

POLITECNICO DI TORINO

Master Degree in Energetic and Nuclear Engineering

Master's Thesis

**Tool development and validation
for fast aeromechanics feedbacks
in LPT preliminary design**



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Ai miei nonni...

Summary

Thanks to the cooperation between Avio Aero and the Politecnico di Torino, it was possible to participate to GREAT 2020 research program, which aim is to find new methods to reduce CO₂, NO_x and noise emissions. The purpose of this thesis work is the development of a tool named *PRIME* (Preliminary Aeromechanics Integrated Environment) able to evaluate, in an automatic and simplified way, the preliminary mechanical and aerodynamic behaviour of a Low Pressure Turbine blade of an aeronautic engine. In this way the interactions between aerodynamic and aeromechanics design are optimized, making the process more robust and smarter, obtaining clear results and saving a lot of time.

The tool generates the 3D airfoil, then it completes the CAD adding consistent inner and outer parametric templates. This process is handled in the Unigraphics NX environment with a managed wizard of an in-house developed tool (*Dynbooster*). Afterwards a Finite Elements Model is created in Ansys Workbench in order to perform static and modal analysis. Results are displayed in a clear and global visualization in a dedicated dashboard.

This thesis work concerns the development and validation of the CAD generation tool, fixing problems occurred testing the entire process and implementing new features inside. In particular template positioning was fixed and a new method to update parameters was introduced to avoid some construction problems. As new features, it was implemented the possibility to have *hollow blades*, creating an internal cavity that follows the external profile. Another feature was implemented in order to create other *four* CAD blades, with each one inclined of a small angle in the axial and tangential directions; this is a fundamental method to assess the correct balance of the blade.

Further developments of *PRIME* will include the development of parametric FE models, able to handle the newly introduced CAD features. In this way the tool will be able to manage the complete preliminary design of next generation LPT stages.

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Chapter 1

Introduction

Focus of this chapter is to introduce the reader to Greatlab, the collaborative project involving GE Avio and Politecnico di Torino. Objectives and development of thesis's workflow will be also introduced.

1.1 GREAT 2020

The GREAT 2020 (GReen Engine for Air Traffic) is a research program intended for development of new technologies necessary to achieve the ACARE goals (Advisory Council for Aeronautics Research in Europe).

Instituted in 2009, GreatLab is the best Italian center of research aimed to the development of strategic technology for the production of eco-compatible aircraft engines that will come into service in 2020.

The main actors of the project GREAT 2020 are:

- *Regione Piemonte*, always committed to promoting the competitiveness of the industrial system of the territory;
- *Avio Aero, a GE business*, leader in the design, production and maintenance of components and systems for civil and military aeronautics;
- *Politecnico di Torino*, contributes to the project through the Department of Mechanical, Aerospace and Energy, Applied Science and Technology Engineering;
- *ISTEC-CRN* (Istituto di Scienza e Tecnologia dei materiali Ceramici), carried out research activities aimed at the study of environmentally friendly processing systems on aeronautical use alloys;

- *Other companies* with high technological content, with specialized and complementary industrial skills and capabilities, especially in the fields of advanced manufacturing, advanced multidisciplinary design, materials science and mechatronics.

The main concrete points of the project to be reached by 2020 are reduction of CO₂, NO_x and noise emissions.

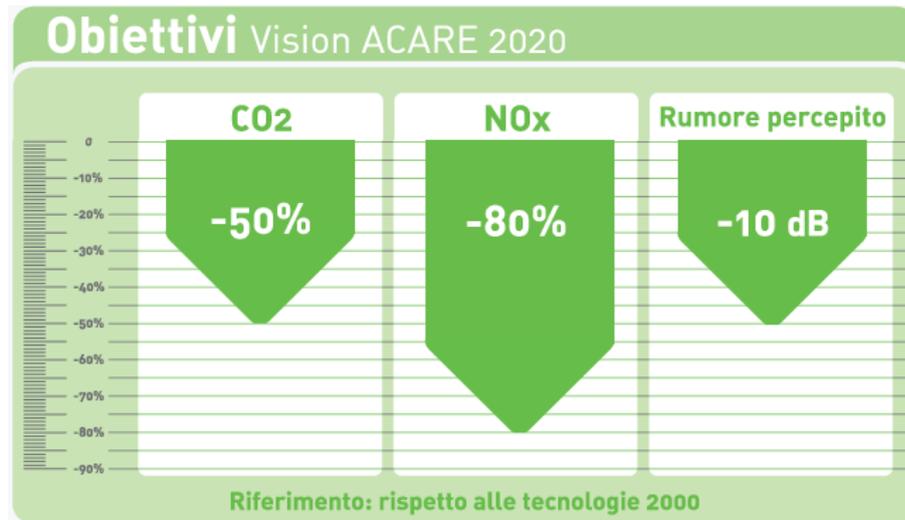


Figure 1.1: GREAT 2020 main goals[1]

If the quantity of CO₂ produced is directly proportional to the quantity of fuel burned, the formation of NO_x also depends on the thermal conditions of the combustion chamber: for example, during take-off, when the temperatures in the combustion chamber are at the highest level, NO_x emissions are maximum.

Increasing the thermal engine efficiency, there is the reduction of CO₂ emissions but it could be disadvantageous for NO_x emissions without specific combustion technologies. The most promising technology, Lean-Burn, is a combustor configuration that provides a high ratio of air to fuel quantity in the area where the flame is generated, limiting the peak temperature and the residence time at high temperatures. [1]

Another way to reduce CO₂ emissions is reducing the weight of the engine. In this field Avio Aero is working in Additive Manufacturing. The process consists in deposit dust layers and then the melting process to make three-dimensional objects. Technologies are Direct Metal Laser Melting (DMLM) which uses a laser beam to fuse the material into the desired shape and Electron Beam Melting (EBM) which uses an electron beam in the material melting process. Blades are made in Tial

alloys so they have better mechanical properties. Other advantages are: dust can be reused because these processes are vacuum, lower weight, lower lead time, lower cost and also possibility to integrate more components all in one. [2]

1.2 Thesis purpose

This thesis work aims at developing a Workbench wizard (PRIME - Preliminary aeRoMechanics Integrated Environment) able to automatically perform all needed mechanical and flutter analysis for the preliminary design of a low pressure turbine (LPT) stage, starting from aerodynamic inputs.

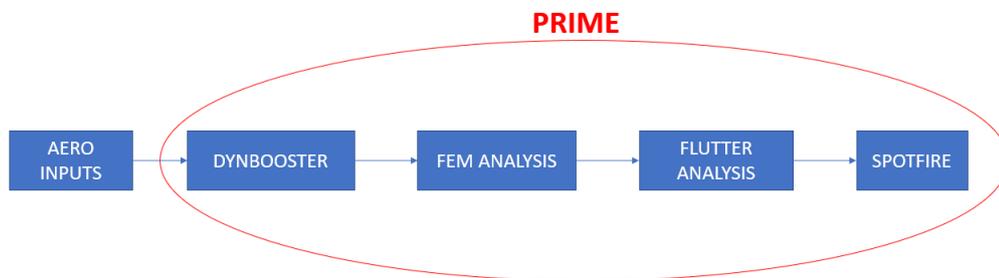


Figure 1.2: PRIME basic scheme

Dynbooster is a GE property software that, having aerodynamic inputs, generate the CAD. It start creating the 3D airfoil and then adding inner and outern components, the 3D blade CAD. It is a complex code written in part in matlab and in part in C++ language.

Then in PRIME a finite element model is constructed and the required preliminary analysis is done. This tool has the purpose of automatizing, simplifying and speeding up the process of analysis between aerodynamic data and structural constraints. It gets back fast aeromechanics feedbacks with an easy way to visualize them thanks to a dedicated dashboard.

Focus of my work was to test and validate Dynbooster process. Testing it, there were found some mistakes expecially in the positioning of the templates respect to the airfoil. As regards this aspect, a new updating method is implemented to avoid some software limitations.

As new features, it was implemented the possibility to create hollow blades to reduce as much as mechanical constraints can the weight of the blade and consequently of the entire engine. At the moment this configuration is easily achievable thanks to Additive Manufacturing processes. To evaluate the correct balance of

the blade a new feature was implemented in PRIME process. It consist in creating four different CAD inclined of a small angle in the axial and tangential directions and perform with them static analysis to find if there are critical stress areas.

The results and graphics will be presented in a qualitative way and the parts will be referred to without specifying any absolute engine, in order to preserve the intellectual property of the company.

Chapter 2

Aeronautical Engines

In 1913 a French engineer, Renè Lorin, patented a jet propulsion engine, but this was at that period impossible to manufacture or use, since suitable heat resisting materials had not then been developed and, in the second place, jet propulsion would have been extremely inefficient at the low speeds of the aircraft of those days. However, today the modern ram jet is very similar to Lorin's conception.

In 1930 Frank Whittle was granted his first patent for using a gas turbine to produce a propulsive jet, but it was eleven years before his engine completed its first flight.

The Whittle engine formed the basis of the modern gas turbine engine. The jet engine, although appearing so different from the piston engine-propeller combination, applies the same basic principles to effect propulsion. [3]

Jet propulsion is a practical application of Sir Isaac Newton's third law of motion which states that, "for every force acting on a body there is an opposite and equal reaction". For aircraft propulsion, the "body" is atmospheric air that is caused to accelerate as it passes through the engine. The force required to give this acceleration has an equal effect in the opposite direction acting on the apparatus producing the acceleration.

2.1 Turbojet

The gas turbine engine is essentially a heat engine using air as a working fluid to provide thrust. To achieve this, the air passing through the engine has to be accelerated; this means that the velocity or kinetic energy of the air is increased. To obtain this increase, the pressure energy is first of all increased, followed by the addition of heat energy, before final conversion back to kinetic energy in the form of a high velocity jet efflux.

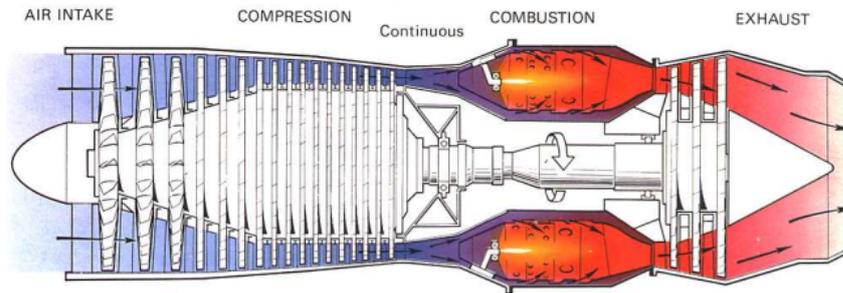


Figure 2.1: Cross section of a turbojet engine

The engine is composed of 5 basic components (figure 2.2): [4]

1. Diffuser (air intake), taking air from the outside and regulating the flow for the compressor, generally with a divergent shape to decelerate the flow;
2. Compressor, usually divided into LPC (low pressure compressor) and HPC (high pressure compressor);
3. Combustor, where combustion of a mixture of air and fuel (around 50:1 ratio) takes place. The limit temperature of combustion is always defined by the materials of the components;
4. Turbine, usually divided into HPT (high pressure turbine) and LPT (low pressure turbine), has the task of expanding the gas to extract power and keep the compressor rotating;
5. Nozzle (exhaust system), where air is further expanded and accelerated behind the aircraft.

A stream of fresh air enter in the compressor, (figure 2.3) point 1, and part of the energy associated with the aircraft velocity increases the static pressure of the air and the flow is compressed, point 2.

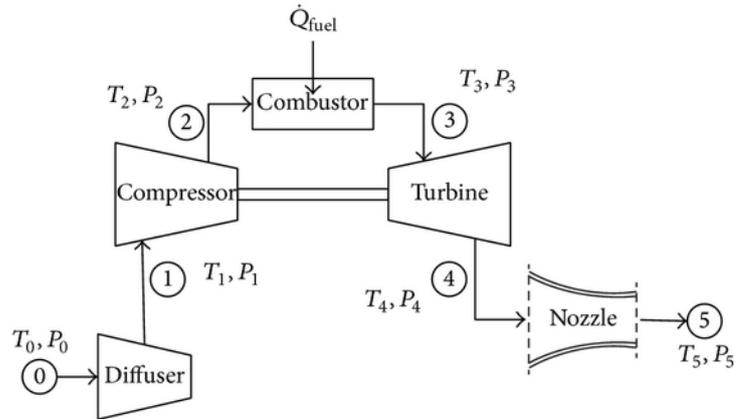


Figure 2.2: Schematic layout of turbojet components

Compression is ideally isentropic ($s=\text{const}$) but in reality the vertical line in T-S diagram leans to the right because of the increase in entropy of the flow.

The combustion process in the burner occurs at constant pressure in points 2-3. The temperature difference depends on the type of fuel used and the fuel-air ratio and is limited by the combustion chamber material.

The hot flow is then passed through the power turbine in which work is done by the flow from point 3 to point 4. Being the turbine and compressor are on the same shaft, the work done on the turbine is exactly equal to the work done by the compressor and the temperature change is ideally equal.

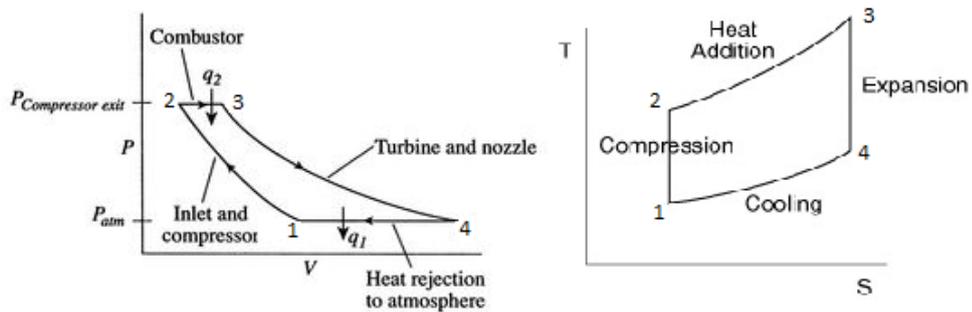


Figure 2.3: T-S and P-V diagrams of Joule-Brayton cycle

2.2 Turboprop

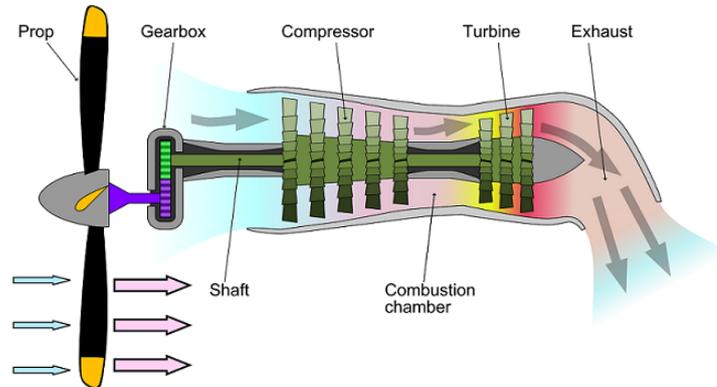


Figure 2.4: Cross section of a turboprop engine

The turboprop engine is most suitable for relatively slow aircraft because high speed leads to transonic effects lowering its efficiency.

It is quite similar to turbojet engine but the thrust is provided in two different ways: while the turbojet accelerates a relatively small mass of air through a nozzle, the turboprop engine makes use of a propeller to move a large mass of air backward, thus obtaining high propulsive efficiency.

The rotating spool is connected to the propeller through a gearbox, which allows it to rotate at a proper rotational speed.

2.3 Turboshaft

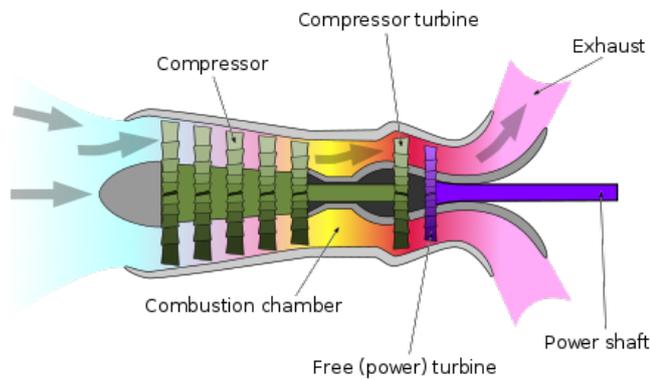


Figure 2.5: Cross section of a turboshaft engine

The turboshaft is similar to the turboprop engine but the gearbox is mounted on the aircraft structure. The propeller is mounted transversely with respect to the engine axis and for this reason it is mostly used in helicopters.

2.4 Turbofan

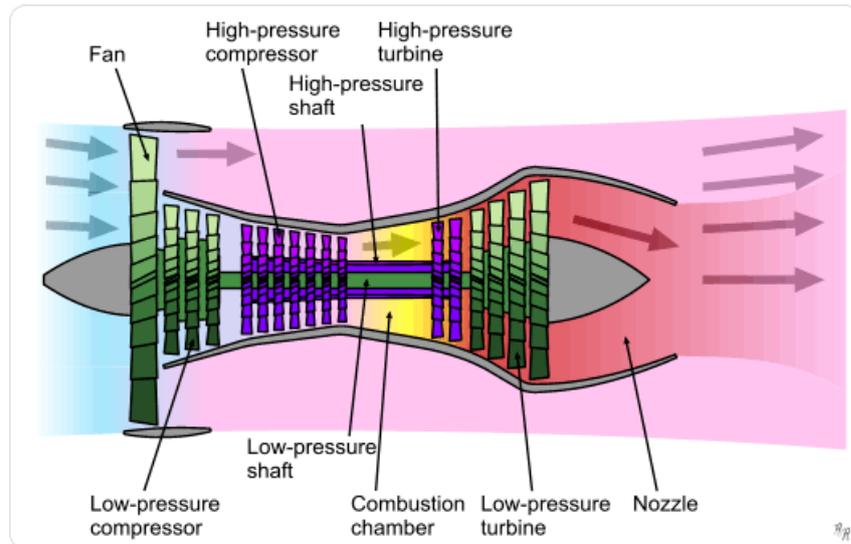


Figure 2.6: Cross section of a turbofan engine

This is the most used aeronautical engine for civil transportation; it is a compromise between turbojet and turboprop.

It is composed of a fan that behaves in a similar way to the propeller, but, since it is mounted inside a duct, the air flow can be controlled by the intake, allowing the aircraft speed to rise without incurring in undesired transonic effects and efficiency losses.

Then the air flow is splitted into two: the larger flow rate by-passes the hot core of the engine, i.e. where the burner is, while a small part of it is further compressed, heated and then expanded in the turbine.

2.5 Low Pressure Turbine

Among the components of the aeronautical engine, this work thesis is concentrated on LPT stages. As regards aeronautical turbines they are axial turbines because they can move bigger air mass respect to radial ones. Turbine has to transform the chemical energy of hot gases into mechanical energy, in order to provide the power needed by the compressor stages to rotate. Turbine module is divided in two components: HPT and LPT. The first is located after the combustor so it deals with high pressure and temperature loads, the second instead is located just after HPT on the same shaft.

The number of stages is bigger for LPT and, due to pressure drop, blades become radially larger as we move from stage to stage to keep the axial velocity constant.

Each stage is in fact composed of a stator (not rotating vanes), that directs and diverges the flow, and a rotor (rotating blades) transform the kinetic energy of the flow into mechanical work to the shaft.

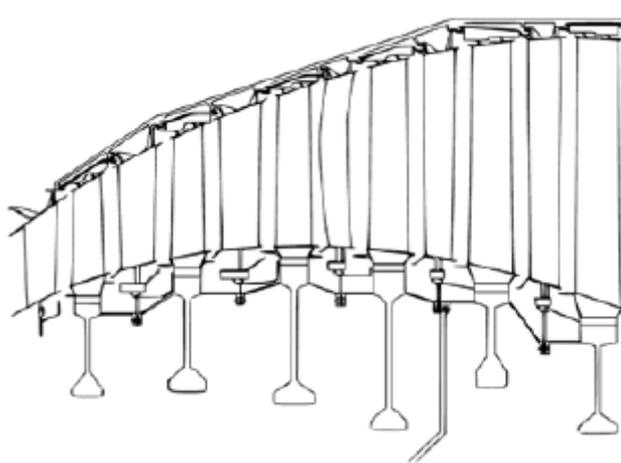


Figure 2.7: Turbine section view [5]

Since a single stage can't produce a pressure drop large enough to match the global inlet/outlet pressure ratio, each stage is further subdivided into sectors.

2.5.1 Stator and Rotor design

The 1D design of blades is represented by aerodynamic profiles. In order to achieve the optimal flowpath, the air must be deflected in specific directions, thus determining the leading and trailing edges geometry. The fluid path through the machine is represented by velocity triangles (figure 2.8). Due to interactions between their

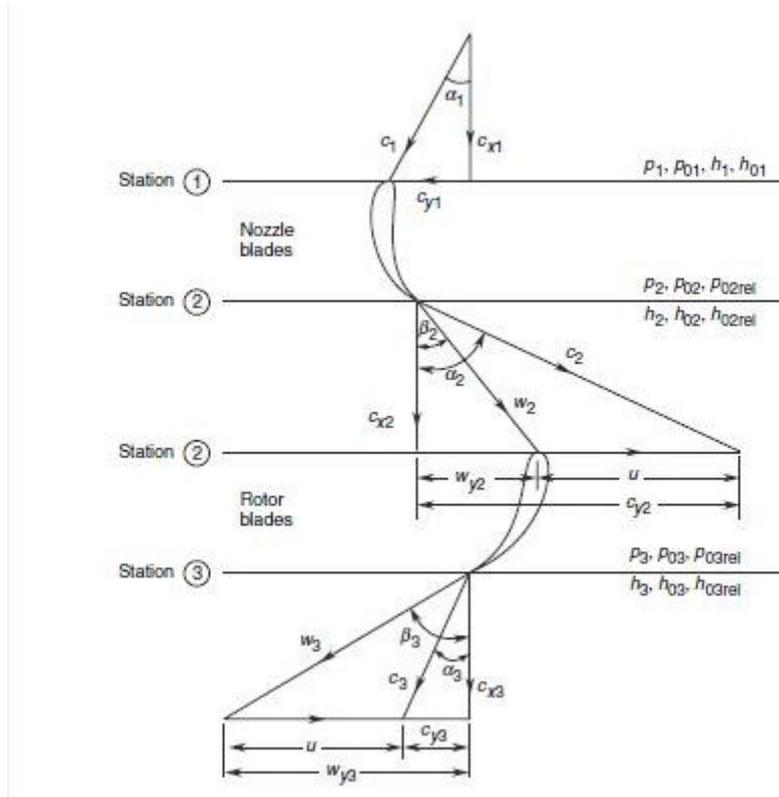


Figure 2.8: Velocity triangles of a LPT stage

structures and the air flow, the profile of blades must be designed in order to perform the exact expansion required by the thermodynamic cycle but it must also sustain the loads which come from temperature, pressure and rotation. The turbine speed diagrams differ compared to those of the compressor since the variation of the tangential component in the rotor has a direction opposite to the peripheral speed of the blades. The consequence of the variation of the tangential moment of the fluid is a torque on the rotor in the direction of motion, so the flow performs work on the rotor. By applying the equation of conservation of the angular momentum, it is possible to derive the following expression for the power supplied:

$$P = \dot{m} \cdot (U_2 c_{\theta 2} - U_3 c_{\theta 3})$$

where, by convention, the subscripts 1, 2 and 3 respectively indicate the sections of stator input, rotor input and rotor output; u represents the peripheral speed of the blades, c the tangential speed of the fluid. In an axial turbine $U_2 \cong U_3 = U$. The work per unit of mass is then

$$W_T = U \cdot (c_{\theta 2} - c_{\theta 3}) = c_p \cdot (T_{01} - T_{03})$$

with c_p specific heat at constant pressure per unit mass of the fluid and

$$\Delta T_0 = T_{01} - T_{03} = T_{02} - T_{03}$$

temperature jump per stage.

The "work ratio" per stage is then obtained:

$$\frac{\Delta T_0}{T_{01}} = \frac{U \cdot (c_{\theta 2} - c_{\theta 3})}{c_p \cdot T_{01}}$$

The maximum speed of the blades depends on the inertial stresses that they are able to withstand at the operating temperature, while the limit on the variation of the tangential component is imposed by the efficiency that is intended to be achieved. In order to minimize losses it is necessary that the fluid undergoes a great acceleration inside the array (which translates into a considerable pressure drop).

The degree of reaction R is also introduced, an adimensional parameter defined as the ratio between the enthalpy jump of the rotor and the total one of an entire turbomachine stage:

$$R = \frac{h_2 - h_3}{h_{01} - h_{03}}$$

Since in an action turbine the enthalpy through the rotor is constant, we have $R=0$. If instead in the stator there is no change in static pressure, but only a variation in the direction of the flow, we speak of pure reaction machines ($R=1$). The action turbines are used in engines with a high thrust/weight ratio, because they reduce the number of stages, but their efficiency is lower than in reaction machines, which is why the engines fitted to the transport aircraft are equipped with turbines with $R=0.3$ to 0.5 .

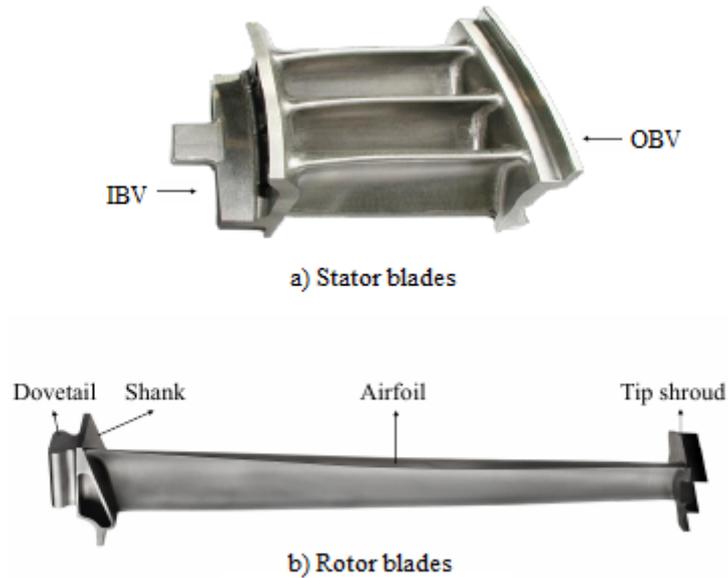


Figure 2.9: Blades of a turbine stage [6]

As regards the 3D shape of blades, it has to consider vanes and blades separately; they have different components for the disk and casing connections.

Starting from the top, Vane is composed of the Outer Band Vane (OBV), then the Airfoil and finally the Inner Band Vane (IBV). Blade instead has the Shroud, where is located the interlocking surface between blades, Airfoil, Shank and Dovetail that is the component locked at the disk. (Figure 2.9)

Disk mass must be concentrated at low radius, in order to prevent it from being torn apart by the effect of rotational speed. On the other hand, thermal loads can be ignored for disks, because the hot air does not flow into the disk area consistently.

The airfoil of both, vane and blade, is pre-twisted in order to have the same work along the radial direction and to ensure that the flow entering the exhaust system has uniform axial velocity. In case of high thermal loads blades can be also hollow to permit to a cold flow to reduce temperature.

Chapter 3

Rotordynamics

During his life span, a rotor is subject to diverse load typologies like thermal, inertial and aerodynamic loads. It is possible to classificate them on their trend over time:

- Static loads: forces that are constant over time or that have a lot of variations slow;
- Almost static loads: forces generated by dynamic phenomena but with timing characteristics static;
- Dynamic loads: time-varying forces with very high gradients they produce non-negligible dynamic effects.

The characteristic that distinguishes a static load from a dynamic one is its frequency, in fact if this is much lower than the lesser of the natural frequencies of structure vibration then the load is static or almost static. If this does not happen since the order of magnitude is the same or higher then the load is dynamic.[7]

3.1 Static

The task of the static analysis is to study the effects of loads on structure since they could cause excessive displacement in the structure with consequent problems of interference and excessive internal tension up to the break, if the limit stress is exceeded. In modal analysis for dynamics purposes, the pre-stress is only given by an inertial load and the only results considered are eigenvectors. In static analysis instead, more loads combine together, each with specific settings and specific ways.

- **Inertial Load**

The inertial load is the principal one acting on the structure due to the high rotational speed of aeronautical engines.

$$F_c = \int_r^R dF_C = \rho \cdot \omega^2 \cdot \int_r^R r dV = \rho \cdot \omega^2 \cdot \int_r^R r \cdot A(r) dr$$

where ρ is density of the material, ω is the rotational velocity and $A(r)$ the cross section at a generic r . From the formula, it is evident that the blade root is the section that most suffer the centrifugal load.

- **Pressure Load**

The pressure of the hot gases acting on the surface creates a bending moment which determines stresses at the root, mitigated by the inclination of the blade. There is a practice called "camber" which includes the inclination of the airfoil of some degrees with respect to its center of gravity generating an opposite moment using centrifugal force. This mechanical balance between moments is realized only for a specific rotation speed. Under conditions other this, the load will be decreased but not be absent. The load creates a pressure distribution that varies along the radial of the blade and also along the tangential direction. In this way a flexion is generated due to the tangential force applied by the fluid and a bending due to the axial thrust determined by the pressure drop along the engine axis.

$$q_a = \rho \cdot u \cdot d \cdot (u_2 - u_1)$$

$$q_t = (P_1 - P_2) \cdot d$$

- **Thermal Load**

The engine's components experience a thermal strain effect ε_T that is proportional to the difference between the hot gases temperature and the reference temperature at which the material thermal expansion is considered null (T_0).

$$\varepsilon_T = \alpha \cdot (T - T_0)$$

where α is the coefficient of thermal expansion. The choice of the material is very critical because with high temperature (especially for first rows of LPT) also creep could happen.

- **Pre-Twist**

During assembly, the low-pressure turbine blades undergo a preload of rotation around the radial axis. This procedure is necessary to optimize the position of the profile with regard to the flow during operation. Every blade is in fact pushed by adjacent blades until there is no more interference.

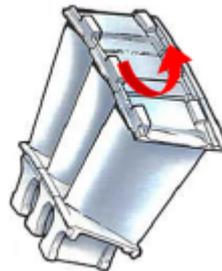


Figure 3.1: Pre-twist effect on blade[5]

3.2 Dynamic

The vibrations in the turbines are one of the main causes of failure since the emergence of resonance phenomena could lead the structure to exceed the fatigue limit and therefore cause the break. Turbine blades are particularly susceptible to high cycle fatigue damage due to the large range in frequency responses excited by the rotation, indeed each throttle setting means a different rotational speed and different cyclic and steady stresses induced by thermal and mechanical loads.[8]

3.2.1 Aeroelasticity

Aeroelasticity studies the interaction between aerodynamic, elastic and inertial forces whether they be static or dynamic.

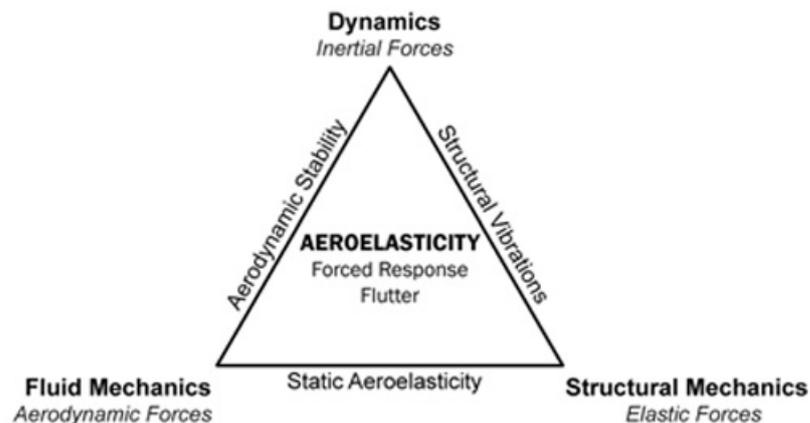


Figure 3.2: Collar triangle

Static aeroelasticity (bottom on Figure 3.6) studies the coupling between elastic and aerodynamic forces and the deformation which the component undergoes when the aerodynamic load is applied. In this branch the system is supposed to be stationary (time invariant) and the key phenomena to be avoided are divergence and inversion. Vibration mechanics studies the interaction between elastic and inertial forces and identifies the free response of the system, in terms of natural frequencies. The left side of the triangle is dedicated to the study of flight mechanics, the interaction between inertial forces and aerodynamics. What we identify as aeroelasticity lies in the middle of the triangle: the three components all interact simultaneously and lead to two more key phenomena:

1. **Flutter** that is a dynamic instability of an elastic structure in a fluid flow, caused by positive feedback between the body's deflection and the force exerted by the flow. It refers to the phenomenon of auto-excited oscillation of a structure, in which the vibration originates from the natural frequencies of the component;
2. **Forced response** is obtained when the frequency of the harmonic of the aerodynamic load coincides with the natural frequency of the system. It considers the determined stress conditions from external forcing that could lead to resonance phenomena. To identify forcing one uses the Engine Order defined as the ratio between the pulsation of the forcing and the speed of rotation:

$$EO = \frac{w}{\Omega}$$

3.2.2 Modal Analysis

Vibrations characteristics are determined by natural frequencies and corresponding mode shapes. The properties of mass, damping and stiffness of this modes determine the matrices, in the real boundary conditions of the structure. This data can be used in a FE (finite element), in order to define the subsequent problem solving with more optimum dynamic response [9]. In such a way the FE analysis determine the structural dynamic properties as well as the natural frequency and the modal shapes. Geometry is divided into small elements and a number of nodes is associated to each element. All the nodes have an amount of degrees of freedom (DoFs) connected to them. The FE softwares are programmed to solve the equation of motion:

$$[M]\ddot{x}(t) + [C]\dot{x}(t) + [K]x(t) = f(t)$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, while x and f are respectively the DoFs and the external forces vector. The undamped system solution with no external excitation is calculated reduced the equation to the following eigenproblem:

$$([K] - \omega_i^2[M])u_i = 0 \quad i = 1, \dots, N$$

where ω_i^2 and u_i are respectively the i^{th} eigenvalue and eigenvector. The solution to this equations set out the natural frequency (eigenvalues) and the non-damped mode shapes (eigenvectors).

3.2.3 Modeshapes

In the analysis of the vibration modes, it is necessary to identify the modal shapes associated to the vibration frequency. The cyclic symmetric structure presents several particular vibration modes called nodal diameters (ND) and nodal circumferences (NC). The former are straight lines passing through the disk center, where the modal displacement is null, similarly the latter are concentric circles with null modal displacement.

In rotationally periodic structures the eigenvector would have the form:

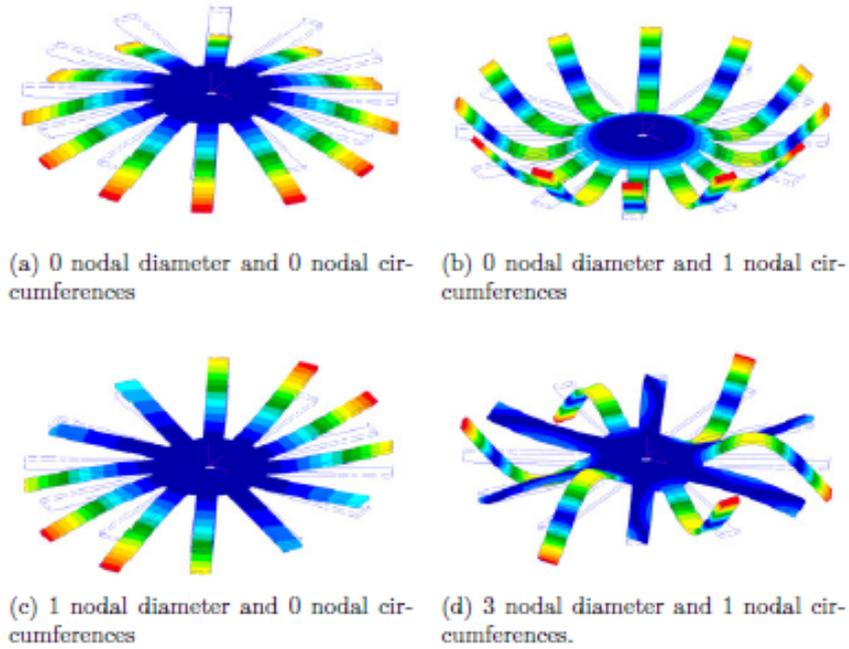


Figure 3.3: Deflected shapes of a blade disk with 12 sector[10]

$$\{u\} = \{u^{(1)}u^{(2)}u^{(3)}u^{(4)}u^{(N)}\}^T$$

where $\{u^{(j)}\}$ contains the displacements associated with the J degrees of freedom on the N^{th} substructure.

To obtain valid results, it is necessary to have a very fine mesh that involves a high computational cost. To limit the calculation load and the computational time, it is preferred to study a single sector of the bladed disk system so to allow the user a much faster analysis. This simplification is possible by exploiting the assumption of cyclic symmetry and the application of its boundary conditions, usable however

only in the case of perfect equality with the previous and next component.

The bladed disk is a structure which have rotational periodicity or cyclic symmetry,

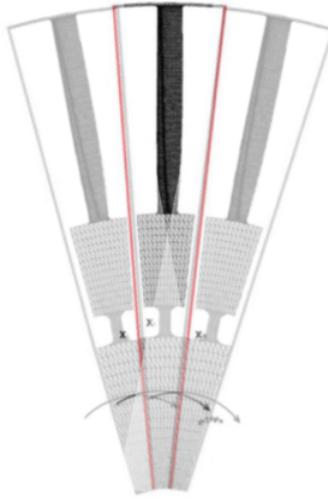


Figure 3.4: Sector of a bladed-disk

this means that if the geometry for any radial and axial position is defined at some angle θ , it is identical at $(\theta + n\phi_0)$, where ϕ_0 is $\frac{2\pi}{N}$, N being the number of blades and n any integer less than N . It follows that, if the geometry has been defined over a sector, the rest of the structure can be obtained by repeated rotation of the substructure.

3.2.4 Modal families and FRENDD Diagram

The nodal diameter defines different ways of vibrating divided into:

- **Stationary modes** in which all sectors, described by a single real eigenvector, vibrate with the same amplitude and phase;
- **Rotating modes** characterized by a pair of waves traveling in the direction concordant and discordant with respect to the rotation of the disc.

Each nodal diameter has a number of modes equal to the number of degrees of freedom. For FE models the number of modes is finite, but very large, because the DOFs are limited by the number of elements instead for real case there are infinite number of modes because the system is continuous and not discrete. In engineering practice it is important to look only at firsts frequency of a nodal diameter and they

are divided into families. From lower to higher frequency we have Edgewise (EW), Flapwise (FW), Bending (F like "Flessionale"), Torsional (T) and Disk forms. Disk modes are generally correlated to first vibration modes and it is the case when the disk is deformed and blade be undeformed. All others are blades vibration modes and are shown in figure 3.9. The nomenclature is completed with a number before the name to know what is the order of vibration. The order can be seen as the number of peaks in the deflected shape.

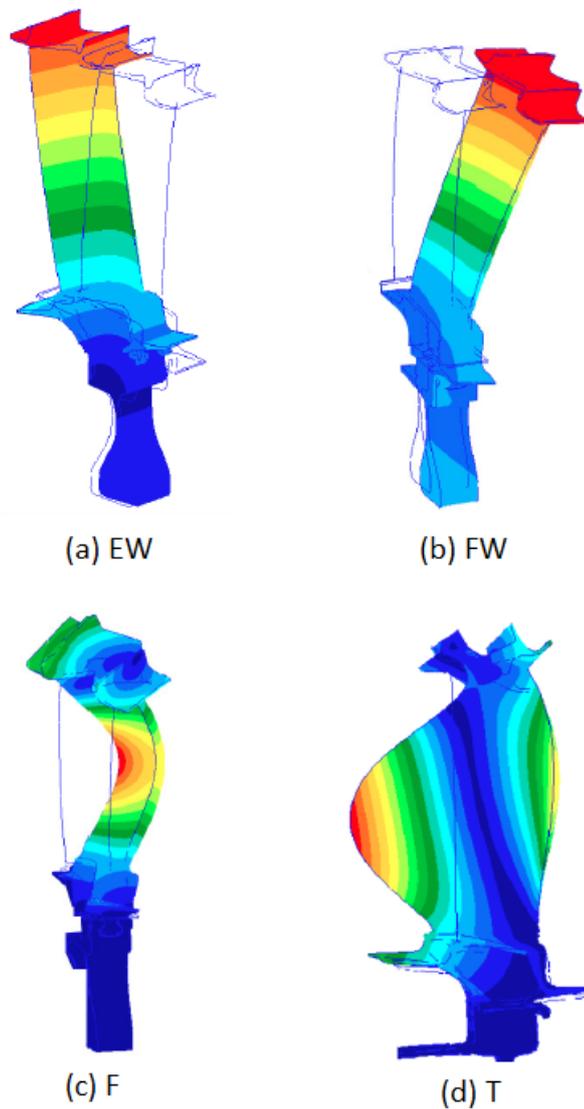


Figure 3.5: Vibrating mode shapes of blades[6]

Modal families are represented on the FREND diagram (FREquency - Nodal Diameter), where each line is a family, x axis is the nodal diameter and y axis is the frequency.

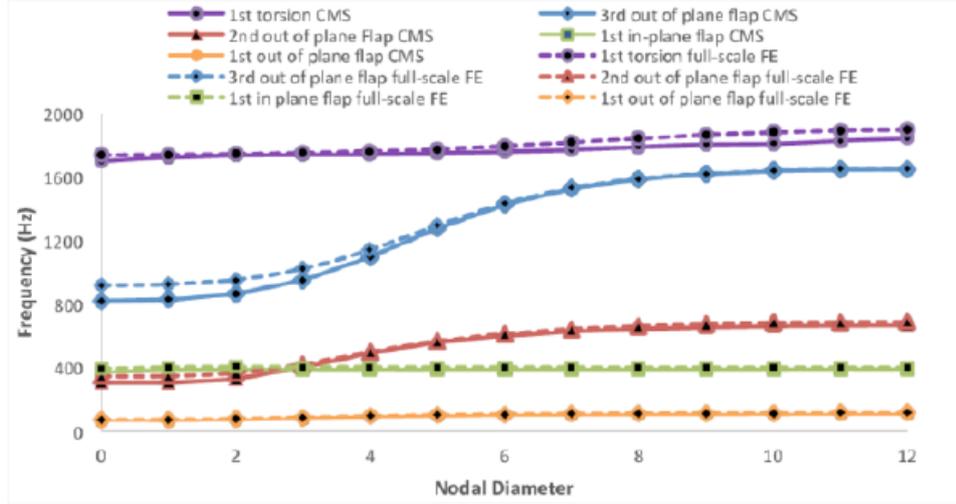


Figure 3.6: Example of a FREND diagram[11]

Lines with a frequency increase represent modes of the disk while the horizontal ones are modes of the blade. The *veering zone* is the region of this diagram where there is a mixing of the modes and so where two curves get close together.

3.2.5 Flutter

As mentioned before, flutter is the union between self-sustained and self-excited vibration of structure, where the natural frequencies of the system generate its vibration modes. The flutter phenomenon can influence the mode shape of the interested bodies: turbine blades have a single mode with frequency close to their free response. Immediate destructive failure can occur when systems are undamped or not sufficiently damped because vibrations can grow much in a very small time.

Aerodynamic force is not in phase with vibratory behaviour of the component so it is necessary to evaluate the needed damping of a component, in order to prevent this phenomenon. Turbine stages are in contact with the previous and the following, so they are mechanically coupled and vibrate at the same frequency of the same mode shape, out of phase with a certain angle defined as:

$$IBPA = \frac{2\pi n}{N}$$

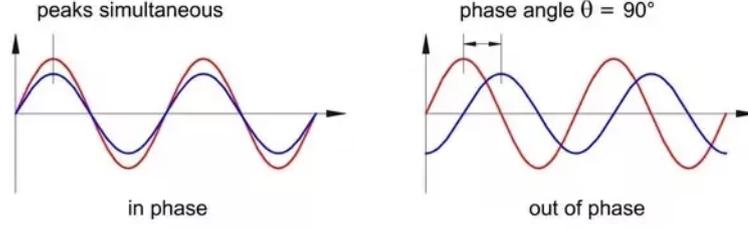


Figure 3.7: Example of in phase and out of phase

where n is the number of nodal diameter and N the number of blades of the stage.

The effect on a single blade can be calculated as the combination of the effects of the single perturbation fields because mutual interaction between blades. The behaviour of blades is generally studied with energy and work:

$$L_a = \int_t^{t+\delta t} \int_S -p\vec{n} \cdot v \, dS dt$$

in which:

- S is the instant surface of the blade
- v is the speed of the blade associated to the mode
- \vec{n} is the unit vector of the blade surface

Having the work, the critical damping factor is calculated:

$$\zeta = \frac{-L_a}{8\pi E}$$

where E is the kinetic energy of the blade calculated knowing the modal mass m and a the vibration amplitude:

$$E = \frac{1}{4}m\omega_n^2 a^2$$

3.2.6 Campbell Diagram

Another interesting diagram is the Campbell diagram which plot the natural frequencies of the modes and the frequencies of the forcing load for various Engine Orders depending on the rotational speed. So frequency is represented on the y-axis instead rotational velocity on the x-axis. The EO gives the inclination of the slope for the frequencies related to forcing load. The crossing between modes curves and EO are potentially resonance conditions. Most dangerous are the ones inside the operative range of the engine because resonance phenomena could lead to the rupture the structure.

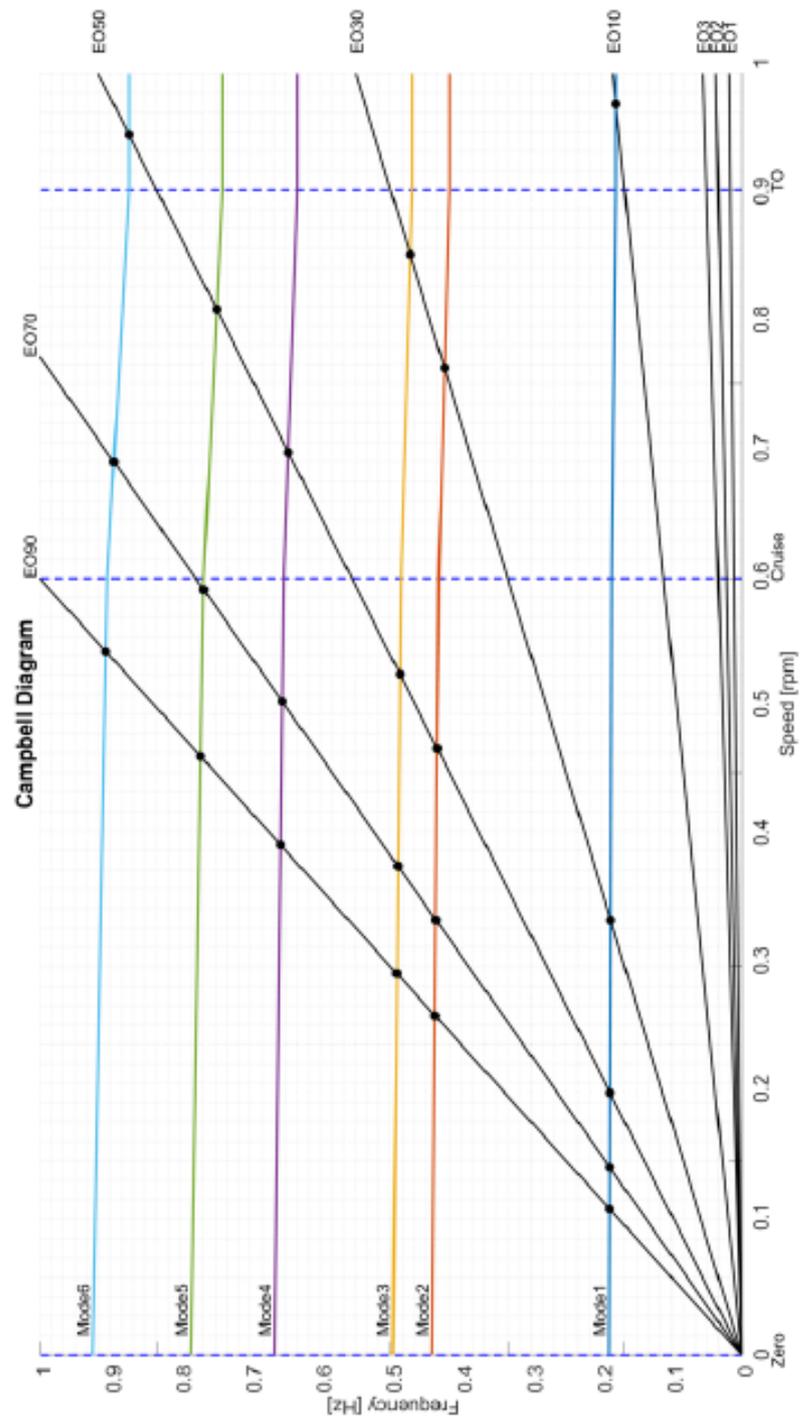


Figure 3.8: Example of a Campbell diagram[5]

3.2.7 Tuning and Mistuning

Until now, ideal rotor systems (tuned) have been considered, characterized by no material and fabrication imperfections. For a real component instead in the analysis some factors, that lead to inhomogeneities (mistuning) such as the tolerances required during the construction phase and the wear caused by operation, must be considered. In this case it is not possible to use the cyclic symmetry assumption and there is a change in the dynamic characteristics of the system.

The effects caused by mistuning are relevant so during a complete analysis of the bladed disk system it is necessary to provide a prediction of behavior also considering these phenomena. So during design to predict behaviour in a precise way, mistuning is intentionally imposed on the system. In particular disk could be modeled considering mistuning and calculate the forced response, or the best mistuning configuration is determined and study only critical blades or some coefficients are changed in the calculation determining their influence.

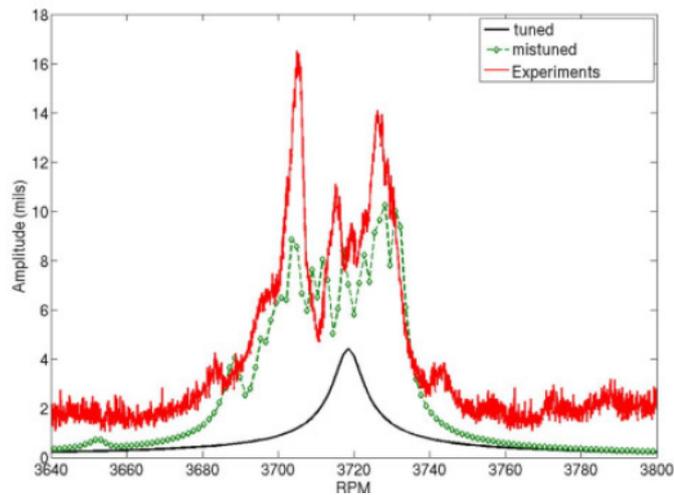


Figure 3.9: Forced response - Tuned and Mistuned [12]

3.3 Fatigue behavior

High Cycle Fatigue (HCF) is the main cause of breakage for vibrating components. This phenomenon can occur also if the stresses are lower than the limits of material resistance because the dynamic vibrations determines a continuous deterioration of performance over time. It is therefore essential to define a fatigue limit which represents the limit stress tolerable by the component without leading to break. If the stresses are lower than this limit, the component can be defined as designed with an infinite life. Characteristic quantities relating to fatigue behavior are:

- *Mean stress:* σ_m ;
- *Alternating stress:* σ_a ;
- *Stress ratio:* $R = \frac{\sigma_{min}}{\sigma_{max}}$;
- *Stress failure:* R_m where object achieve an instability point;
- *Stress yield:* R_e it determines an enduring deformation of 0.02 %;
- *Stress boundary:* σ_{D-1} associated to the condition $R = -1$.

On the other hand dynamic stress is caused by resonance phenomena generated by the vibrations that the component undergoes, which vary over time, determining the presence of cyclic stresses.

3.3.1 Haigh diagram

This diagram represents the oscillatory stresses to which the structure is subject, reporting the value of the alternating stress in the ordinate and the value of the average stress in the abscissa. In this way it is possible to observe the distance between the stresses that the structure must bear and the limits defined by the mechanical characteristics of the material to guarantee the correct operation for the entire operational life. The very high amount of experimental data make the construction of the diagram so difficult.

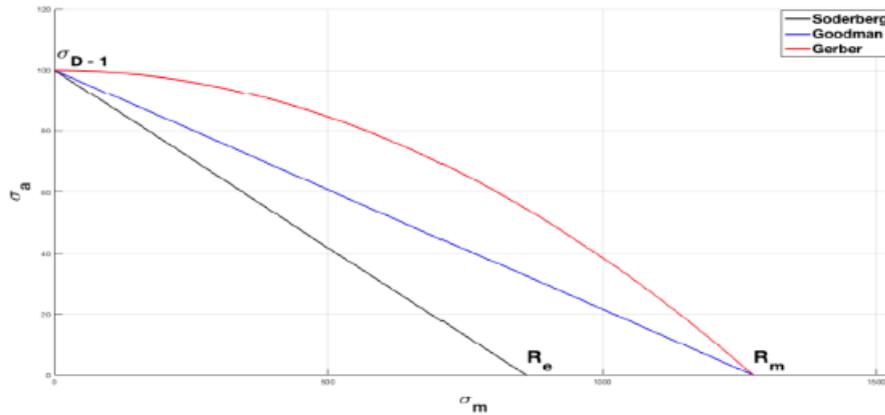


Figure 3.10: Example of a Haigh diagram[7]

There are three different empirical solutions:

- *Goodman:*

$$\frac{\sigma_D}{\sigma_{D-1}} + \frac{\sigma_m}{R_m} = 1$$

- *Gerber:*

$$\frac{\sigma_D}{\sigma_{D-1}} + \left(\frac{\sigma_m}{R_m}\right)^2 = 1$$

- *Soderberg:*

$$\frac{\sigma_D}{\sigma_{D-1}} + \frac{\sigma_m}{R_e} = 1$$

All points that fall above those curves are stress conditions which bring the component to breakage due to fatigue. Normally, Goodman solution is considered the easiest and the most conservative.

3.3.2 Goodman Area

In the Haigh diagram it is possible to define the Goodman area that represents the place of the points where the operational safety of the component is guaranteed. The breakage of a component can be reached for fatigue but also for yielding of the material.

- **Fatigue limit**

$$\sigma_a \leq \sigma_D$$

- **Yielding limit**

$$\sigma_{max} = \sigma_a + \sigma_m \leq R_e$$

The distance between limits determine the safety factor:

- **Static safety factor**

$$C_s = \frac{R_e}{\sigma_{id}}$$

where σ_{id} can be defined by Tresca or Von Mises criterion;

- **Fatigue safety factor**

$$C_F = \frac{\sigma_D}{\sigma_a}$$

in the case of evaluation of the margin at constant mean stress.

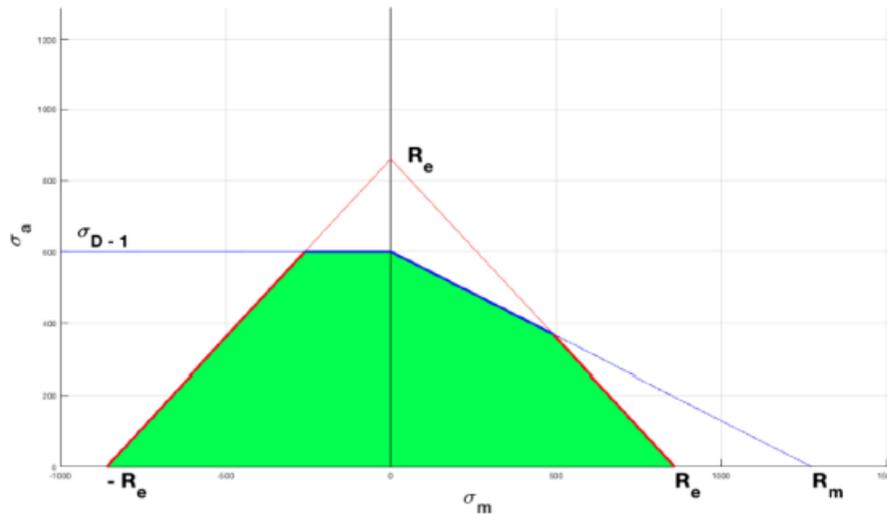


Figure 3.11: Goodman Area[7]

It should be noted that what is reported is valid only in case of fixed temperature. In fact, there are Haigh diagrams that show Goodman's lines as a function of the operating temperature and which make it possible to extend the proposed considerations to wider and time-varying thermal ranges.

Chapter 4

Aero-Mech Concept

Inputs necessary for the design of an aeronautical engine are the maximum measures of the propeller, power to generate and the cross section. For the design of a low pressure turbine it is important to evaluate both aerodynamics and structural mechanics. Aerodynamics study how to optimize the conversion of the energy contained in the flow into mechanical power transferred to the shaft. The purpose of the second instead it is to guarantee the structural resistance of each component subjected to static and dynamic loads.

First step of the design is to define the flowpath of the turbine. After studying the 1D and later 3D shape of the profile, CFD (Computational Fluid Dynamics) analysis are carried out to determine the turbine response. So Aero computations are over and they give airfoil informations to perform structural analyzes.

Designers must generate the CAD in order to perform analysis, adding to the airfoil the outer and inner elements. Blade profile coming from the Aero team is determined in hot condition so it is necessary to do a scaling from hot to cold in order to assemble in cold condition. To do this, blades profile are scaled due to thermal expansion influence, twisted around radial direction, because in operative condition this effect disappears, and elements are positioned to keep fixed the airfoil.

Once the entire blade has been designed, it is possible to proceed with the analysis using a suitable FE model to obtain displacements and tensions caused by the different loads applied.

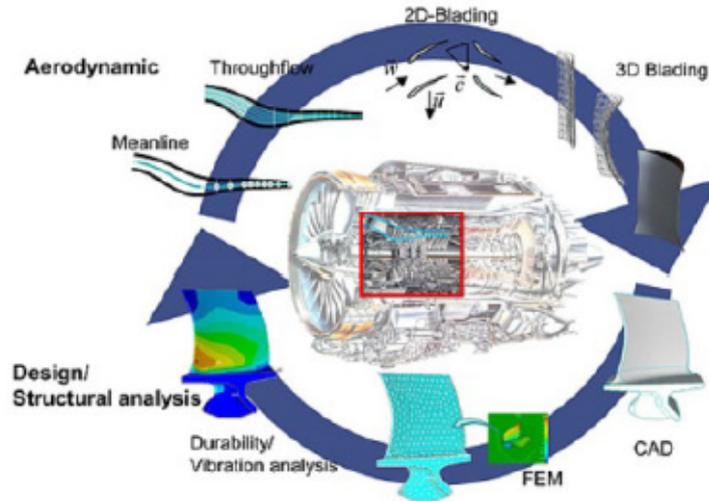


Figure 4.1: Aero-Mech process[7]

A static analysis is the first check of the model, if satisfactory results are not obtained the blade will undergo new modifications from the aero team and so a new CAD will be created and a new FE model. When static step is cleared, it is necessary to evaluate dynamic analysis. Results obtained could notice a dynamic instability but only making the blade stiffer, adding mass or constraints, is possible to improve the situation.

Obviously those changes are not aerodynamic advantages and so there is a conflict between the two optimization loops: one for the aerodynamic behaviour and one for the mechanical response. This iterative loop ends when all the processes works and for this reason it could take lots of time.

4.1 PRIME tool

PRIME (Preliminary aeRomechanics Integrated Multidisciplinary Environment) is a tool created to overcome the problem related to the optimization loop. The main purpose of the PRIME tool is to find at preliminary level the right trade-off between aerodynamic and structural requirements including in the process the generation of the 3D airfoil and the static and dynamic analysis in a single loop. At the moment, it works only with blade only configuration simulating the disk blocking the contact faces.

The advantages of this tool are:

1. Less **time** respect to the classical procedure because it is a global process;
2. **User-friendly**, because process is completely automated and easy to use;
3. Produce **feedbacks** and informations to aero team as regards the mechanical response;
4. **Results** are easy to see thanks to a post-process dashboard.

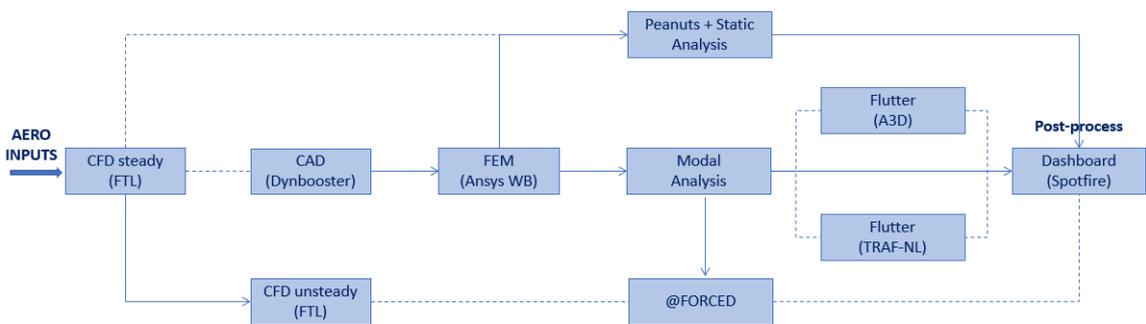


Figure 4.2: PRIME workflow

Inputs, necessary to the process, are taken from the aerodynamic team. Starting from them, using the potentials of the Unigraphics NX and ANSYS Workbench softwares, some functionalities are implemented.

CAD generation: using data from aerodynamic inputs, Dynbooster is able to create first the 3D airfoil and later, choosing the inner and outer components, the complete CAD (it will be discussed in detail in the next chapter).

FEM model: inside Ansys Workbench there is a developed wizard able to produce the FE model and user can choose the type of structural analysis to run.

Static analysis: it is possible to understand the static deformation of the blade for all kind of load cases and boundary conditions.

Modal analysis: is performed on the FEM model in order to calculate as outputs main mode, natural frequencies, inputs for flutter and forced response and finally the Campbell diagram is generated.

Flutter analysis: information is obtained regarding the stability of the structure through a graph representing aerodynamic damping.

Forced response: the amount of work performed by the force is calculated exciting aerodynamics on the structure considering a specific way, so to evaluate possible energy accumulations and therefore resonance phenomena.

Post processing of data: using a dashboard, the user has in an integrated, simple and clear way the graphs and informations provided by the analyzes carried out.

4.1.1 Inputs for Wizard

It was developed a GUI (Graphical User Interface) to request all inputs necessary to the process and here user can select the kind of the analysis he wants to do.

It is organized in sheets to have a more clear visualization. GUI requests are the name of the project, units and the workspace.

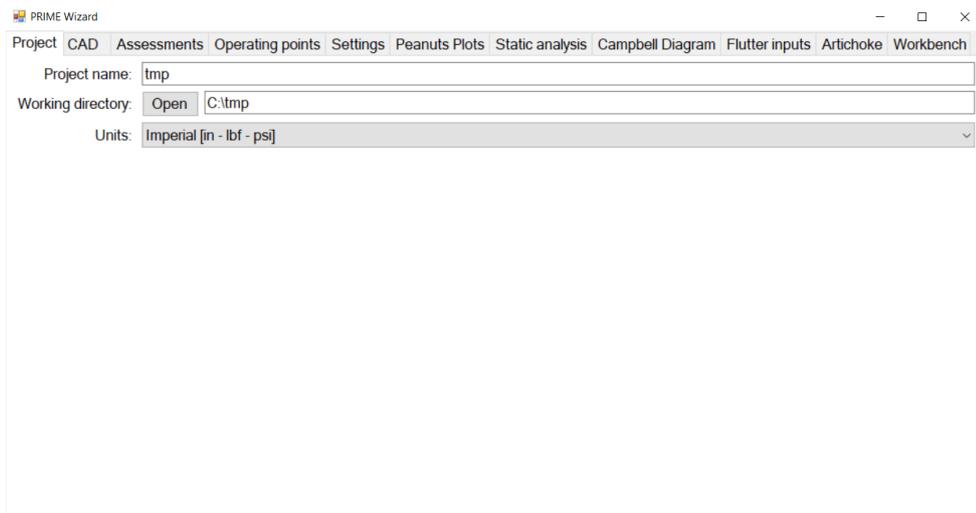


Figure 4.3: PRIME wizard GUI

Other inputs necessary for FEM analysis are the material of the blade, the boundary conditions and loads.

Chosen all the parameters of the analysis that user has selected, Ansys Workbench is launched and it starts loading external data. Named selections are used to keep track of each relevant surface on which the user wants to access during the ongoing of the process.

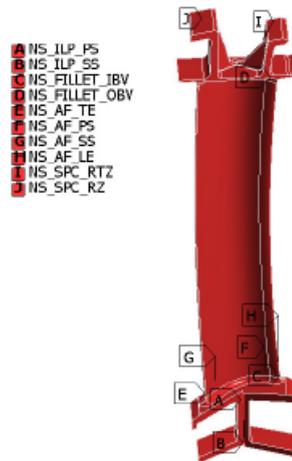


Figure 4.4: Named Selection

The process goes on automatically through all the analysis requested and produce output file that dashboard has to read to look at them.

4.1.2 Spotfire Dashboard

TIBCO Spotfire is a customizable and automatable software where the dashboard for PRIME results is developed. The data displayed can be modified by the user so as to make possible further checks on the most significant information. It is organized in sheets to make the visualization more clear and fast to the user.

Blade Model: The nodes of the model are represented in the undeformed condition and in the deformed one to facilitate the comparison.

Stress: It represents the stress acting in different sectors of the blade.

Spanwise metrics: This sheet takes into account all the geometrical information about the blade, the material and the boundary condition that are applied in order to make it easier for the designer to keep track of each following version.

Displacement: All the relevant displacement of the blade are keeping into account in order to verify that they meet the prescribed requirement.

Campbell Diagram: The Campbell diagram is shown through preliminary analysis with the possibility of choosing the type of mode.

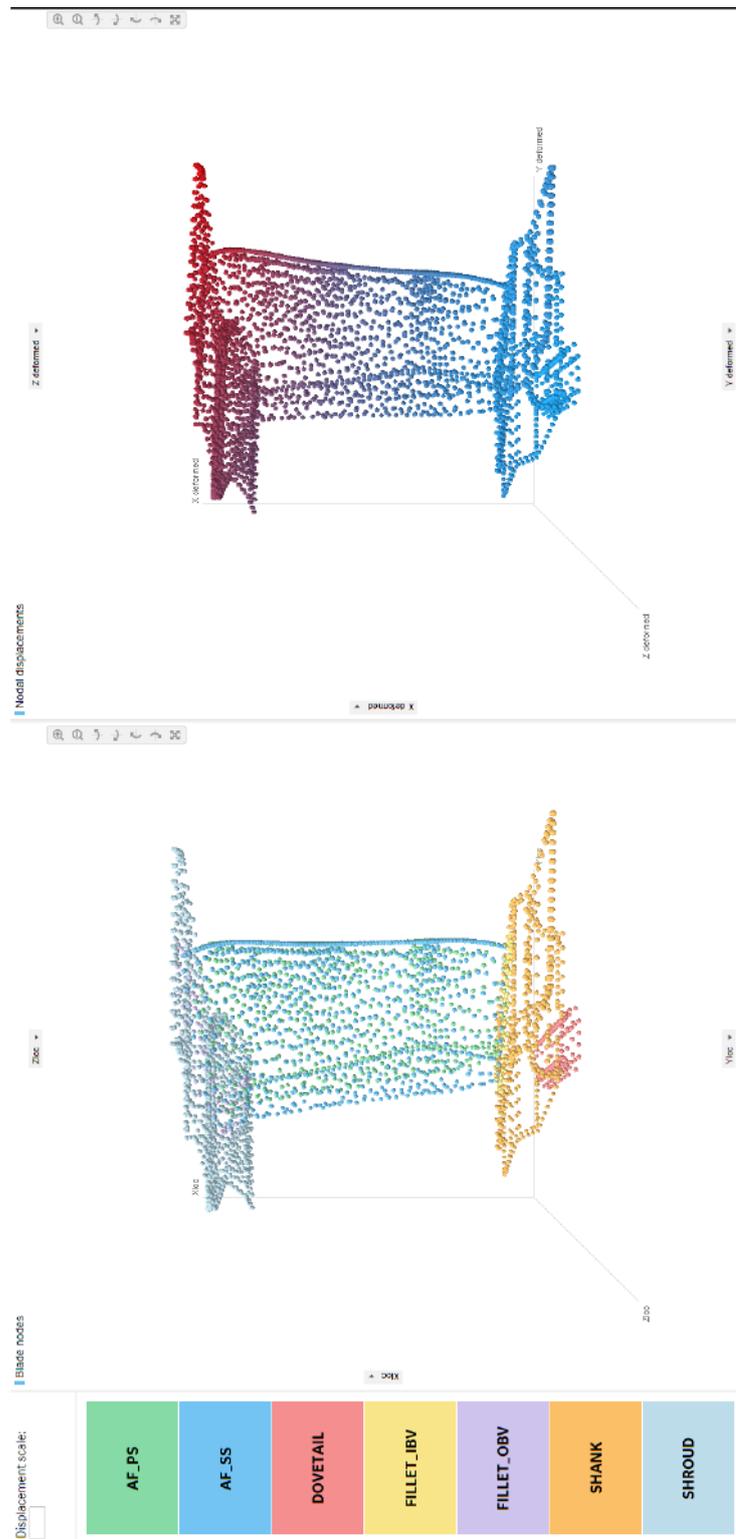


Figure 4.5: Example of Blade Model sheet [7]

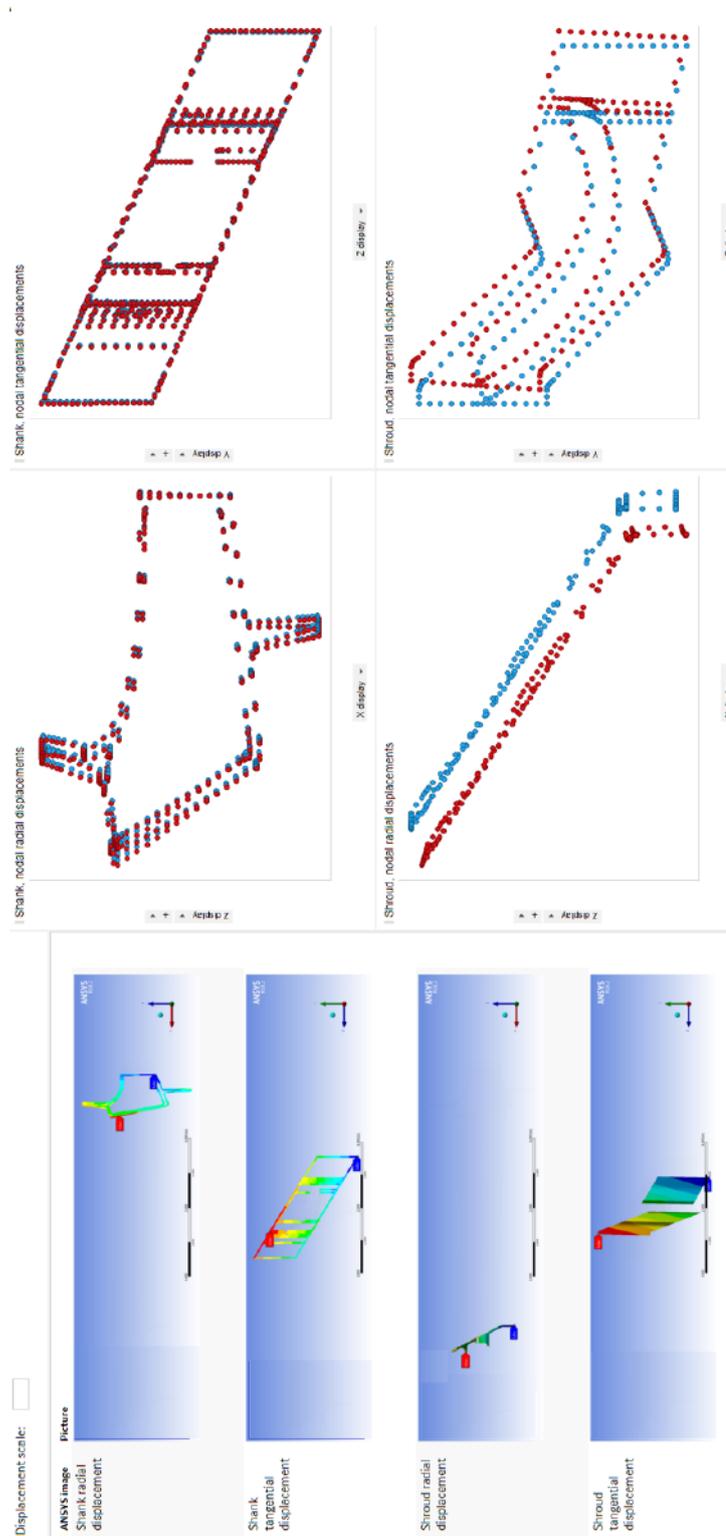


Figure 4.6: Example of Displacement sheet [7]

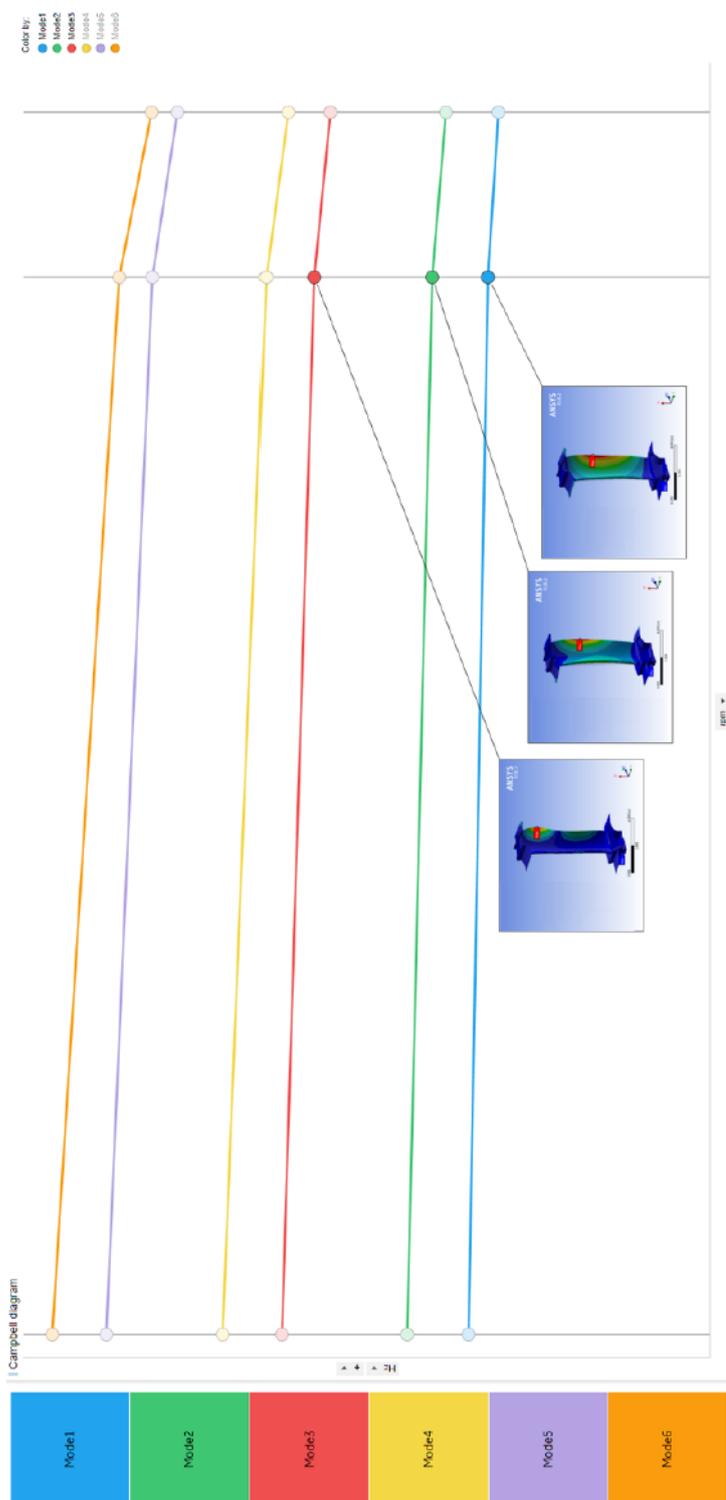


Figure 4.7: Example of Campbell diagram sheet [7]

Chapter 5

Dynbooster: CAD generation tool

The creation of a complete CAD is a slow and complicated procedure that leads to the introduction of the concept of parametrization for the insertion of the templates on airfoil. The model is generated using Unigraphics NX software developed by Siemens PLM Software which allows automated management of processes using C++ language. Airfoil is generated taking into account data from aerodynamic input while templates depend on the airfoil itself.

In fact the template is generated from a cross-section that has different parameters appropriately grouped. All kind of template follow this robust and parametric approach. Parameters are divided in system, coupled and costum. The latter is a group of parameters that user can modify and choose itself.

This procedure is enclosed in Dynbooster tool, written in part on Matlab and the rest on C++. There is also a GUI to generate new CAD configuration choosing different inner and outer templates and to change the custom parameters.

Focus of my work was to develop and fix the bugs of this tool expecially on the shroud and shank templates. All Dynbooster operations are analyzed in-depth.



Figure 5.1: Examples of custom configurations

5.1 Workflow

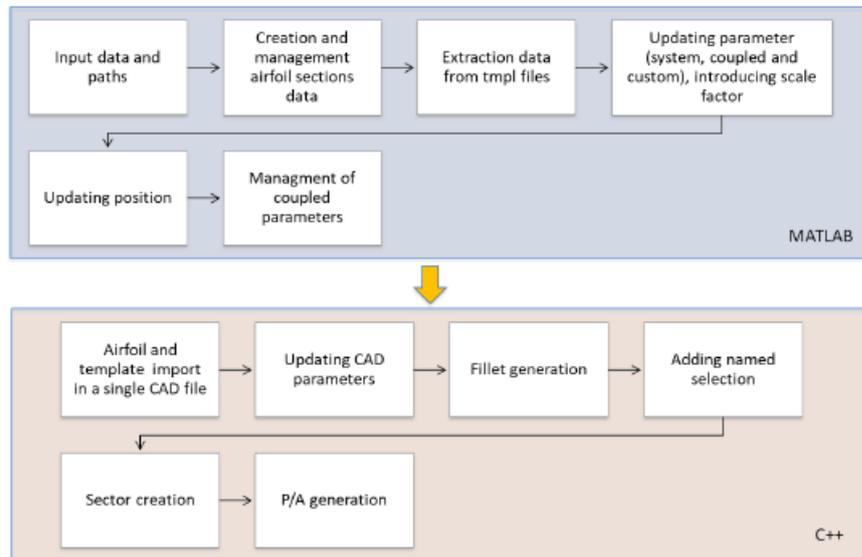


Figure 5.2: Matlab and C++

As before mentioned, the tool is divided in two languages:

- Matlab part, in which is developed the reading of the input and later the calculation of the parameters for the template selected.
- C++ part that is the executive one. It is written in this language because it is well interfaced with Unigraphics NX in fact here it is possible to update parameters and unite bodies, including also fillets.

In particular, in the first step the workflow of DynBooster code, name of template and important folders paths are requested. Later, it reads from aero input and define the parameters of the templates. An important point is to identify the coupled parameters in order to have an optimal positioning and centering of the airfoil templates and the scale factor of them. In DynBooster core, processes are performed interfacing with Unigraphics NX. First of all the airfoil part is generated then templates are imported and parameters are updated. Before my thesis work, the procedure of updating parameters was very slow because every parameters was updated one at time and the global model was updated too. Testing the process it was found a problem on this procedure also due to software limitations. In fact for very big or small blades, as an example, if the height of the template was updated, some angles or lengths not yet updated went in conflict with the model updating. A new procedure has been implemented updating in block all parameters and so scaling the template in one time. This has reduced also the computational time of toll procedure. Each component is assembled considering also the generation of fillets. Other important operation concerns in adding tags on faces where the loads, constraints or specific mesh requests are applied. They are called named selection and they are used in Ansys Workbench analysis FEM. At the end the body of the blade is united and it is possible to create a sector of several blades. The generation of P/A file is used to calculate the P/A value, through the ratio between centrifugal force and plan section of the blade evaluated at different distances from the engine axis.

The Dynbooster code can be launched in two different working modes:

- **Default mode** is the quickly one in which user select from the wizard the vane or blade configuration. No possibility to create a sector, hollow blade or modify template's parameters.
- **Custom mode** is composed by a GUI that allows user to customize all custom parameters and create innovative configuration trying to select different template shape.

5.1.1 Custom mode GUI

In this mode user can create about 96 configurations of blades and can edit all custom parameters for each template. This is an innovative way to try to have different CAD configuration and select the best one without losing lots of time.

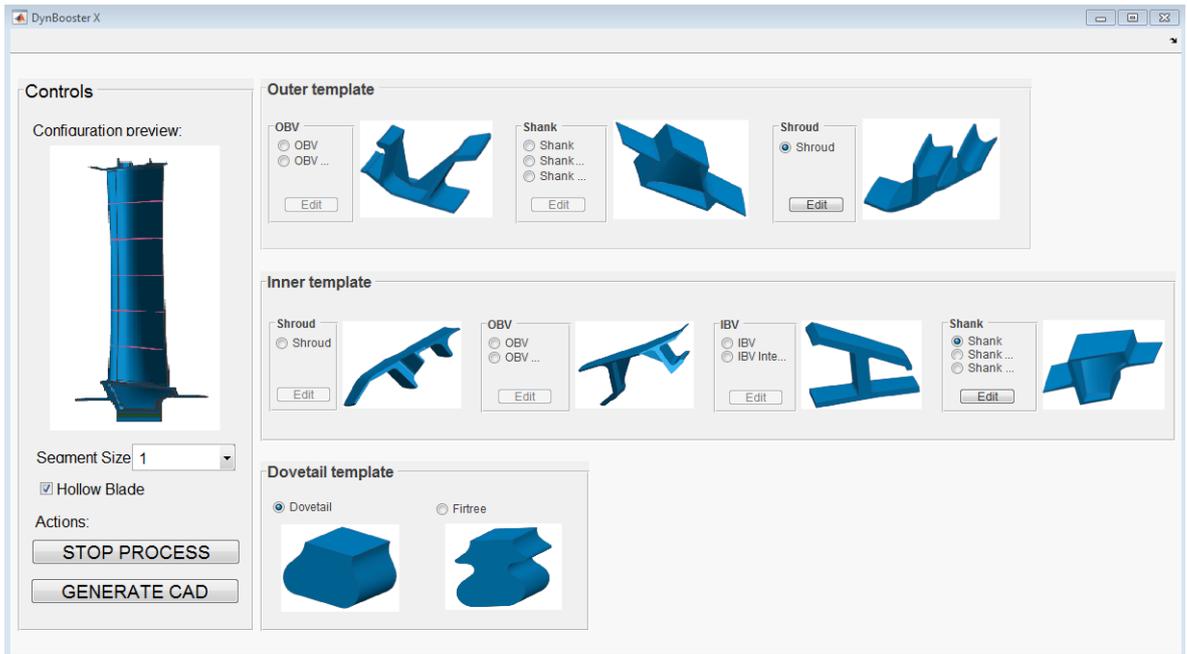


Figure 5.3: Dynbooster GUI

As shown in figure, the GUI is very easy to use but it is also programmed to avoid the selection of templates that cannot be matched. There is also a preview of the configuration how it will look like.

The possibility to create a sector of blades is possible changing its number from a drop down menu. This process is very simple because when the 3D single blade CAD is completed, some functions are inserted to copy and offset the blade by an angle equal to $360/\text{Number of blades}$. With this feature is possible to create the whole ring.

In this part of the process my work was to implement in the GUI and also in the code, the possibility to have an hollow blade. It was inserted a thick box to select or not the possibility to have or not the hollow airfoil. Thanks to this kind of structure for the future, if new templates will be implemented, no modification

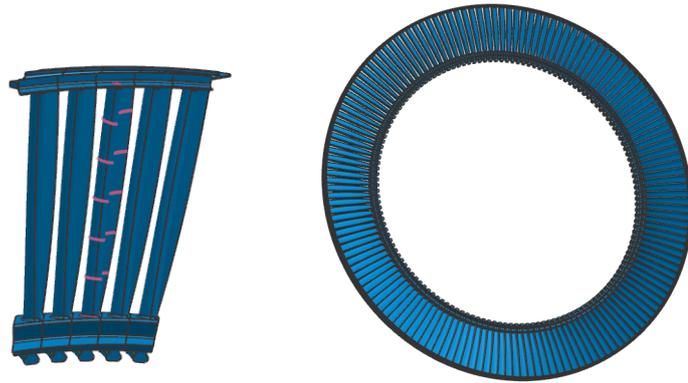


Figure 5.4: Possibility to create sectors

to code will be required. Pushing the edit button instead, a new window will be opened and here there are sketches without geometric dimensions associated to the custom parameters.



Figure 5.5: Dynbooster editing interface

5.2 Airfoil creation

Initially the data related to the aerodynamic 2D profiles of the blade are read in the various sections defined by the aerodynamic input file, through which it is possible to generate reference splines. Each section has reference points that are useful to build the spline (Figure 5.6).

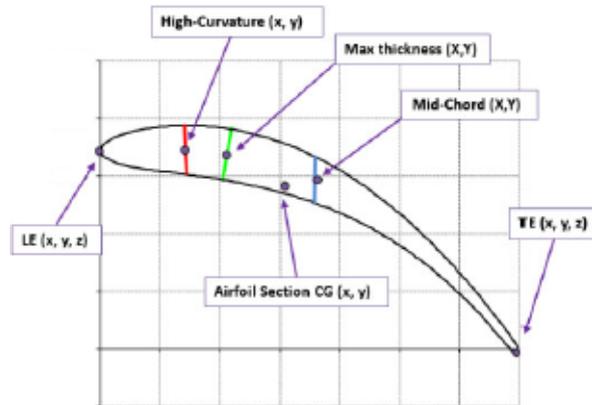


Figure 5.6: Airfoil section

These are initially projected on a cylinder and then on a cone having both as main axis the engine axis. The construction of the airfoil is realized through the creation and subsequent union of four surfaces lateral that define pressure side, suction side, leading edge and trailing edge. Generated the airfoil, it is necessary to guarantee a complete contact between this part and the subsequent additional elements so the adjacent surfaces are extruded so as to generate an offset.

The named selection, in this case, is arranged to differentiate the leading edge, trailing edge, pressure and suction side used for FEM analysis.



Figure 5.7: 3D airfoil created with Dynbooster

5.3 Hollow Blade

During the thesis stage it is implemented also the possibility to create the hollow blade, selecting the costum mode. The geometry of the hollow blades is very variable since the internal cavity can be different in terms of volume. The extremes are represented by a null cavity, which corresponds to the case of a full blade, and by a second configuration of maximum internal cavity limited by geometric and production constraints. The greatest advantage is the weight reduction which in the case of a minimum blade volume value is approximately 40% compared to the full configuration. The creation of an internal cavity also does not change the external aerodynamic profile that remains unchanged, but guarantees the possibility of making any changes due to critical situations manifested in the analysis phases without revolutionizing the entire structure. It is clear that for an increasing of the wall thickness of the blade correspond a lower mass saving (Figure 5.8).

The solid blade is therefore advantageous from the point of view of mechanical performance such as strength and fatigue, unlike the hollow configuration which reduces weight and promotes the dynamic aspect, as will be explained later. For a static point of view, as example imposing a centrifugal load, the solid blade has the lowest centrifugal stress. As the resistant section decreases, there is an increase in centrifugal stesses, but there is a greater weight saving in the area between shank and dovetail, due to the lower mass of inertia that must bear.

For dynamic loads comparing different geometries, characterized by a different volume of the internal cavity, it is possible to observe variations in natural frequencies with respect to the case of a full blade. The frequencies in fact decrease as the

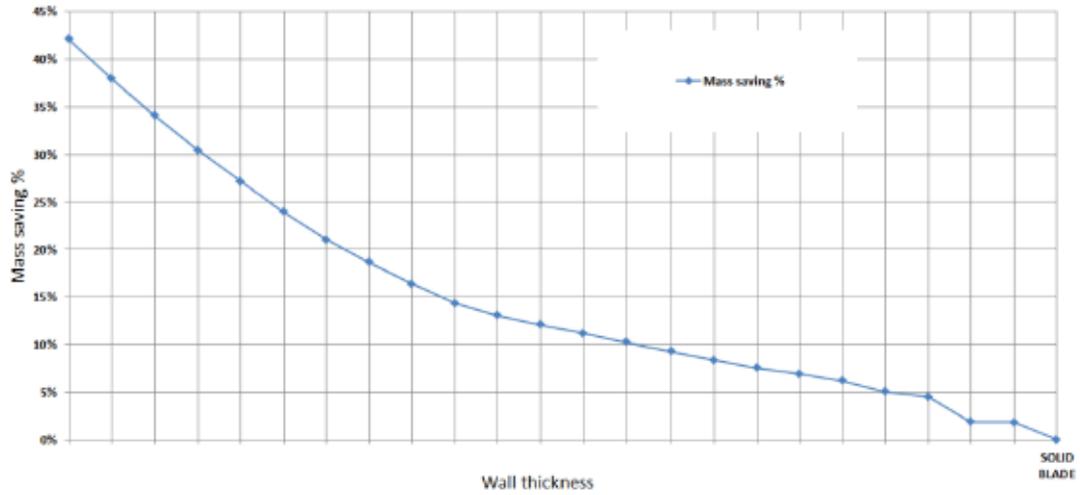


Figure 5.8: Mass saving percentage respect to wall thickness trend [7]

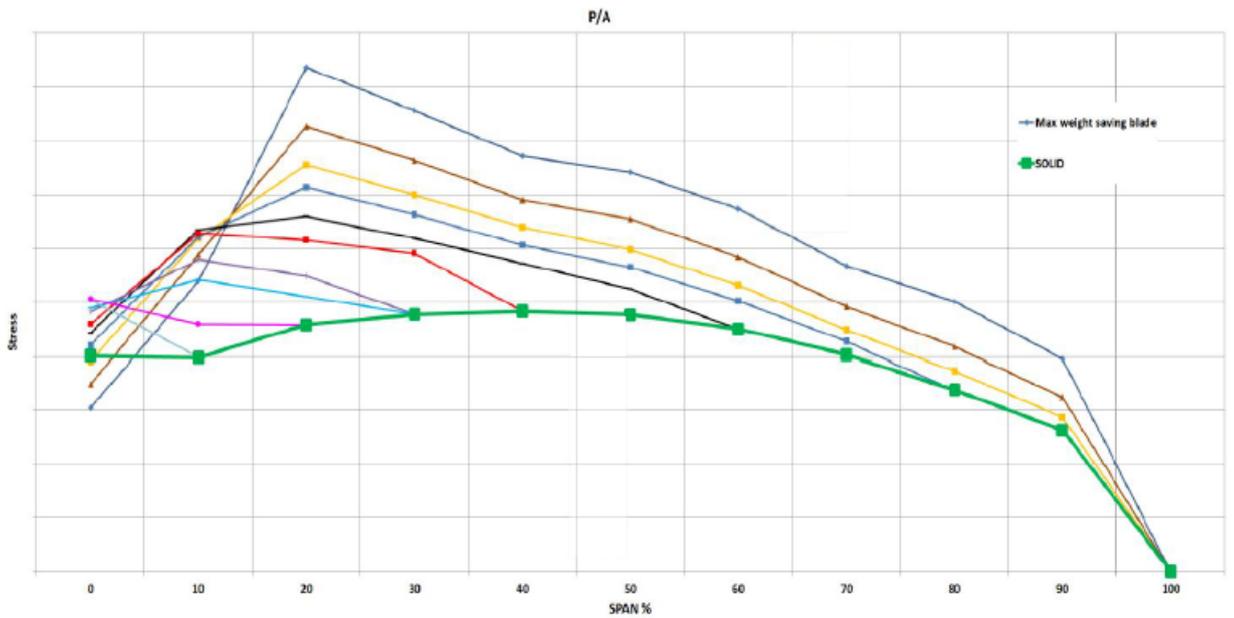


Figure 5.9: Centrifugal stress trend along blade [7]

volume of the internal cavity increases. In particular, in the case of a blade made with a 43% reduction in mass, it would be possible to move the resonance condition outside the operating range.

Finally for the fatigue behaviour it was studied that the solid blade is the best configuration because its points have more distance from Goodman line in Haigh diagram. The parts most stressed from the point of view of the fatigue resistance

of the model are the shank and the airfoil. Points of max dynamic stress must not be analyzed because they are generated from a local mesh distortion.

5.3.1 High temperature influence on materials

Temperature influences the material properties and, considering the high operating temperatures of the turbine blades, it is essential to guarantee sufficient structural performance to avoid critical situations. Some properties depend on temperature in a linear way while others are more critical, for example resistance decreases very quickly and creep speed grows exponentially. So materials can deform due to plasticity, for dislocations, or, at high temperature, due to diffusional flow or exponential creep. In the case of reduced stress and temperature the deformation is elastic.

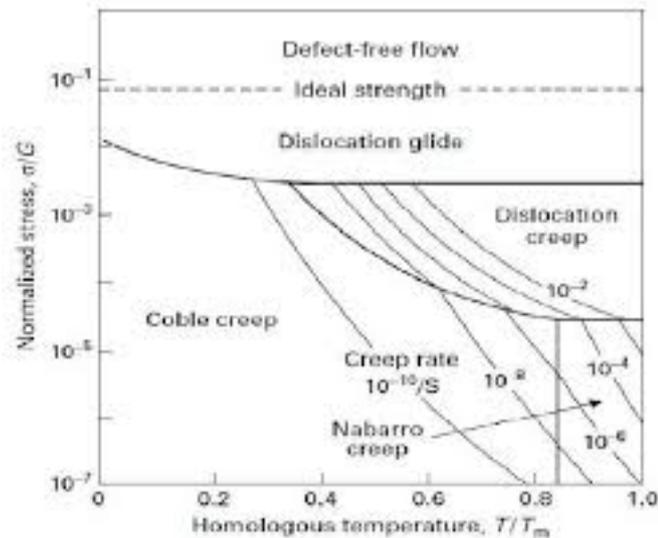


Figure 5.10: Kind of deformations

As the temperature increases, loads, which are too low to induce deformations permanent at ambient temperature, induce a viscous flow in the material which causes a slow and continuous deformation over time until breaking. The design must therefore evaluate how the speed of deformation and the breaking life time depend on loads and temperature. Since the activation energy variations is small, exponential speeds cause significant speed variations, but they are difficult to measure and sensitive to small changes in composition.

In the case of turbine blades, in particular, the material must resist to high stresses, such as the centrifugal force due to the high rotation speed, and to high

temperatures, caused by the interaction with the flow of hot gases coming from the combustor.

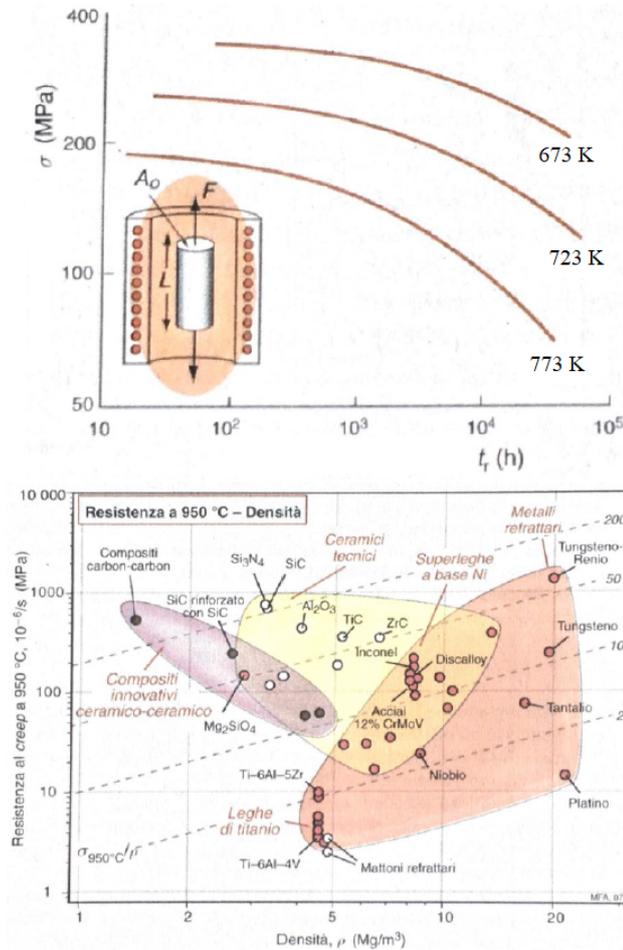


Figure 5.11: Creep resistance and lifetime of the component [7]

In the case of high-pressure turbine blades or first stages of LPT, given the extremely high temperatures, it is also necessary to provide an air-cooled surface through internal channels. In this perspective and to reduce the weight the hollow blades are born.

5.3.2 Automatic creation in tool's process

Inputs integrated to create the hollow airfoil are: the minimum thickness of the blade, the internal radius of the leading edge and the internal radius of the trailing edge. To make the generation of the hollow blade automatic, a series of functions have been added during the airfoil construction. The surfaces of pressure side and

suction side of the external profile are copied and moved inwards with an offset equal to the thickness value entered by the user. The maximum value is set equal to half of the maximum thickness of the external profile subtracted by a tolerance to guarantee a management margin. In the case of a custom value greater than the limit, the tool automatically uses the maximum offset value.

Creating those two surfaces, depending on the value of the offset, three possible scenarios can occur:

- *No intersection*: this happens when a very small offset value is chosen by the user. The program independently manages the value of internal radius of TE and LE neglecting the values selected by the user.
- *One intersection*: thanks to the geometry, the single intersection is ever on TE. The tool autonomously manages only the internal radius of the LE, while TE is defined by the user through the custom input values.
- *Two intersection*: this occurs when user choose a very big offset value. The tool uses the internal radius of the LE and TE chosen by the user.

Using the aerodynamic cones generated previously, the internal profiles are defined through the intersection between these and the translated surfaces. Following the profiles, the internal surfaces are recreated and joined, even those shifted, to avoid tolerance problems. The inner surface is extruded in both directions so as to guarantee a complete intersection with the airfoil. Using the split command on the airfoil with the reference surface the internal one, the hollow blade is obtained.

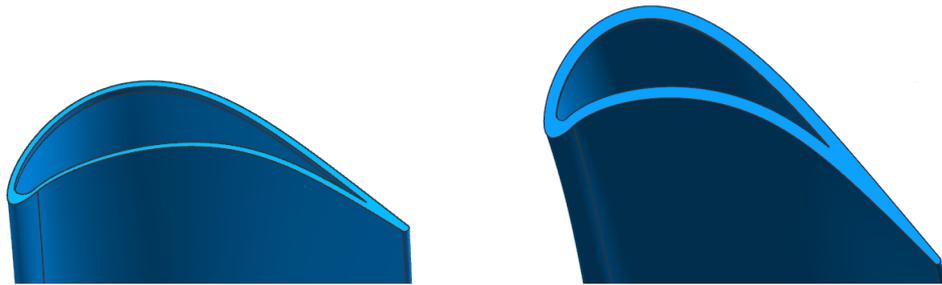


Figure 5.12: Different types of hollow airfoil changing the user inputs

5.4 Parametric template creation

To complete the CAD generation it is necessary to insert the missing inner and outer elements. There are several dummy templates that are created. Each one has three types of parameters which are able to scale the geometry.

- *System parameters*: they are automatically updated by the tool and are needed to guarantee a correct connection and positioning of the component with respect to the airfoil;
- *Coupled parameters*: are common data sets between two templates (for example shank and dovetail) and they are used to realize optimal positioning and assembly.
- *Custom parameters*: they are normally scaled like other parameters but they can be customized by the user in the GUI. They are divided in lengths, thicknesses, fillets radius and angles. Changing them size and shape of templates could change.

All the parameters identified, before being customized by the user, are appropriately scaled and some key parameters (as cut angles) are modified due to aerodynamic input like stagger angle or chordal length. The parametric templates have been generated considering the engine cross-section as reference. The procedure to generate new template is to start from the 2D sketch of it and then revolve the latter around the engine axis. Knowing the numbers of blade in a single stage, the 3D component is trimmed with surfaces which are aligned to an angle equal to $\frac{360}{N}$, where N is the number of blades.

5.5 Centering and uniting of templates

The key step of the 3D blade creation process is the positioning of the template respect to the airfoil. In fact, testing all the possible configuration available, there were found some mistakes because that is strongly dependent on the kind of the template considered. The assembly operation is done in a single part where the airfoil CAD is imported and geometrically centered. Then templates are positioned thanks to the determination of the cut angles and the definition of the axial and tangential offset.

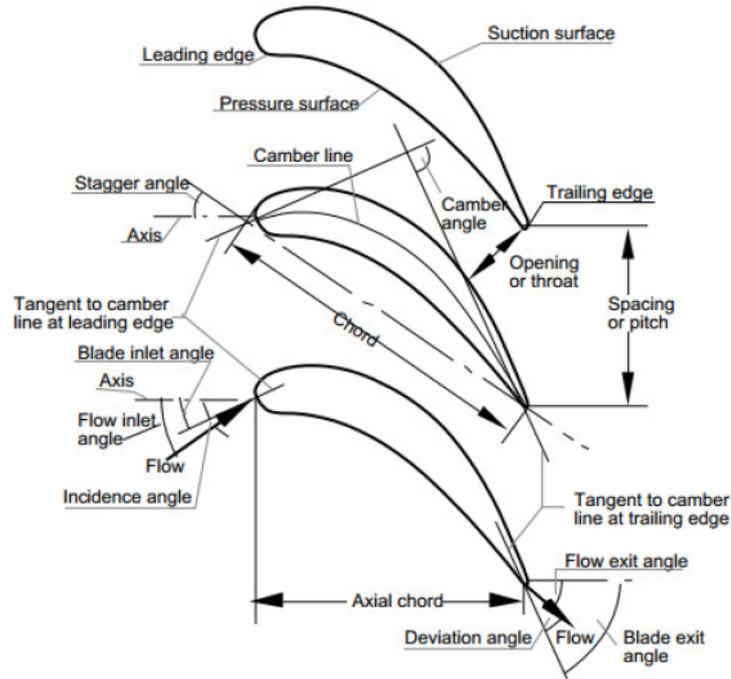


Figure 5.13: Blade Nomenclature [10]

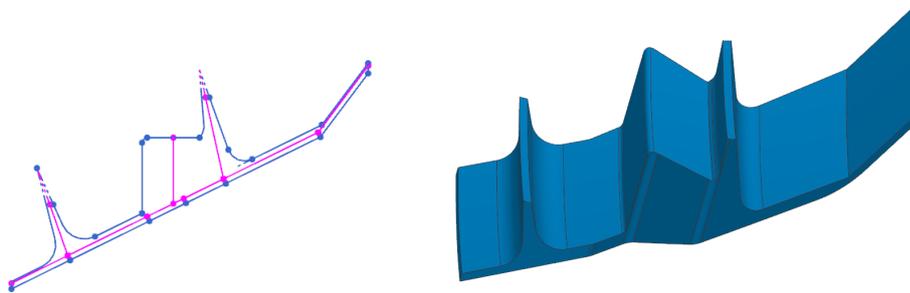


Figure 5.14: Sketch and 3D template

5.5.1 Shroud

The centering approach for the shroud template is that three key points will be each one at equal distance to the cutting planes. Another important argument is that the interlocking can change its position axially to increase possibilities to balance the blade. This aspect was not yet implemented but now is possible thanks to an additional axial offset at the interlock face which allow to slip on the sketch.

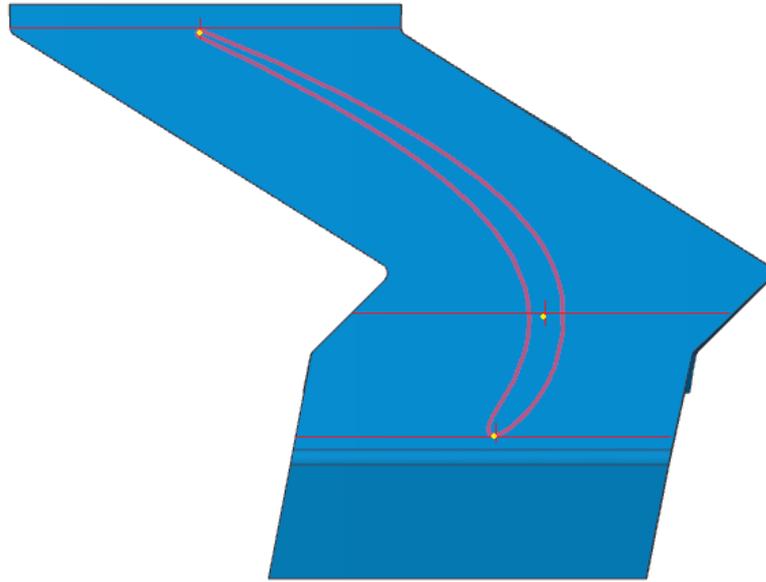


Figure 5.15: Centering strategy

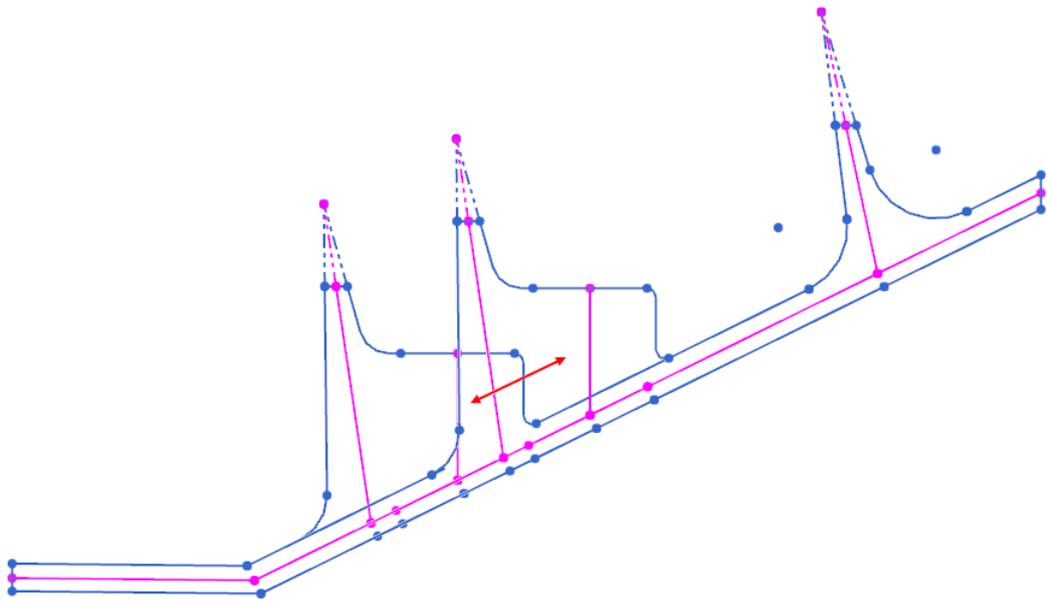


Figure 5.16: Slip of interlock face

5.5.2 Shank

In general, the shank is divided into two sub-components, the external one and the inner pocket.

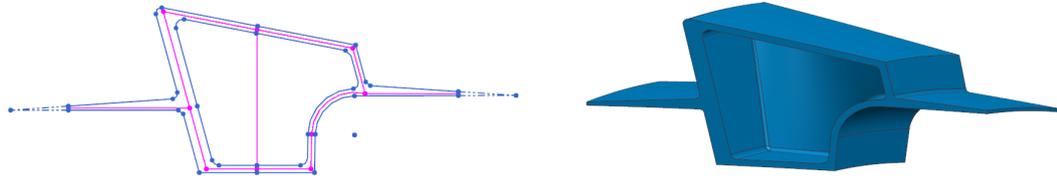


Figure 5.17: Sketch and 3D template

In this situation coupled parameters are used.

Starting from the positioning, it is different from other templates because it has a single cut angle. The approach used consist of extracting the shape of the airfoil section, drawing the chord between Leading Edge e Trailing Edge, outlining the parallel on the SS (suction side), passing through the max thickness, drawing the central axis and find the intersection points with other lines and finally, determining the centerline point, we are able to define the tangential offset to have a perfect centering on the platform shank.

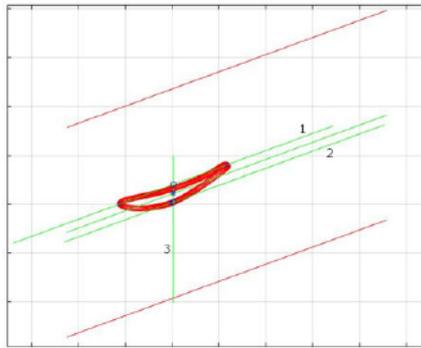


Figure 5.18: Shank centering technic with one cut angle [10]

Also in the internal part of the shank, testing the tool, there were some problems with the previous strategy of centering. The idea was that pocket had a four points centering strategy, in order to follow the profile of the hub airfoil section in the upper part and the geometry of the dovetail on the lower part. With an offset, two sheets were generated and they trimmed the internal body. It happened that for some airfoil 's shape the internal part was hollow or was bigger and went out from the shank. Now, after some geometrical modifications, the offset of the sheet is not

equal from each side but it is lower on the pressure side and higher on the suction side to ensure that it will not go outside the shank.

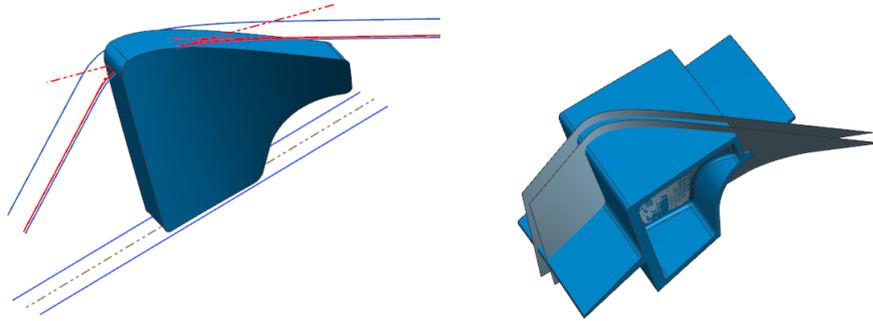


Figure 5.19: Sketch details of the pocket

5.6 Optimization process for stacking

The stacking of the profiles, characterized by the line joining the center of mass and the line joining the cutting centers, may not be defined by polylines as a function of the radial. A blade only, with the geometrical and kinematic characteristics known, can deform in infinite ways depending on the loads acting and the point of application.

The blade can take a deformed configuration stable over time (stationary phenomena) or can undergo displacements, with respect to the equilibrium condition, with a fixed periodicity, creating vibrations characterized by a constant, increasing or decreasing amplitude over time. In this case the analysis must guarantee the absence of uncontrolled vibrations in the structure (oscillatory phenomena). During the oscillatory phenomena all loads that operate on the blade must be considered at the same time. For this reason a check of the stacking of the blade must be done.

When values of the stress for pressure side and suction side are quite similar, especially in the central zone, CAD is well configured. Moreover areas characterized by critical tension can't be present because they could lead to break. To check if the correct stacking of the blade is obtained, it was developed in Dynbooster the possibility to create the same model rotating it around the radial axis by a small angle in all the normal directions. Each blade is analyzed from a static point of view to look at possible breaking points or critical stress areas. From the aerodynamic and later the mechanic side it was decided to implement this possibility in PRIME

tool.

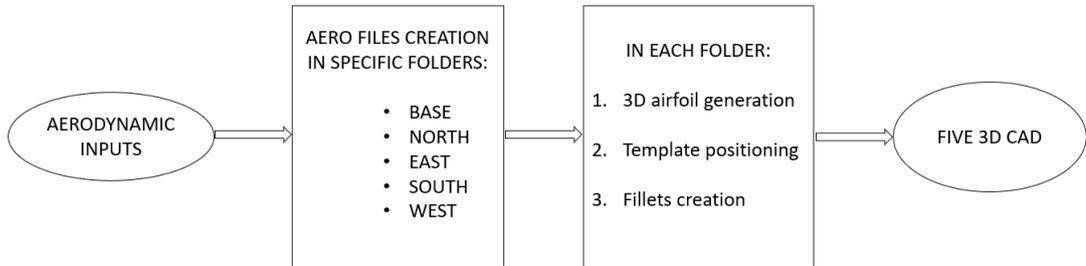


Figure 5.20: Workflow of the optimized stacking process

The generation starts from separating the workspace path of Dynbooster in 5 different folders: base, north, east, south and west. In each one, the CAD generation process is repeated as it was, but in the preliminary phase, in Matlab code, the tangential and axial offset values of the shroud template change according to the inclination in the directions. As regard airfoil, starting from the bottom to top sections, each one has an offset which increase from one section to another. This offset is the same of the template to be coherent with blade creation. The compass is organized watching the blade from TE to LE. Next figures can explain better the argument, knowing that the yellow one is the base.

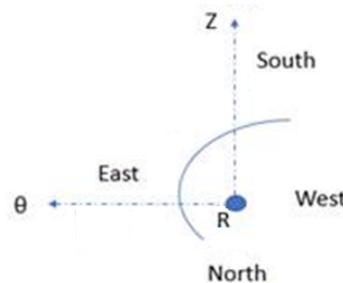


Figure 5.21: Directions respect to the airfoil

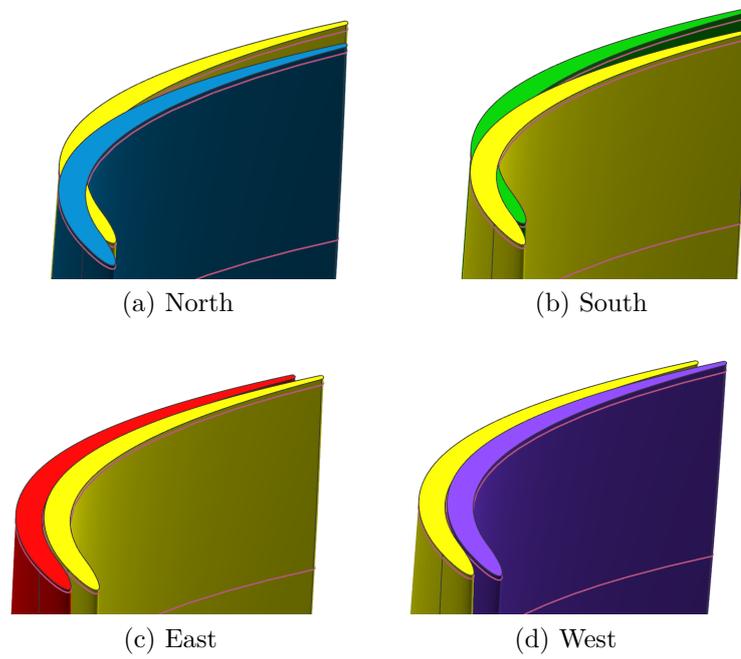


Figure 5.22: Detail of the airfoil inclination respect to the four directions

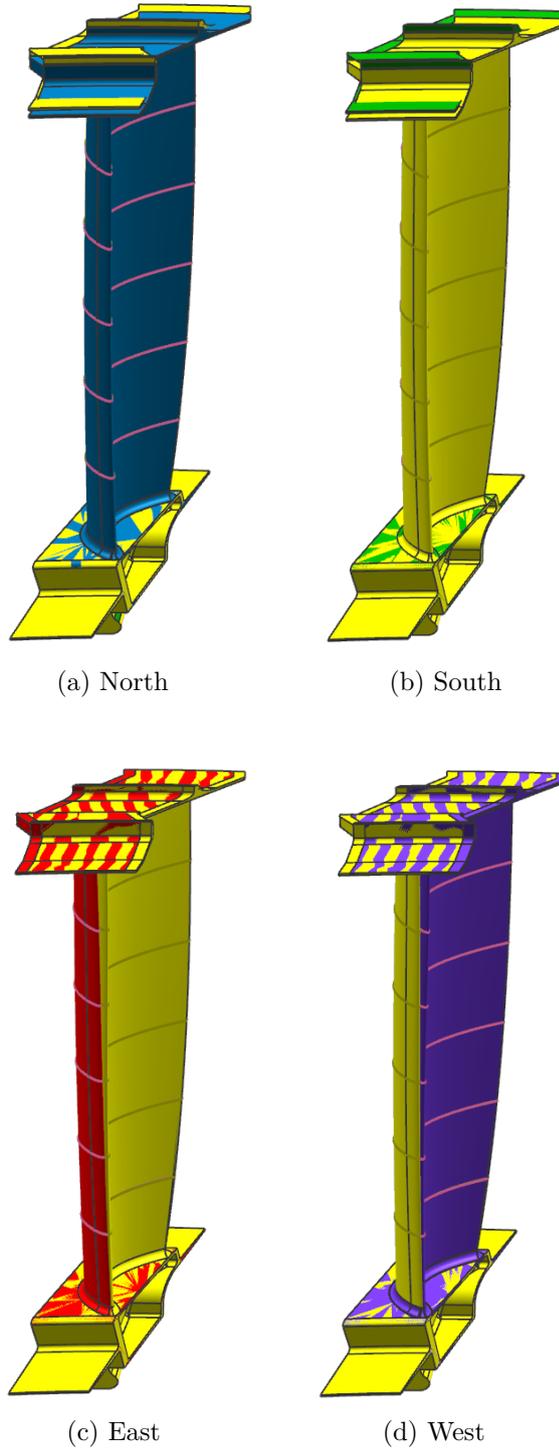


Figure 5.23: Global 3D CAD inclined respect to the four directions

Chapter 6

Conclusions

This work thesis was based on the development and improvement of a tool for fast aeromechanics feedbacks in LPT preliminary design.

In particular, some new features has been implemented inside Dynbooster code, which creates the 3D CAD. First of all, it was fixed the updating process of parameters, having found some troubles with the older method. Now templates parameters are updated immediately all together, and not one at time, saving lots of time and fixing geometrical mistakes.

The generation of the hollow blade has been introduced in the code, creating a hole in the airfoil section automatically. Advantages obtained with this configuration are:

- Weight reduction;
- Stiffening of the blade;
- Air cooling, considering the high operative temperatures;
- Reducing of creep problems.

As regards templates, new positioning methods have been studied to obtain an universal procedure suitable for all configurations. For the Shroud, a three points method is realised to center the template respect to the cutting planes and the possibility to slip the interlocking face is implemented to well balance the blade. At the moment shank has a new creation method of the internal part that has been validated and follows the blade profile.

Last but not the least implementation, a check of the stacking of the blade must be done to guarantee the absence of uncontrolled vibrations. This is possible thanks to the creation of 5 CAD inclined of a small angle in the geographical directions respect to the radial axis.

All those new features have been tested and validated for some different aerodynamic inputs.

Finally, the next short-term goals are to integrate the possibility to generate the complete hollow blade, boring also the inner and outern templates, and to include the development of parametric FE models, able to handle the newly introduced CAD features.

The new version, currently available on Avio, allows a great modularity of CAD creations and a preliminary screening on the quality of the model created. Hopefully, these researches and developments can be useful to achieve the goals set by the ACARE.

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