.3208	0.2925

Table 6 – Calculated Blade Spanwise Distribution of Velocities, at cascade inlet, Andrei I. C. [10]

Parameter	Blade Spanwise Sections				
	B Blade HUB	**BM**	**M** MID Span	**MV**	**V** Blade TIP
Axial velocity, C_a, $[m/s]$	140.107	177.567	195.919	200.251	202.122
Radial velocity, C_r, $[m/s]$	106.546	69.494	33.740	16.940	-2.130
Tangential velocity, C_u, $[m/s]$	0.00	0.00	0.00	0.00	0.00
Mach number, absolute velocity flow, M_C	0.5320	0.5750	0.6050	0.6120	0.6160
Mach number, relative velocity flow, M_W	0.7690	0.9250	1.0800	1.1620	1.2720

Table 7 – Calculated Blade Spanwise Distribution of Velocities, at cascade exit, Andrei I. C. [10]

Parameter	Blade Spanwise Sections				
	B Blade HUB	**BM**	**M** MID Span	**MV**	**V** Blade TIP
Axial velocity, C_a, $[m/s]$	153.941	170.392	179.392	181.263	178.813
Radial velocity, C_r, $[m/s]$	106.662	70.656	36.78	19.839	-0.771
Tangential velocity, C_u, $[m/s]$	147.368	127.175	113.063	108.579	107.070
Mach number, absolute velocity flow, M_C	0.6954	0.6497	0.6205	0.6098	0.5949
Mach number, relative velocity flow, M_W	0.5857	0.6564	0.7620	0.8229	0.8954

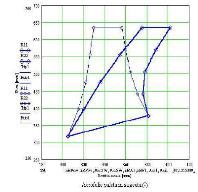
			
(a) – Airfoil Surface	(b) – Airfoil Stacking	(a) – Forward Sweep	(b) – Backward Sweep
Fig. 4 – Resulting Geometry for the first stage transonic Axial Compressor Rotor Blade, [10]		Fig. 5 – Numerical Simulations of sweep: [0, 5, 7, 5, 0], (*left*), [0, -5, -7, -5, 0], (*right*), [10]	

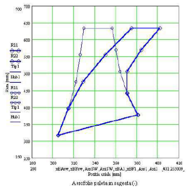
3. DESIGN ENGINEERING IN CASE OF TRANSONIC AXIAL ROTOR SWEPT BLADE

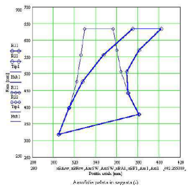
The design application # 2 for a swept rotor blade has been carried on as an extended study of Test Case #1 with the application of sweep, [10]. A **NACA 65(20)10** Airfoil cascade, staggered at Mid Span Section, is considered as a reference. The application of sweep effect is intended to improve the performance of the blade cascade, by mitigating losses, since it reduces the blade cascade relative velocity to a subsonic flow, so as to prevent the occurrence of shockwaves and the boundary layer separation, and/or boundary layer re-attachment.

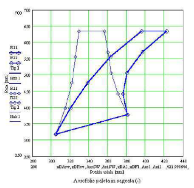
Table 8 – The blade spanwise variation of sweep angle, in case of forward & backward sweep, Andrei I. C. [10]

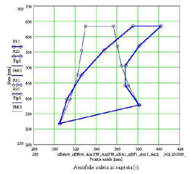
Parameter: Sweep angle χ [°]	Blade Spanwise Sections				
	B Blade HUB	**BM**	**M** MID Span	**MV**	**V** Blade TIP
Un-swept Blade	0	0	0	0	0
Forward Swept Blade	0	5	7	5	0
Backward Swept Blade	0	-5	-7	-5	0

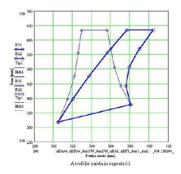

(a) – Sweep [0, -4, -10, -20, -30]

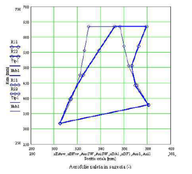

(b) – Sweep [0, 0, -5, -17, -30]

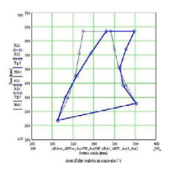

(c) – Sweep [0, 0, -5, -16, -30]

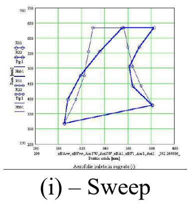

(d) – Sweep [0, -4, -12, -25, -40]

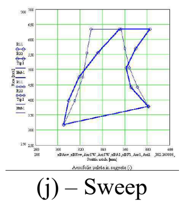

(e) – Sweep [0, 2, -3, -15, -30]

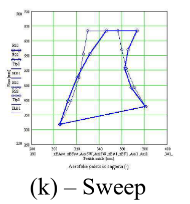

(f) – Sweep [0, -4, -11, -21, -30]

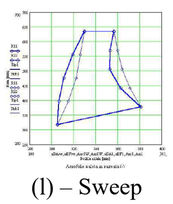

(g) – Sweep [0, -1, -2, -9, -16]

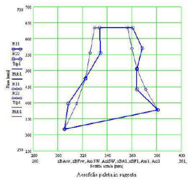

(h) – Sweep [0, 2, -1, -8, -16]

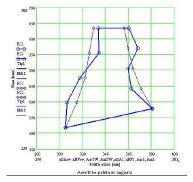

(i) – Sweep [0, -15, -4, 1, -10]

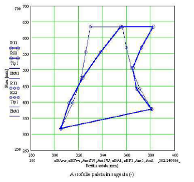

(j) – Sweep [0, 4, 2, -7, -10]


(k) – Sweep [0, 2, 1, -4, -12]


(l) – Sweep [0, 6, 8, 5, 0]


(m) – Sweep [0, 5, 0, -6, -3]


(n) – Sweep [0, 6, 3, -6, -3]


(o) – Sweep [0, 2, -1, -9, -18]

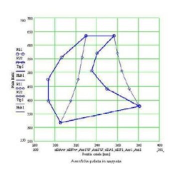
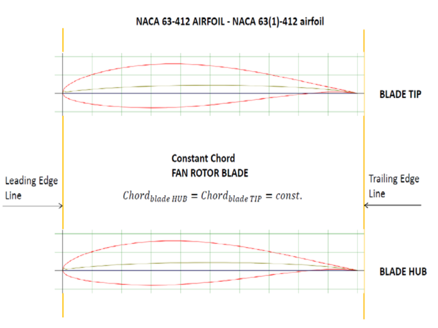

(p) – Sweep [0, 14, 20, 15, 0]

Fig. 6 – Numerical Simulations: Sweep angle χ[°], resulting swept blade vs. un-swept blade shapes, [10]

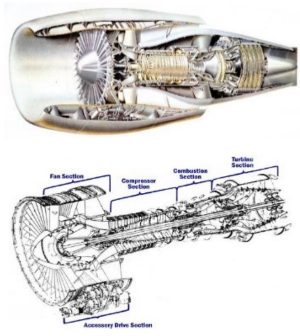
Numerical Simulations of sweep effect applied to a transonic axial compressor rotor blade, generated swept blade versus un-swept blade shapes, Fig. 6, (a÷p), Andrei I. C., [10].

4. CONCEPT DESIGN ENGINEERING DEVELOPMENTS IN CASE OF A SWEPT FAN ROTOR BLADE

The geometry of the fan blade results from the aerodynamics of the cascade, the kinematic and thermodynamic parameters of the stage, similarly with the case of the axial compressor rotor blade.



(a) – Generating the Airfoil Surface in case of a Fan Rotor Blade, with constant chord Blade spanwise and no sweep effect, similar to GE **CF6-6** Turbofan Engine´s Fan Blade



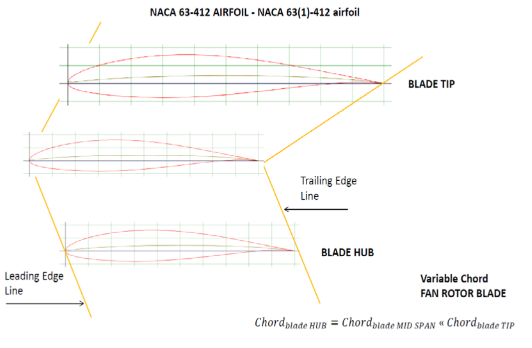
(b) – General Electric **CF6-6** Turbofan Engine, cutaway (*up*), diagram (*down*), https://en.wikipedia.org/wiki/General_Electric_CF6

Fig. 7 – Concept Design Development in case of a Fan Blade with constant chord, no sweep effect

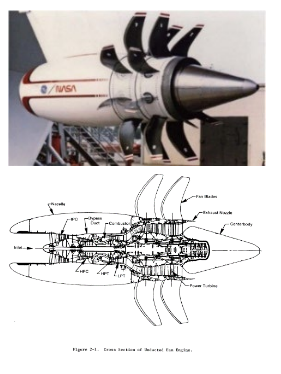
Hence from calculations it results the airfoil at each blade spanwise section, cascade deflection and stagger angle which express the blade spanwise torsion and airfoil stacking. Aerospace engineering design, [26-36], is completed with Concept Design Developments together with Design, Modeling and Shape Generation as grounds for the development of Digital and Smart Tools.

As a result of the sweep effect application, the shape and position of the **Airfoil Surface Generator Lines** are obtained: 1/ **Leading Edge LE Line** and 2/ **Trailing Edge TE Line**. The definition of the Airfoil Surface is completed with the **Blade Hub Line** and **Blade Tip Line**, which is usually a line parallel to the horizontal axis (i.e.: the axis of rotation of the compressor/fan/jet engine).

In case of the blade with spanwise constant chord, the **Airfoil Surface Generator Lines** (**Leading Edge Line**, **Trailing Edge Line**) are straight parallel lines and the **Airfoil Surface** is obtained by arranging the airfoils at the specified blade spanwise sections, being framed by **Leading Edge Line** and **Trailing Edge Line**, as indicated in Fig. 7, in case of a fan blade similar with the General Electric CF6-6 Turbofan Engine.



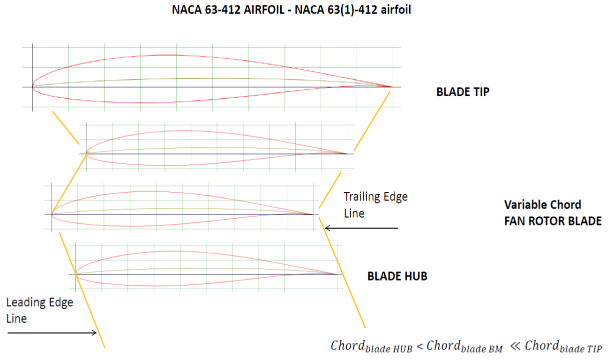
(a) – Generating the Airfoil Surface in case of a PropFan Rotor Blade, with variable chord Blade spanwise and sweep effect, similar to **GE36 Unducted Fan UDF (PropFan)** Engine´s Fan Blade



(b) – General Electric **GE36 Unducted Fan UDF** Engine, cutaway (*up*), schematic diagram (*down*), https://en.wikipedia.org/wiki/General_Electric_GE36

Fig. 8 – Concept Design Development in case of a Fan Blade with variable chord, sweep effect

The **Airfoil Surface Generator Lines** can be defined analytically, by equations describing a line or a curve.



(a) – Generating the Airfoil Surface in case of a Fan Rotor Blade, with variable chord Blade spanwise and multiple sweep effect, similar to **GE9X** Turbofan Engine´s Fan Blade

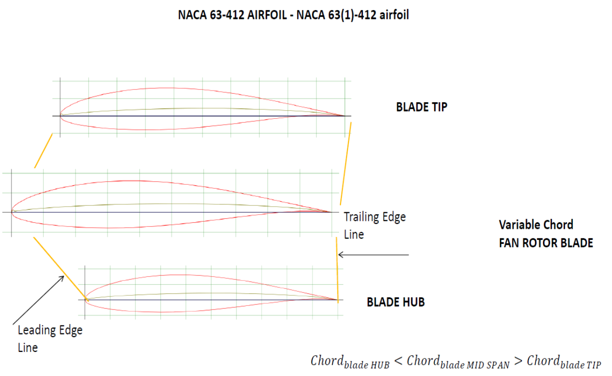
(b) – General Electric **GE9X** Turbofan Engine, cutaway, https://airpowerasia.com/2020/12/20/major-aircraft-turbofan-engine-manufacturers/

Fig. 9 – Concept Design Development in case of a Fan Blade with variable chord, multiple sweep effect

In the case of the blade with spanwise variable chord, the **Airfoil Surface Generator Lines** are split, in accordance with the radial section where the chord modifies.

In case of the blade with sweep effect, the **Airfoil Surface Generator Lines** are split and change the position and orientation in accordance with the radial section where the sweep effect is applied.

In the case of the blade with spanwise variable chord and multiple sweep effect, the **Airfoil Surface Generator Lines** (**Leading Edge Line**, **Trailing Edge Line**) are divided into multiple lines or multiple curves, which may have different positions in space; further, following the setting of airfoils at the specified blade spanwise sections, the **Airfoil Surface** is obtained, being framed by **Leading Edge Line** and **Trailing Edge Line**, as illustrated for similar fan blade constructions, which are parts of operational turbofan engines, Fig. 8÷11.

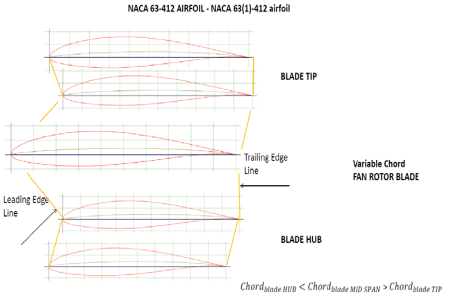


(a) – Generating the Airfoil Surface in case of a Fan Rotor Blade, with variable chord Blade spanwise and sweep effect, similar to General Electric **CF34-10** Turbofan Engine´s Fan Blade

(b) – General Electric **CF34-10** Turbofan Engine, cutaway (*up*), diagram (*down*), https://www.geaerospace.com/propulsion/commercial/cf34

Fig. 10 – Concept Design Development in case of a Fan Blade with variable chord, sweep effect

Concluding remarks for Concept Design Developments in case of swept fan blades:



(a) – Generating the Airfoil Surface in case of a Fan Rotor Blade, with variable chord Blade spanwise and multiple sweep effect, similar to GE **CFM LEAP-X** Turbofan Engine´s Fan Blade

(b) – General Electric **CFM LEAP-X** Turbofan Engine, cutaway (*up*), diagram (*down*), https://en.wikipedia.org/wiki/CFM_International_LEAP

Fig. 11 – Concept Design Development in case of a Fan Blade with variable chord, multiple sweep effect

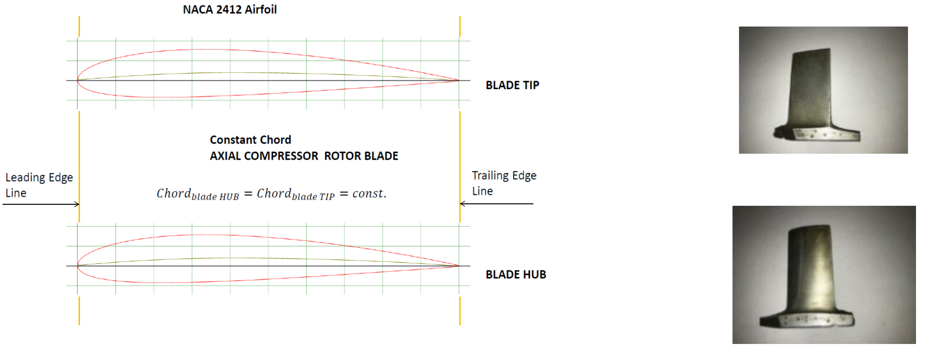
- The geometry of the blade is determined from calculating its aerodynamics, kinematics and thermodynamics parameters, [11-16, 48-49];
- The blade Airfoil Surface is defined by the spanwise distribution of airfoils (usually NACA airfoils; in case of transonic blade cascades, NACA 6 series, NACA 65 airfoils are efficient), being framed by Leading Edge Line and Trailing Edge Line.
- Blade cascade airfoils are stacked from blade hub to blade tip, at each radial section (i.e. blade spanwise section) having different rotations, being influenced by the stagger angle and cascade deflection angle, thus resulting the blade´s torsion.
- After the Airfoil Surface Generator Lines (Leading Edge Line, Trailing Edge Line) have been set, the Airfoil Surface is obtained by arranging the airfoils at the specified blade spanwise sections, being framed by Leading Edge Line and Trailing Edge Line.
- Concept Design Developments for swept fan blades are concluded and highlighted with respect to similar swept fan blade constructions as parts of operational turbofan engines, as follows: in Fig. 7 (GE CF6-6), Fig. 8 (GE36 Unducted Fan UDF/ PropFan), Fig. 9 (GE9X), Fig. 10 (GE CF34-10), Fig. 11 (GE CFM LEAP-X).

5. REVERSE ENGINEERING IN CASE OF AN AXIAL COMPRESSOR ROTOR BLADE

Design application # 4 shows concept design developments and reverse engineering in case of the Study Case: axial compressor rotor blade from intermediate stage of the 12 stage High Pressure HP compressor stages which composes the Spey 512-14 DW low-by pass turbofan engine. The compressor system of the turbofan engine Spey 512-14 DW comprises 5 Low Pressure LP compressor stages and 12 stage HP compressor stages, while the turbine has 2 HP turbine stages and 2 LP turbine stages. Reverse Engineering enables to obtain the geometry of the 3D body, which in this case corresponds to the Airfoil Surface. In case of the axial compressor rotor blade, shown in Fig. 12, from direct observation it resulted that blade spanwise the chord as well as the blade maximum thickness are constant and there is no sweep effect, while direct measurements provided the following data: Blade_chord = 30 [mm] and Blade_max_thickness = 3 [mm]. In case of the blade spanwise constant chord, Airfoil Surface Generator Lines (Leading Edge Line, Trailing Edge Line) are parallel lines. Then the Airfoil Surface is obtained by arranging the airfoils at the specified blade spanwise sections (which usually are defined by Blade Hub **B**, Intermediate Blade **BM**, Blade Mid Span **M**, Intermediate

Blade **MV**, Blade Tip **V**, as defined in Table 3), being framed by Leading Edge Line and Trailing Edge Line.

In this particular case, since the blade chord is constant along the blade span, then the Airfoil Surface is generated by the translation of the NACA 4-digits Airfoil from blade hub to blade tip.



(a) – Generating the Airfoil Surface in case of Study Case Rotor Blade (b) – Study Case Rotor Blade

Fig. 12 – Concept Design Development in case of Study Case Rotor Blade, constant chord, no sweep

Following the selection of the **NACA 2412 Airfoil**, from the NACA 4-digit Airfoils family, then the non-dimensional coordinates (X, Y) as well as the dimensional coordinates (X_r, Y_r) of the **NACA 2412 Airfoil** were calculated. The significance of the digits in case of the NACA 2412 Airfoil, illustrated in Fig. 12, is:

- Max Camber = 2 (%); first digit can range between 0 to 9.5%;
- Max Camber position = 40 (%); second digit can range between 0 to 90%;
- Thickness = 12 (%), third & fourth digit can range between 1 to 40%.
- Remark: for **NACA 2412 Airfoil** the Max thickness is 12% at 30.7% chord and Max camber is 2% at 38.3% chord.

The relations between the non-dimensional coordinates (X, Y) and the dimensional coordinates (X_r, Y_r) are:

$$X_r[mm] = X[-] \cdot \text{Blade\_chord}\ [mm] \tag{1}$$

$$Y_r[mm] = Y[-] \cdot \text{Blade\_max\ \_thickness}\ [mm] \tag{2}$$

Concluding remarks for Concept Design Developments in case of axial compressor rotor blade, which are similar with the case of the fan blade:

1/ The geometry of the blade is determined from calculating its aerodynamics, kinematics and thermodynamics parameters;

2/ The blade Airfoil Surface is defined by the spanwise distribution of airfoils (usually NACA 4 series, but can be selected NACA 5 series or NACA 6 series in higher velocities up to case of transonic blade cascades), being framed by Leading Edge Line and Trailing Edge Line.

3/ Blade cascade airfoils are stacked from blade hub to blade tip, at each radial section (i.e. blade spanwise section) having different rotations, being influenced by the stagger angle and cascade deflection angle, thus resulting the blade´s torsion.

4/ Once being set the Airfoil Surface Generator Lines (Leading Edge Line, Trailing Edge Line), then the Airfoil Surface is obtained by arranging the airfoils at the specified blade spanwise sections, being framed by Leading Edge Line and Trailing Edge Line.

6. REVERSE ENGINEERING IN CASE OF A LIGHT AIRCRAFT WHEEL COVER

Design application # 5 refers to the reverse engineering design of a Cessna 182 Skylane N223IF light aircraft wheel cover, [6].

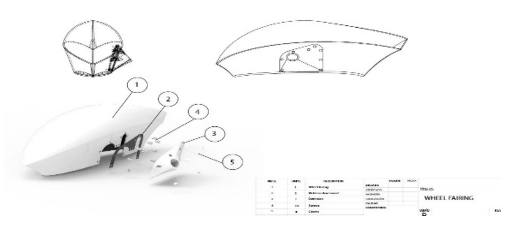


Fig. 13 – Wheel Cover 3D Modelling, [6]

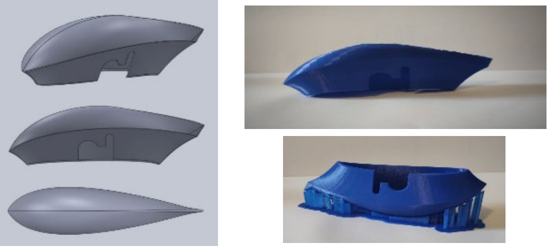
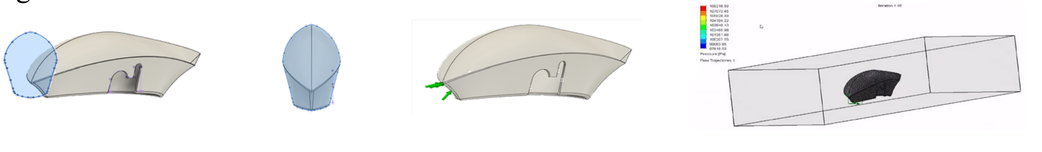


Fig. 14 – Wheel Cover Demonstrator, [6]

This study and specific application of reverse engineering, [6-7], was achieved during the research stage developed in INCAS by the students participating within the international multicultural and pluri-disciplinary project: EUROPEAN PROJECT SEMESTER, within the collaboration (established by the Partnership Agreement) between INCAS and ″POLITEHNICA″ National University of Science and Technology of Bucharest (UPB). The results of the research carried out with the EPS student teams were disseminated through papers [4-9]. As Study Case was considered the Cessna 182 Skylane N223IF aircraft, [6], which is a light aircraft, four seats, incorporating Aluminium alloy, fiberglass, and thermoplastic materials, which belongs to the category of short-range aircraft, purposed for training/ school aircraft and VIP transport. The wheel cover of Cessna 182 Skylane N223IF light aircraft is made by composite materials and it is mounted on the gear legs.

The functions of the wheel cover are intended to: a/ contribute to the reduction of aircraft drag, b/ save fuel, c/ cancel or mitigate the airflow around the tires, d/ prevent the ingestion or the impact on aircraft structure of stones, rocks and mud. The wheel cover is an aerodynamically shaped body, with axial symmetry in top view and no axial symmetry in side view; thus, the design of the wheel cover is based on NACA Airfoils. The NACA 0024 Airfoil was used to define the axial symmetry in top view, and NACA 4418 Airfoil for the side view, in order to developing the design of the light aircraft wheel cover. The design of the wheel cover was completed with 3D modeling, as indicated in Fig. 13. The final product is the Wheel Cover Demonstrator, which was scaled 1 to 10, [6], as result of 3D Additive Manufacturing, presented in Fig. 14.



(a) areas subjected to aerodynamic forces

(b) action: pressure

(c) action: wind flow velocity

Fig. 15 – Aerodynamic loading scheme, [6]

The reverse engineering application was completed with the study of Aerodynamics (i.e. aerodynamic loads) and Structural Analysis. The aerodynamic loading scheme, Fig. 15, with the pressure set to 0.185 [MPa], in correlation with the wind velocity, the aerodynamic analysis based on CFD Fluent code and Structural Analysis based on ANSYS code have been performed for the composite (Lignine + carbon fiber 10%) wheel cover.

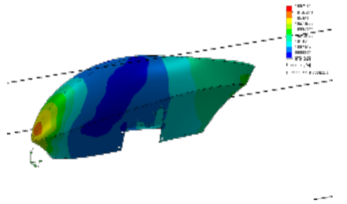
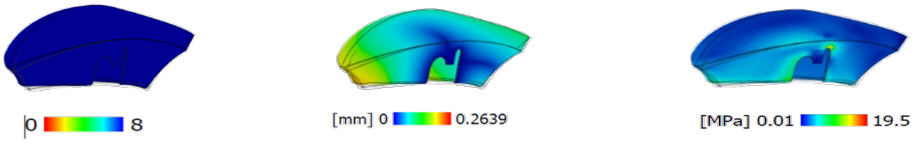


Fig. 16 – Results from Numerical Simulations: Aerodynamics of Flow, [6]



(a) safety factor (b) displacement (c) Von Mises

Fig. 17 – Results from Numerical Simulations: Structural Analysis, [6]

The properties of the material are:

Density = 1.43 E-6 [kg/mm^3],
Young Modulus = 133000 [MPa],
Poisson's ratio = 0.39,
Yield Strength = 300 [MPa],
Ultimate Tensile Strength = 577 [MPa].

The results from Numerical Simulations are concluded graphically in Fig. 16 - Aerodynamics of flow, [6] and in Fig. 17 – Structural Analysis, [6].

7. CONCLUSIONS

This paper presents a thorough study concerning custom solved applications of design engineering, concept development and reverse engineering, in order to develop Digital and Smart Tools for composite additive manufacturing. Such approach is justified by the fact as well as the necessity of the preparations prior to Composite Additive Manufacturing. The research presented in this paper contributes to develop Digital and Smart Tools Applications, intended for integrated digital design, development, manufacturing and further predictive maintenance and services, based on robotic systems, extended automatic control, Artificial Intelligence and Machine Learning. Together with prior INCAS´ researches including Mathematical Modeling and Numerical Simulations for Performance Prediction at Design Regime and Off-Design Regimes for jet engines, the future integration of Digital and Smart Tools with Composite Additive Manufacturing, with the included feature to generate and integrate improvements, optimizations and potential innovative solutions, will significantly contribute to efficient and effective support of green economy, active, responsible, safe and resilient protection of environment, life and climate. This paper presents significant applications of design, concept engineering development and reverse engineering: 1/ the design of a transonic axial compressor rotor blade, 2/ the design of a swept axial compressor rotor blade, 3/ concept design engineering developments in case of swept fan rotor blades, 4/ concept design developments and reverse engineering in case of a HP axial compressor rotor blade, part of Spey 512-14 DW turbofan engine, 5/ reverse engineering design of a Cessna 182 Skylane N223IF light aircraft wheel cover. The study regarding the light aircraft wheel cover reverse engineering design, was achieved during the research stage developed in INCAS by

the students participating within the international multicultural and pluri-disciplinary project: EUROPEAN PROJECT SEMESTER, within the collaboration (established by the Partnership Agreement) between INCAS and ″POLITEHNICA″ National University of Science and Technology of Bucharest (UPB). The results of the research carried out with the EPS student teams were disseminated through papers [4-9]. The research study to support INCAS´ TGA Project was also disseminated through papers [4-7] and [22-25]. From the standpoint of performance improvement, together with the application of sweep can also be included the application of dihedral effect, [10] to be integrated within Digital and Smart Tools, and further, aiming to enhance the abilities of the Digital and Smart Tools, by its adding of new features.
In line with Europe´s vision for sustainable aviation, [1], this research study and INCAS´ TGA Project "Technological Development Platform for "Green" Technologies in Aviation and Ecological Manufacturing with Superior Added Value; TGA - Technologies for Green Aviation" will significantly contribute to the Green Deal, as a production center using "Green" Technologies in aviation and ecological manufacturing, as well as a reliable collaborative developer of Digital and Smart Tools for Composite Additive Manufacturing.

ACKNOWLEDGEMENT

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