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ADDITIVE MANUFACTURING AND TOPOLOGY OPTIMIZATION APPLIED TO IMPELLER TO ENHANCE MECHANICAL PERFORMANCE

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ABSTRACT

The need to be more and more competitive is pushing the complexity of aerodynamic and mechanical design to very high levels. New arrangements are required to enhance the current compressor and expander capabilities from all the points of view: aerodynamic, mechanical, rotordynamic, manufacturing. As we are approaching an asymptotic limit in the performance employing traditional design methodologies, it is needed to explore new frontiers to make additional steps in the rotating equipment improvement. Topology optimization combined with Additive Manufacturing is one of the most promising new approaches to further boost the design.
During the conceptual design phase, different options can be investigated to identify the best configuration that suits specific requirements. Topology optimization is a totally new approach and it can be a very effective enabler to individuate new paths and strategies, not always straight forward, and to go beyond techniques already consolidated in turbomachinery design, such as parametric and shape optimizations.
Together with the description of the design approach, some test cases and manufacturing trials are presented.
For instance, the new design shows a reduced of stress level by 25%, decreasing the impeller mass by 20%, resulting in an increase in max allowable speed and overall performance.
Particularly interesting is the application of new rotor design produced by Additive Manufacturing for compressors, as impeller wheels are usually closed and can spin at very fast speed. Mechanical performance improvement and weight reduction are of fundamental importance for these rotor architectures and Additive Manufacturing guarantees the manufacturability of unconventional designs and can bring significant benefit from rotodynamic and mass reduction standpoint. The authors have applied Topology optimization to centrifugal compressor impellers, optimizing the region outside of the flow path (“dressing”).
Through this document an overview of Additive manufacturing (AM) in particular Direct Metal Laser Melting (DMLM) for Inconel 718 (Inc718) alloy. A comparison between the DMLM material and wrought characteristics showing the main tensile differences. Topological optimization design procedure is presented with some practical examples on centrifugal impeller showing geometries easily manufacturable with AM processes. Finally, an AM process capability on a pump impeller is shown to highlight the current technology level for these components.

Introduction

Additive Manufacturing and 3D Printing refers to manufacturing process that creates a three-dimensional object through a series of "addition-material" operations, following the dimensions of a digital 3D model. The digital model is elaborated by a dedicated "3D printer" and it is then realized, printing layer by layer.
Additive printing today represents the new technological frontier in the industrial production sector. Thanks to it, the constructive limits given by traditional processes are overcome, making what was not previously possible.

The mechanical applications are dominated by the use of metallic component, and so the 3D printing is realized by sintering through laser beam. 3D laser printers use the light emitted by a laser to melt, one layer at a time, a powder (either monocomponent, usually mineral, or a mixture of different materials). A slightly different technology uses an electron beam, more energetic than a laser beam, to melt metal materials with greater speed but less accuracy. The advantages of these techniques are linked to the great variety of usable materials, including aluminum, steel, copper, titanium. 3D laser printers can produce geometrically complex objects with precision and speed, less need for support structures to lose during manufacturing and the pieces produced often have excellent mechanical qualities.

On the other hand, laser 3D machines and materials are expensive (for example, metals must be reduced to a very fine powder through a complex grinding process), energy consumption is often prohibitive, the creation of medium and large objects it is extremely difficult for now, the surface of the objects is typically porous and most of the time it has to be further refined with traditional methods.

The application of additive manufacturing techniques, for Oil & Gas equipment, in particular for the driven machine, as for instance centrifugal compressor or centrifugal pump, need to consider some additional constraint that are specific for the market.

First of all, the material selection. The choice of the material, for component that enter in contact with process gas/liquid must consider different aspects of the design:
- high ductility at different operating temperature (that can go from cryogenic up to 400°C)
- corrosion resistance induced by the presence of water and C02 and/or with presence of H2S
- pitting resistance induced by presence of chlorides
- high strength to sustain the working condition (pressure and speed)
- availability of the material in the market to get it in relatively short time and limited cost

A first indication of the possibility to Additive Manufacturing applied to centrifugal compressor impellers has been shown by [Allison at all].

Another important aspect to consider are the performance. Driven units consume power to operate, so the high efficiency is a fundamental key performance indicator. A new manufacturing technique can't be successful if generate some additional constraint on the aerodynamic shapes optimization, on surface roughness or any other geometrical feature that can reduce the efficiency compared to traditional manufacturing methods.

Aside manufacturing techniques, also the mechanical optimization aiming to design lighter components is of crucial importance. The weight reduction can be of fundamental importance either to improve structural behavior or, when applied to rotating components, to improve rotodynamic behavior. This can allow a more robust dynamic behavior or allow to run at higher speed. Finally, this weight reduction can be an indirect way to improve thermodynamic performance and deliver lighter equipment, that can be of fundamental importance for off-shore applications.

A final important aspect is the time to production and the availability. Either of new project but also in particular for service operation, the Oil and Gas projects are always very sensitive to the lead time to procure and produce components and equipment to improve as much as possible the machines availability. Having a manufacturing method that can reduce significantly the lead time to produce components, is of fundamental importance, to reduce the overall time to put in operation the plant. This is particularly important also for service operation and in particular for remote site, where a 3D printing machine, some metal powder and 3D CAD models, can arrive to substitute a complete chain of forging supplier, manufacturing supplier, workshops, transportations.

Additive Manufacturing release the designers from the traditional constraints, providing advanced means of producing complex mechanical parts. This advantage makes Additive Manufacturing the perfect enabler for Topology optimization. In fact, through this methodology it is possible to design innovative concepts, not feasible with standard manufacturing technologies. Topology optimization improves material distribution within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. Although this approach has never been extensively applied before to centrifugal compressors and expanders, it is very promising for mechanical optimization of rotor and stator components.

The combination of multiple objectives and constraints makes topology optimization suitable for both static and dynamic mechanical performance improvement. This methodology has been applied to rotating components to: reduce the stress level; tune the natural frequencies; reduce the weight of the part. These objectives can be applied alone or in combination, performing a single analysis or a multiple analysis optimization. This new technique can improve the performance compared to traditional ones for both 2D (low flow coefficient) and 3D (high flow coefficient) closed and open (unshrouded) impellers. Combining Topology optimization and Additive Manufacturing therefore seems to be a very promising approach for obtaining optimized mechanical parts.
To better analyze the potentialities and capabilities of the additive manufacturing for Oil and Gas equipment here below is reported the studies and experience that the OEM has gathered on one of the most important component of centrifugal driven machines, that is the impellers.

Material Characterization
One of the most promising material that was studied for additive manufacturing of centrifugal impeller, is the IN718, that by itself is probably one of the best choice in terms of mechanical resistance properties, applicability in low to high temperature, resistance to general and H2S induced corrosion and pitting resistance.
The material has been characterized both from physical resistance (strength, UTS, % elongation to rupture…) and from corrosion resistance (Co2 water and H2S corrosion resistance), with dedicated test according NACE recommendations.
Some material specimens have been produced by 3D printing and then tested together with same specimens geometries but obtained from forgings. Then the performance of both type (additive and forging) of are compared and it was observed that the 3D printing is able to meet and sometime overcome the performance of the forging specimens.
Some of these results and experience will be also published and presented to the NACE committee.

For a design standpoint a complete characterization of the materials has been performed exploring fatigue and tensile properties of the material, directly compared with the corresponding wrought alloy. A good matching of the characteristics has been obtained after a welding parameters set up phase finding that the DMLM has a better ductile behavior that is found both in higher elongation and lower UTS at lower temperature. Variability in the DMLM process is comparable to the forging one since the data statistically processed shows approximatively the same Standard deviation for the two processes.

Metallographic examination shows a similar material grain size and disposition of the base material.
Moreover, corrosion resistance behavior is in line with wrought material. In conclusion it's possible to assert that the AM Inc718 is a very good alternative to forgings at least for components sizes that are within printable dimensions.
The accurate description of the material characterization and outcomes is not in the core subject of this paper but is widely explained in dedicated papers [Cappuccini et all].

Obtained satisfying mechanical characteristics of the material and a full characterization the path for the design optimization has been traced and presented following.

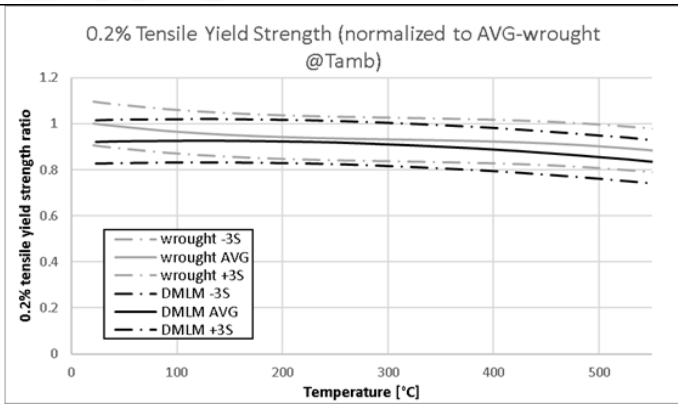


Figure 1 0.2% Tensile yield strength comparison

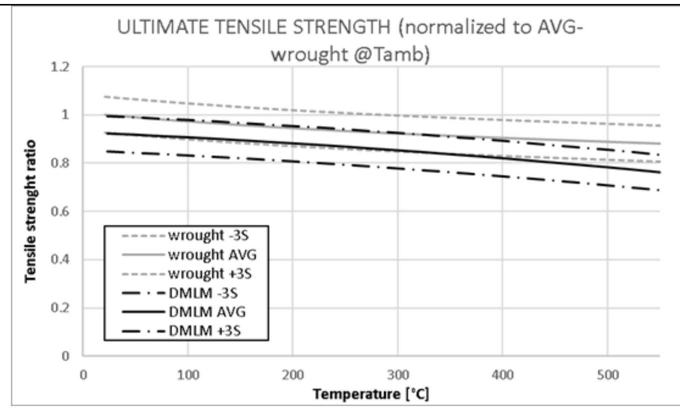


Figure 2 UTS comparison

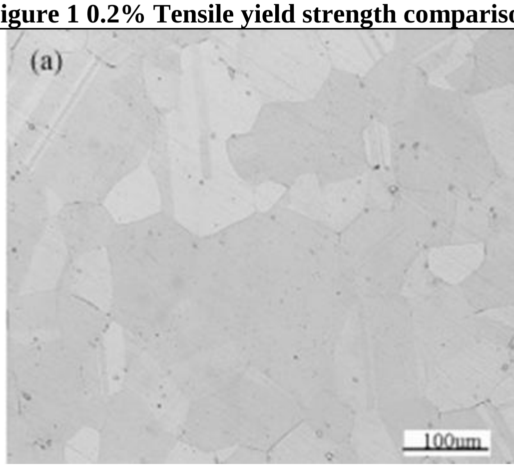


Figure 3 Wrought inc718 micrographic examination

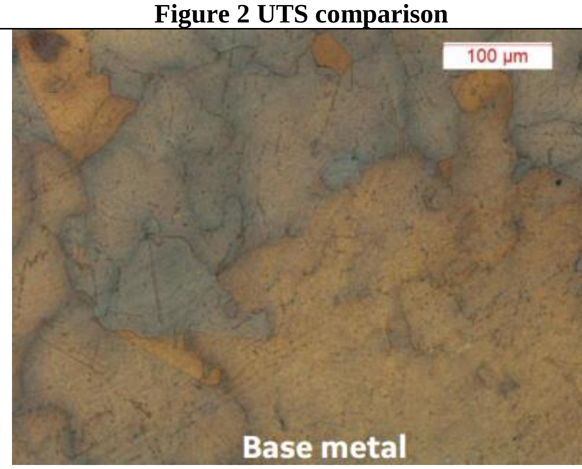


Figure 4 DMLM inc718 micrographic examination

Manufacturing Challenges

Typical manufacturing methods for Oil and gas components such as impellers are "subtractive", starting from bigger raw material, typically forged and then machined and eventually composed by different type of joint, bolts, welding, or brazing. The main manufacturing development the last decades was in the direction to maximize the use of single piece full milling machining, reducing the welding/brazing joints, that required dedicated heat treatment, are suitable not for all materials and can induce defects and geometrical distortions to the final piece. Anyhow, single piece or 2 piece composed impeller, both requires extensive milling operations. CNC milling machines typically consist of a 3, 4 or 5 axis motorized cutter - driven by a PC and a CAM program - which "digs" the desired shape from blocks of various types of material

Figure 5 – (a) CNN milling machines; (b) Impeller machining.

The advantages of CNC milling machines are that they can work a large variety of traditional materials while maintaining all their mechanical and durability characteristics, as well as the fact that it is a technology that uses long-proven processes and tools.
The main defects are related to the cost of professional machines and their spare parts, moreover the process uses the material in an intrinsically inefficient way, often producing a large amount of waste. The production of the pieces is slow and energetic and the realization of hollow objects or with undercuts is difficult.

Figure 6 –Impeller milling operations.

Another traditional manufacturing method, for those impeller with narrow passage and simple flow passage is the electro-erosion, by mean of EDM (Electrical Discharge Machining). This method is today extensively used, allows the production of very low flow coefficient impellers in "single piece" and with a very high geometrical quality and low roughness. The main disadvantage of this method, as for milling machining, it the limited possibility on machining complex shapes and the time associated to the machining itself.

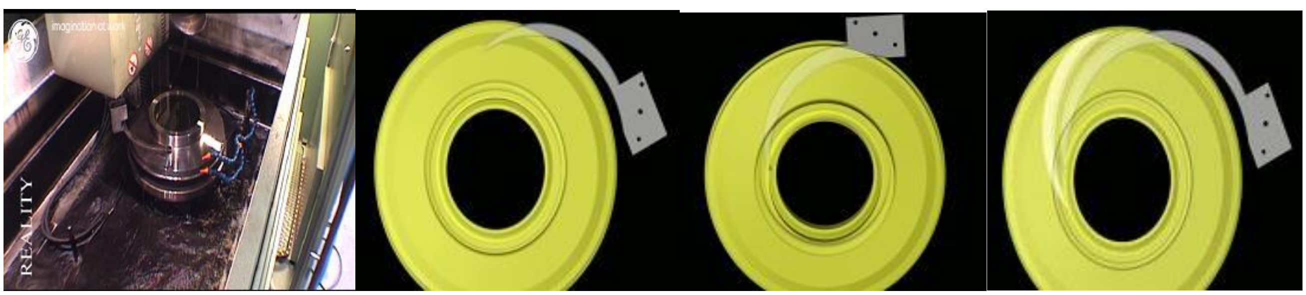


Figure 7 –Impeller EDM operations.

Following the industrial trends that award solutions with higher efficiency, fully 3D aerodynamic flowpath impellers, lighter and faster rotors are a design "must" for modern turbomachinery companies.
Additionally, modern design software allows shape optimizations in a relative short time leading to geometries unconstrained from equations description unleashing a wider solution space than with conventional design methods.

According to these trends standard manufacturing processes set the boundaries to the design, mainly because of the constrain that the machining location shall be reached by the tool.

For this reason, additive manufacturing goes well together with complex shapes, blind cavities and undercuts exploiting advanced optimization capabilities but adding new challenges strictly related to the new process.
The 3D printing technique works by adding powder layer by layer, and then a laser beam melts the metal powder to the bottom layer, placing the required material where needed. In this way the raw material (powder) is very much optimized compared to the final geometry, while with traditional manufacturing methods, there is a big difference from the raw material weight and the final material weight.

Anyway, also the 3D printing techniques introduce some challenges and the most notable are:

- the surface roughness that can be reached through different 3d printing techniques are well far from the convectional machining techniques,
- the necessity to accommodate the object into the printing space so that its self-sustaining during the process or design printed supports to be removed later

The first point has been addressed adding a conventional machining finishing at the end of the printing cycle just in the locations lapped by fluid to obtain the required roughness for impeller performance. This method can anyhow have some limitation if there is limited accessibility from the external to the machined vanes.
Another used technique is related to chemical processes that act directly on the surface, reaching worse results but with the advantage to be a static process [Longhitano et all], so no repositioning operations on the machining equipment is required.

Results of these techniques are beyond the scope of this paper but their introduction is necessary to demonstrate the final applicability of the manufacturing process to real impellers, otherwise advanced shape optimization wouldn't be a technology enabler for these components.

Figure 8 machining finishing vs rough printed finishing

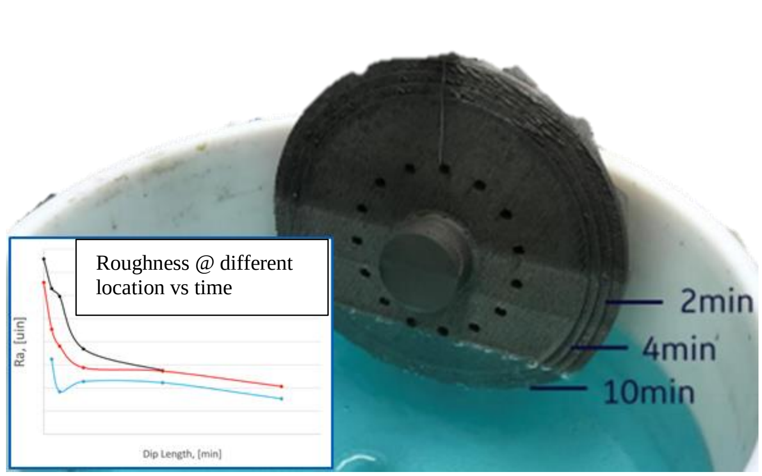


Figure 9 chemical finishing

Design Capability: topology optimization

As described in the previous section, Additive Manufacturing allows producing parts of significantly greater complexity compared to traditional processes, without increasing the cost of the production. It may be possible to manufacture in a single piece geometries that are not allowed through standard techniques, such as full milling or EDM.

This peculiarity offers exciting opportunities for the designer to create innovative concepts and, in particularly, Topology Optimization is able to fully explore the capabilities of Additive Manufacturing. Topology Optimization provides to the designer a great freedom, allowing complex structures, not immediately imaginable with traditional design methodologies, such as parametrical optimization.
Topology optimization is quite new in the turbomachinery field and it has been regarded as one of the most challenging and promising method in structural optimization. It is a process aimed to determine the optimal distribution of a given amount of material under certain loads and constraints, to get the optimal connectivity, shape and number of holes until the specified structural performance is maximized or minimized [Bendsøe et all]. It allows to change the topology (e.g. holes or cavity) and it has the capability to allow many degrees of available for the design variable settings, so that the optimal design can be obtained without prior knowledge of the specific function of the component.

Topological optimization problems are solved using the density method, also known as the Solid Isotropic Material with Penalization (SIMP) method, where a pseudo material density is the design variable [Shu et all]. The material density is defined between **0** and **1**where **0** represents void state and **1** is the solid state. The SIMP method applies a power-law penalization for the relationship between stiffness and density in order to set density toward 0/1 distribution [Altair web site]. The Level Set Method is then used to solve the problem arising from the introduction of pseudo material density. Detailed explanation of the Level Set Method applied on Topology Optimization is described in [Rindi et all].

Topology Optimization has the very powerful feature to leave to the algorithm the optimization task, allowing the complete modification of the structures, exploring design and concepts that may be very difficult to be conceived with traditional mindset. It is needed to define the area of the structure that can be manipulated during the analysis (design space) and the area that must remain unchanged (non-design space). It is a methodology widely used in the aeronautical and automotive sectors, where weight reduction is one of the main driver in the development of new products (see Figure 10), whilst it has not been applied to rotating structures, due to the difficulties coming from boundary conditions such as inertial loads.

The authors have applied Topology optimization to 3D and 2D centrifugal compressor impellers (see Figure), considering the flow path (blade and internal surface of shroud and hub regions) as non design space and the rest of the impellers (so called "dressing") as design space.

Topology optimization, since it is very flexible, allows to consider:

- various external loads;
- various imposed mechanical constraints (boundary conditions);
- various optimization objective (compliance, volume);
- various optimization constraints (stress, displacements).

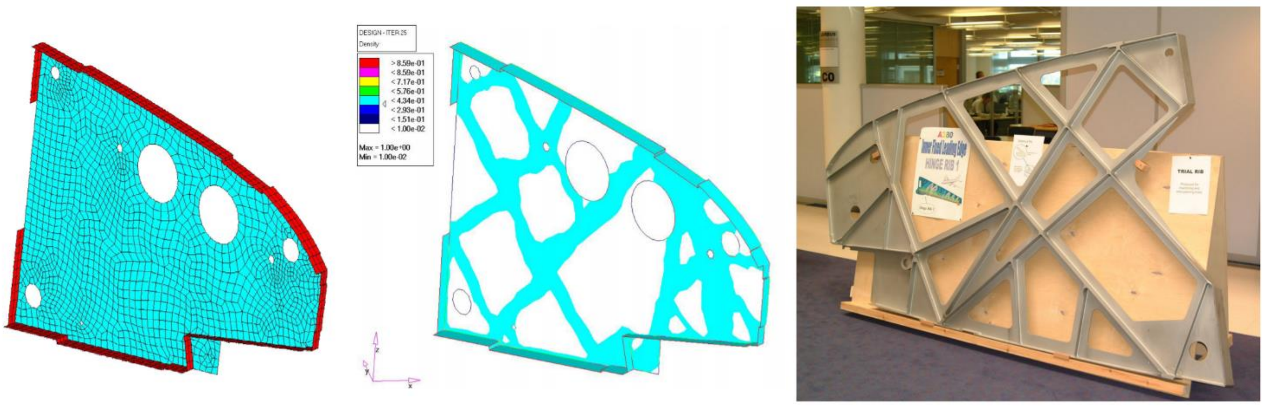


Figure 10 – Topology Optimization of Leading Edge Rib of A380 airplane. The left picture shows the designable and non-designable areas for the rib; the middle pictures shows the result from the optimization; the right picture the produced part. [from Krog et all]

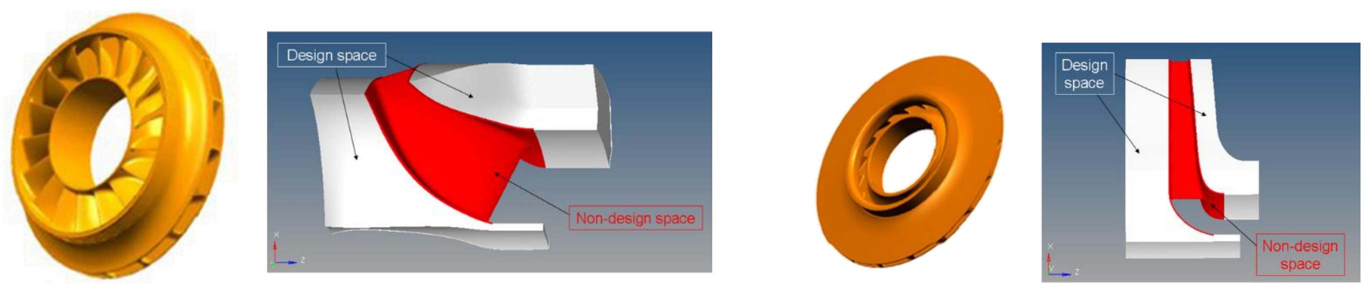


Figure 11– Design space and non-design space definition for 3D and 3D impellers

In Figure 12 a simplified scheme of the most important steps followed during the optimization analysis is illustrated. These steps are:

- definition of test cases and baseline performance;
- definition of physical and geometric features, boundary condition (nodes constrained at impeller front hub in the tangential direction and at impeller back hub in the axial direction) and external loads (rotational velocity);
- definition of design space, an extended area that is allowed to be modified during the topology optimization;
- definition of objective function (compliance minimization) and optimization constraint (stresses, displacements, manufacturing and volume fraction);
- topology optimization: changing in the topology of structures layout is allowed, through the density method a pseudo density is introduced and a topology optimization algorithm based on the Level Set Method solves the problems arising from this density method application;
- surfaces rendering, to smooth surfaces after optimization tests;
- comparison with standard configuration (in terms of results obtained in the weight, stresses, displacements and velocity).

A conceptual design can be imported in a CAD system using an isosurface generated after each optimization test. A new design has been developed for both 2D (low flow coefficient) and 3D (high flow coefficient) closed Impellers

Test cases definition
The study concerns particularly closed impellers of a centrifugal compressor. In Table 1 there are the machine specifications concerning the two components analyzed.

	2D Impeller	*3D Impeller*
Flow Coefficient	*0.0444*	*0.1600*
Mach	*0.73*	*1.0*
Diameter [m]	*0.390*	*0.390*

Table 1 – Specification of analyzed stages

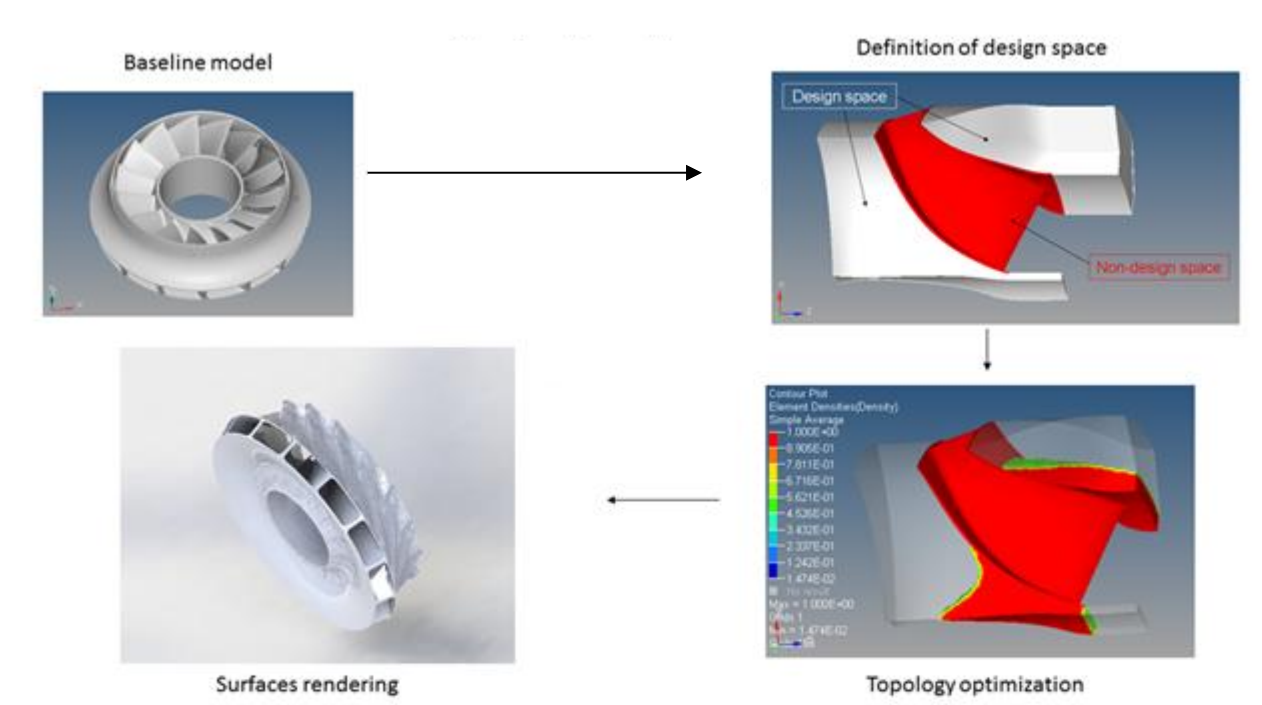


Figure 12 – Design Methodology

For static analysis it is supposed that impeller is fully constituted by the material with linear elastic isotropic properties (see Table 2).

Young's Modulus (E)	*$2.2 \cdot 10^5$ MPa*
Poisson's Ratio (ν)	*0.3*
Density (ρ)	*$7.85 \cdot 10^3$ kg/m^3*

Table 2 – Material Properties

The boundary conditions to be applied to the Finite Element Analysis are:

- two nodes at impeller front hub constrained in the tangential direction;
- two nodes at impeller back hub constrained in the axial direction.

The only load applied is a static loading condition due to a centrifugal force field. The rotational velocity is 14700 rpm (1539 rad/s). The test cases, in its original configuration, are used for the reference test as a benchmark.

Definition of design space

The blade region must be kept as it is and then it belongs to the non design space. The analysis design space to be considered includes both hub and shroud regions. The design space is the area that is changed during the topology optimization and it is expanded with respect to the basic model.

This expansion provides to the solver much material to be used in the optimization respect to the real case and a greater area in which the material can be distributed.

An example of design and non design space are reported in the Figure 11. The white volumes represent the design space and the red ones are the non design space of the topological optimization.

Objective function and optimization

In the formulation of optimization problems, some quantities can be used as objective function to be minimized (usually global quantities) and some others as constraints (usually local quantities): compliance, natural frequencies, volume (or volume fraction), mass (or mass fraction), displacements, stresses and strains.

The minimization of objective functions is imposed to have a new optimized geometry and two main strategies have been tested in this work: minimizing the volume and minimizing the compliance. Minimizing the volume (see 1) is not a good path to follow, as often there may be convergence problems and the final geometries are quite irregular.

$$V(\rho_f) = \int_\Omega \rho_f d\Omega \quad (1)$$

where ρ_f is the material density and Ω is the domain.

It is worth to highlight that minimizing the volume is different compared to minimizing the mass, as the latter depends on the density of the material, that is not constant but can vary between 1 (standard material) and 0 (no material) in a continuous way. The volume instead does not depend on the density and so is a more reliable control parameter.

On the contrary, the objective of minimizing compliance is very interesting and promising [Wang et all].

$$l(u) = \int_\Omega \underline{f}\,\underline{v}\, d\Omega + \int_{\Gamma_T} \underline{t}\underline{u}\, ds \ (1)$$

where ρ_f is the material density, $\underline{f}$ are the body forces (centrifugal load in this work) on the domain Ω and $\underline{t}$ are the boundary tractions on the traction part $\Gamma_T \subset \partial\Omega$.

The compliance is the strain energy of the structure and it can be considered a reciprocal measure for the stiffness of the structure. It is defined for the whole structure, since the objective functions must be referred to a global parameter. The objective of the minimum compliance problem is to find the material density distribution that minimizes the structure deformation under the prescribed support (boundary conditions) and loading condition.

The optimization constraints used in this work are on the displacements in the area of interference between the shaft and impeller (in order to avoid detachments), on the maximum value of the stress and on the volume fraction. The volume fraction is defined as the ratio of the difference between the total volume at current iteration and the initial non-design volume to the initial design volume. This constraint is applied to guarantee the permanence of a volume fraction in a specific part: in particular, in the light of the results, it has been decided to introduce this constraint to the outer disk, because the solver tends to delete whole this part.

The various constraints could be defined as follows:

$$\begin{cases} \sigma_{max} < \sigma_r \\ u_{max} < u_r \\ V_{fr,min} < V_{fr} \end{cases} \quad (2)$$

where:

- σ_{max} is the maximum allowable values of stress in the optimized model;
- σ_r is the maximum values of stress, equal or lower than the benchmark value, to be set in the optimization test;
- u_{max} is the maximum interference area radial displacements allowable in the optimized model;
- u_r is the maximum radial displacements to be set during the optimization test;
- $V_{fr,min}$ is the minimum volume fraction for the optimized model, to avoid the whole part deletion by the solver;
- V_{fr} is the minimum design volume fraction to be set in the topology optimization test.

Static Optimization

At an early stage, a preliminary static analysis on the existing components must be carried out as a baseline test (benchmark) and to understand the constraints to be set in subsequent optimization test. All these subsequent tests are compared with the benchmark.
In Table 3 there are the results obtained in terms of displacement and stress; rotational velocity for this test was set to 14700 rpm

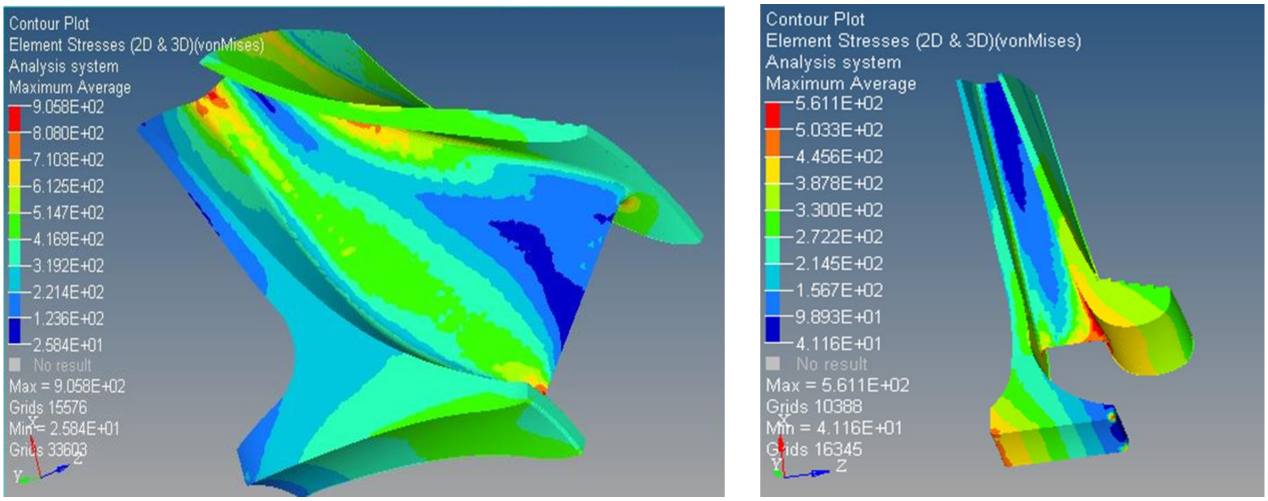


Figure 13 – Baseline stress distribution

	3D Impeller	2D Impeller
Maximum stress [MPa]	905	561
Maximum displacement [mm]	0.17	0.14

Table 3 - Maximum stress in the whole impeller and maximum radial displacement in the interference region between impeller and shaft

Maximum displacements are radial displacements of the contact area nodes between the shaft and the impeller; it is an important check to avoid any possible detachment between the two components. The contact is not modeled indeed, but it has been decided to control these displacements.

In the Figure 13 it is possible to view the distribution of von Mises stresses on the benchmark geometries. The maximum values of 550 MPa for 2D impeller and 905 MPa for 3D impeller are relevant to set the constraints for the consecutive optimization test.
Two main strategies are tested in this work: minimizing the volume and minimizing the compliance.

Minimizing the volume turned out to be a critical approach, as it often generates convergence problems and the final geometries are quite irregular (see figure 14).

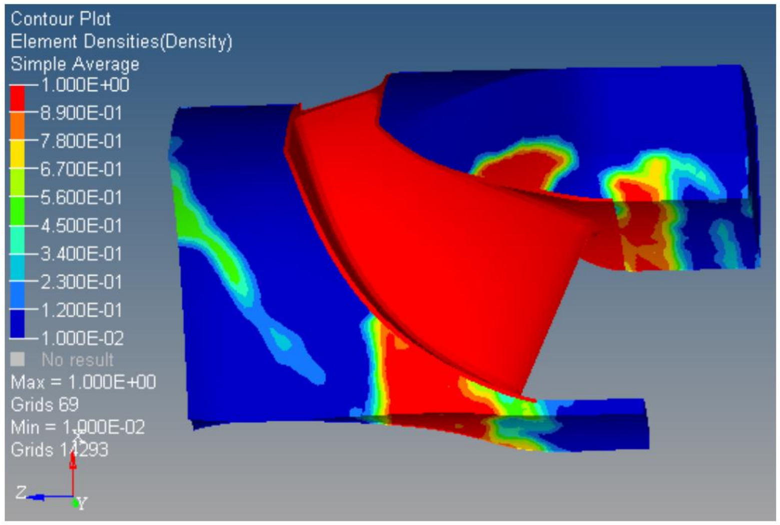


Figure 14 – Example of volume minimization with a constraint on the maximum stress value, on displacements and volume fraction

The red regions are the unit density zones (e.g. the undeleted regions by the solver), while the blue areas are with zero density (e.g. deleted areas that are not in the final geometry). Between these two extreme cases there is also a small area with intermediate colors, which corresponds to an area with intermediate density.
On the contrary the objective of minimizing compliance is a very interesting and promising tool. Through this method new geometries are smoother and more regular. Then the best promising results are obtained with an objective function minimizing the compliance of the whole system.

The best performance for a static topology optimization in the case of 3D impeller is shown in the figure 15. The constraints on stress, displacements and volume are set as follows:

- σmax < 800 MPa;
- umax < 0:146 mm;
- Vfr;min > 20 %, on the outer disk.

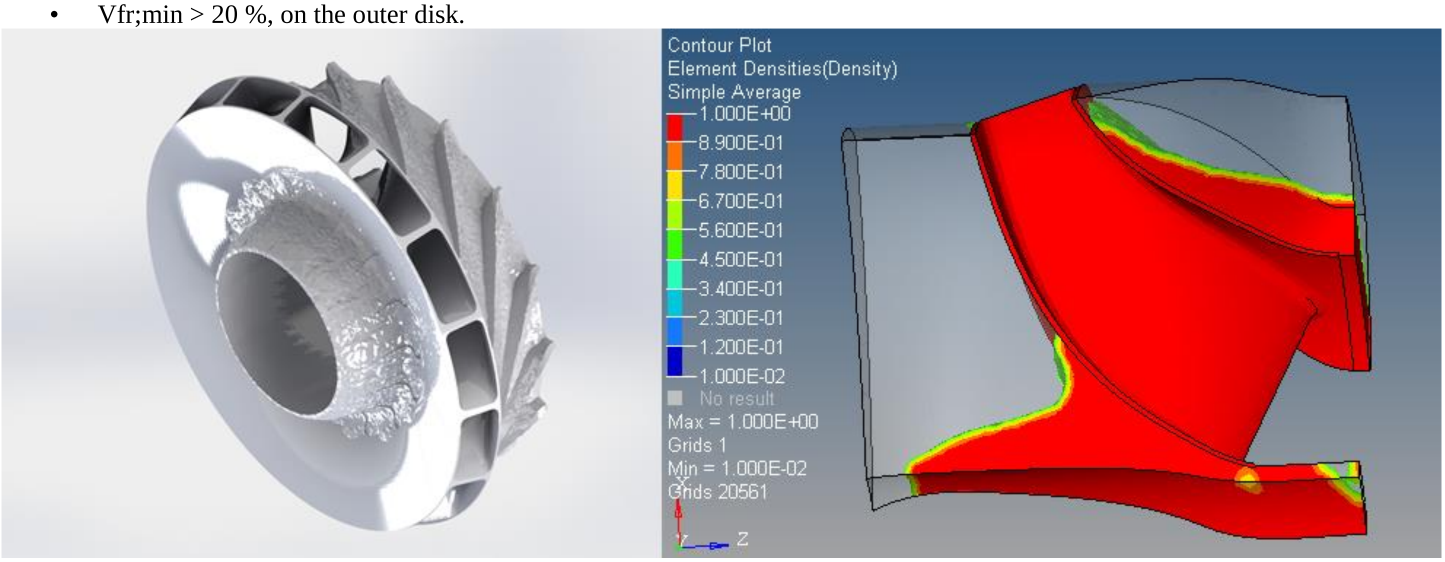


Figure 15 - Optimization result for the 3D impeller

In the figure, the red regions are the unit density zones, while no results areas are no density respectively no material.
The values of maximum stress and radial displacement are checked as usual and they are summarized in table 4.
The seal region has not been modelled as non-design space, as this approach can easily bring to ill-conditioned problems, leading to not optimized results. The seal region is added in a separate phase and does not change the result in terms of mechanical behavior.

	Baseline	Optimization	Reduction
Maximum stress [MPa]	905	680	25%
Maximum displacement [mm]	0.17	0.14	17%

Table 4 – 3D impeller optimization results

Significant improvements have been achieved compared to the geometry starting point, considering also a reduction in mass of 15%.

The best performance for a static topology optimization in the case of 2D impeller is shown in the figure 16. The constraints on stress, displacements and volume are set as follows:

- σmax < 500 MPa;
- umax < 0:100 mm;
- Vfr;min > 20 %, on the outer disk

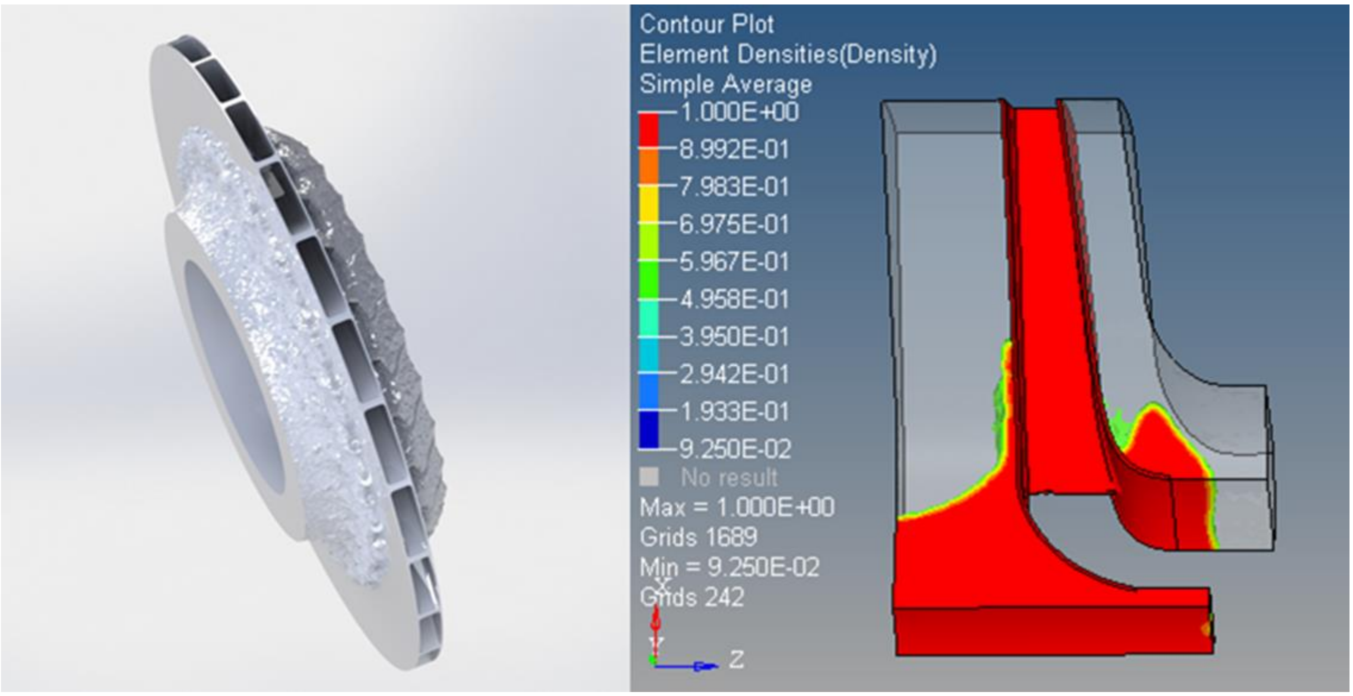


Figure 16 - Optimization result for the 2D impeller

Analogously, also in this figure, the red regions are the unit density zones, while *no results* volumes are no density respectively no material volumes.

The values of maximum stress and radial displacement are summarized in the table 5.

	Baseline	Optimization	Reduction
Maximum stress [MPa]	561	408	27%
Maximum displacement [mm]	0.14	0.10	28%

Table 5 – 3D impeller optimization results

Also in this case, very impressive results have been obtained, with a reduction in mass of 11%.

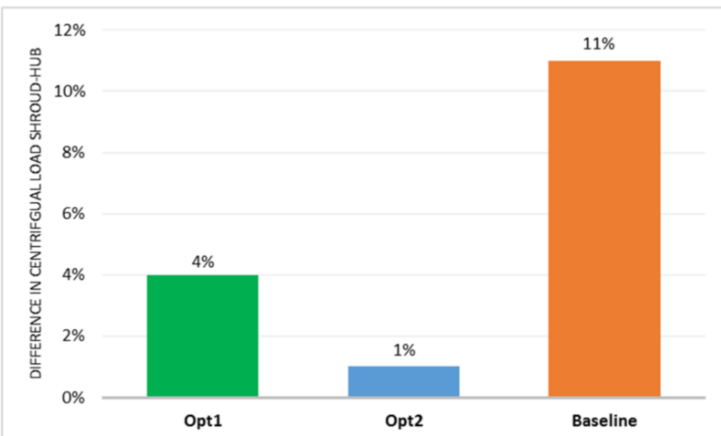
Particularly interesting is the case of 2D impeller optimization described, as the final results of the optimization has produced a counterintuitive design. In fact, the traditional way to reduce the stress level on the blade is to remove material in the shroud region, to reduce the centrifugal load on that region. In this way, however, the difference in centrifugal load between hub and shroud will increase, worsening the tensional status of the blade, that is stretched with different intensity in the two sides (hub and shroud).

Considering shroud, blade and hub as three separate parts, the centrifugal load acting on each part can be assumed as:

$$F_{CF} = m * R_c * \omega^2 \quad (4)$$

Where:
F_{CF} is the centrifugal load
Rc is the radius of the center of gravity
ω is the rotational speed.

As the rotational speed is the same for shroud and hub, the difference in the centrifugal load is proportional only to the product of mass and the radius of the centroid. In the baseline case, the product of the mass and the radius of the centroid of the hub region is 10% above the value of the shroud region. It means that it is necessary to reduce the centrifugal load on the hub region and to increase it on the shroud region, to have coherency of load on the top and bottom sides of the blade. As can be appreciated in Figure 17, the optimizations performed had always as results to balance the centrifugal load in the two regions, reducing the difference between hub and shroud below 5%. This has the effect to reduce the stress level in the impeller.
In this case, the mass of the part has not been reduced; on the contrary, to balance the centrifugal load between shroud and hub regions, it was necessary to slightly increase the overall impeller mass.



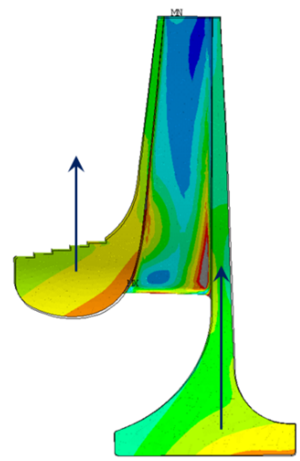


Figure 17 – Difference in Centrifugal load applied on Hub and Shroud regions.

		Opt1	Opt2	Baseline
Mass (kg)	Shroud	0.214	0.214	0.181
	Hub	0.268	0.259	0.258
Rc (mm)	Shroud	124	124	128
	Hub	104	101	101
Mass * Rc	Shroud	26.62	26.52	23.22
	Hub	27.80	26.20	26.16
Delta		4%	1%	11%

Table 6 – Difference in Centrifugal load applied on Hub and Shroud regions.

All the previous analyses have been performed without changing the blade region. An additional step in optimization consists in keeping the same external shape of all the parts, allowing the creation of internal holes and reinforcements.
The design space has been set up as all the internal volume of the impeller, keeping 0.1mm of non design space from the flowpath (see Figure 18). The same constraints of the previous analysis have been applied, allowing the optimization algorithm to modify the internal part of shroud, blade and hub regions.

The result is reported in Figure 18. The material has been eliminated to create a series of reinforcements in the tangential direction, with a thicker dorsal along the blade tip; the geometry is similar to the stiffening structures typical of airplane wings, with the central spine and the horizontal ribs. It is interesting to observe that in the region of the trailing edge, the ribs assume an inclined direction, corresponding to the direction of the deformation of the blade. This is due to the constraint on the maximum blade maximum deformation at the trailing edge zone; this effect was less evident removing the constraint.

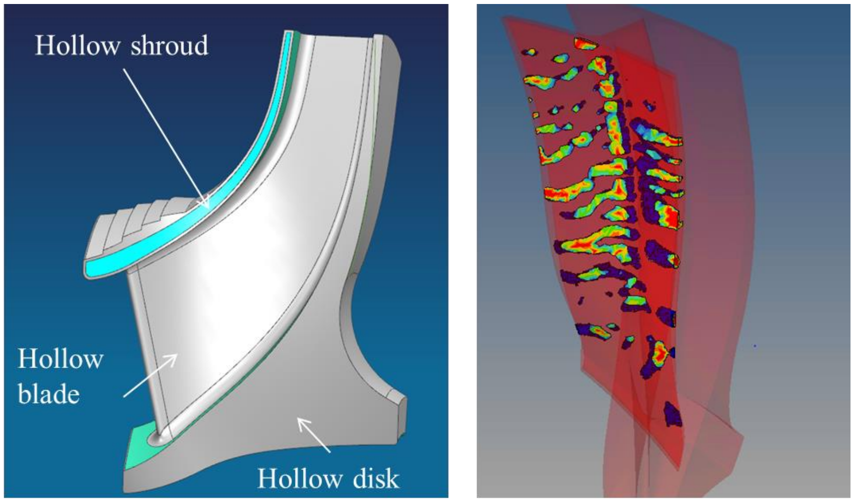


Figure 18 – Design space defined considering all the internal volumes of the impeller.

The geometry shown in Figure 18 would be impossible to manufacture with traditional technologies. Only Additive Manufacturing can provide the necessary capability to produce a structure that presents such succession of holes and reinforcements.

Modal optimization

Different types of analyses can be performed during a Topology Optimization. Among those, modal analysis can be seen as one of the most promising application, with the objective of moving away from the operating range particular impeller vibrating modes.

The natural modes of a test case impeller are reported in Table 7. The modes from 9 to 13 are within the operating range and should be kept outside it, with a margin of at least 5%. At the same time, it is important not to bring additional modes inside the operating range, as the mode 14.

The optimization was done combining static and modal analyses. The constrains applied are:

- $\sigma max < 900$ MPa;
- Mode 13 frequency < 3000 Hz;
- Mode 14 Frequency > 4000 Hz;

A first result is provided in Figure 15. It is interesting to observe that, as the scope was to reduce the frequency of the mode shown if Figure 19, the algorithm has removed mass at the zone at higher diameter, that is the area that vibrates more, reducing the stiffening of the structure. At the same time, to keep the stress level below 900 MPa, a series of reinforcement along the blade tip has been created, together with a concentration of mass on the eye region, above the blade leading edge. The scope of these features is to reduce the stiffness of the impeller, at the same time keeping the blade deformations and stresses at an acceptable level.

Mode	Frequency (Hz)
1	1544
2	1717
3	1718
4	2085
5	2086
6	2365
7	2366
8	2540
9	3376
10	3377
11	3397
12	3398
13	3400
14	4735
15	4736
16	4963

Table 7 – Impeller natural modes.

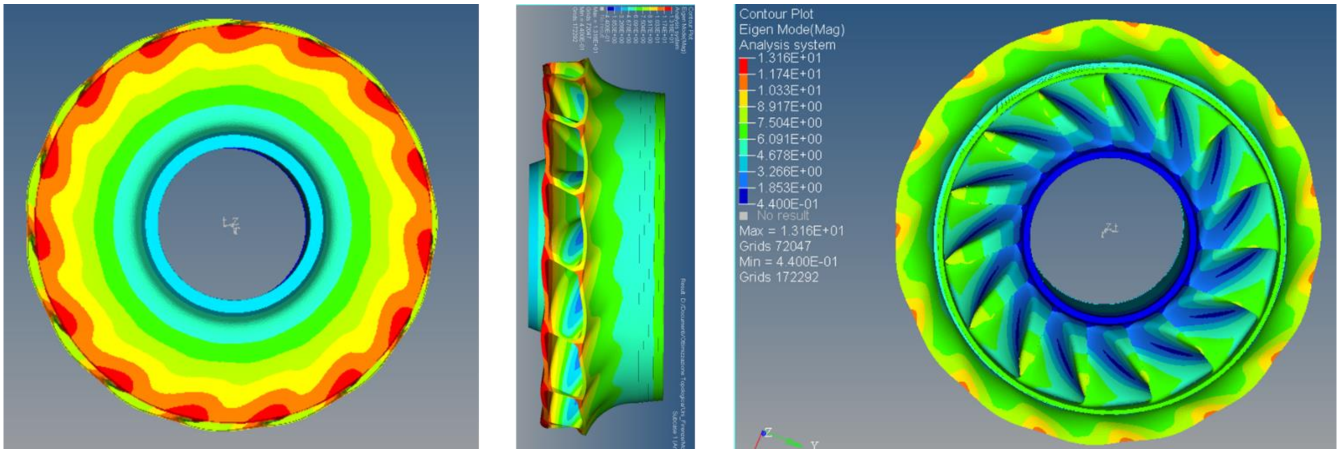


Figure 19 – Modal Shape of the impeller mode (Mode 13) to be moved below the operating range.

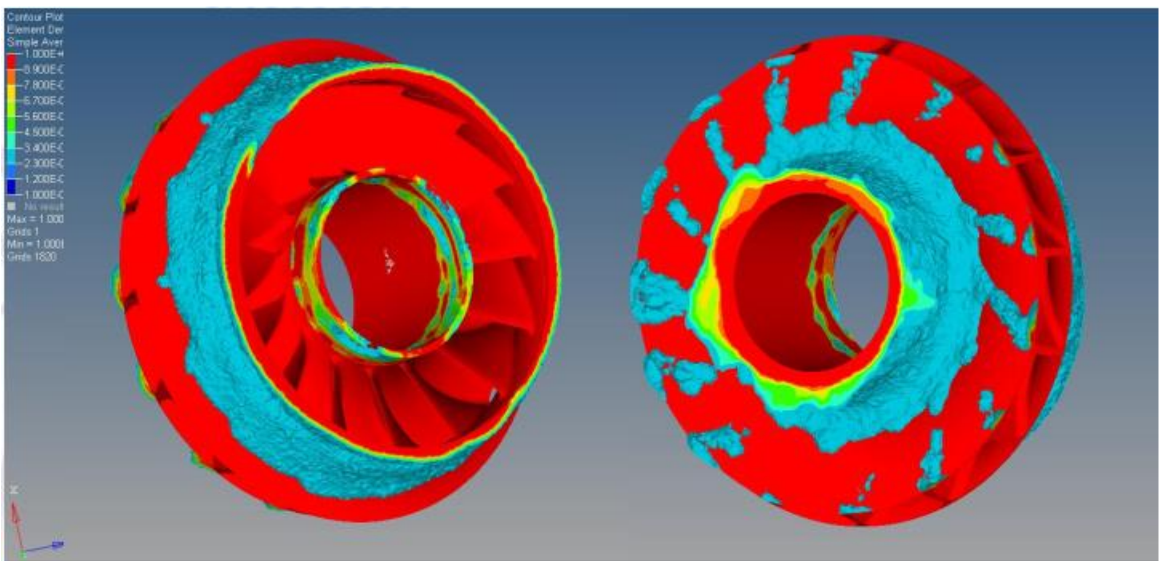


Figure 20 – Modal Optimization result.

The results are summarized in table 8. All the constraints in terms of frequency and stress have been respected, reducing the impeller mass by around 20%.

Mode	Baseline Freq (Hz)	Optimized Freq (Hz)
13	3400	2900
14	4735	4040

Table 8 – Baseline and optimized Impellers natural modes

New design

As seen in the previous chapters, Topology Optimization can be used to develop and scout new designs. Multiple types of analysis can be combined to consider different design constraints, such as max stress level and impeller natural mode frequencies. This approach is not easily applicable with traditional methodologies, such as parametric optimization, as the objectives of the analyses can lead to different geometries, not always in accordance with each other.

Particularly interesting is the case of the optimization of open impellers. Those impellers are typically used in overhung compressors, to provide a significant pressure rise in a single stage. To increase the maximum peripheral speed achievable by the rotoric component, the shroud can be removed, keeping the blade unconstrained on the tip region.

The stress level on the impeller is reduce in such way, but other kind of problems may arise. In fact, for open impeller the main sources of risk are the blade vibrating local modes, as the 1st and 2nd bending modes and edgewise modes. Furthermore, in these types of impellers, each blade is acting as separate component and the matching between acting force and modal shape of the mode in terms of Nodal Diameters is not relevant anymore. In fact, in closed impellers, the whole structure acts as continuous body, and the response of the impeller is deeply influenced by the matching between impeller modal shape and unsteady pressure fluctuation shape. If the matching is not good enough, it is very unlikely that the impeller mode could be excited by the aerodynamic forces and that the resonant condition could occur. On the contrary, on open impellers, irrespective on the matching in terms of Nodal Diameters, each combination of aerodynamic forces and blade local modes could potentially lead to a dangerous resonant condition.

For the above reason, it is very important to avoid any potential risk of crossing between aerodynamic sources (for instance statoric vanes in front or after the impeller) and blade local modes, such as bending and edgewise modes. Avoiding all the crossing is not always possible, as the frequencies of blade modes are irrespective of the Harmonic Index, as each blade act as separate component. For instance, in Figure 22, the first row of baseline modes at slightly below 2000 Hz is formed by all the 1st bending blade modes.

To increase the frequency of the blade 1st bending modes, a Topology Optimization was run, applying a design space as circular crown around the blade leading edge, setting constraints on the max allowed stress and on the frequencies of the blade modes. The design space and the outcome of the analysis are shown in Figure 21.

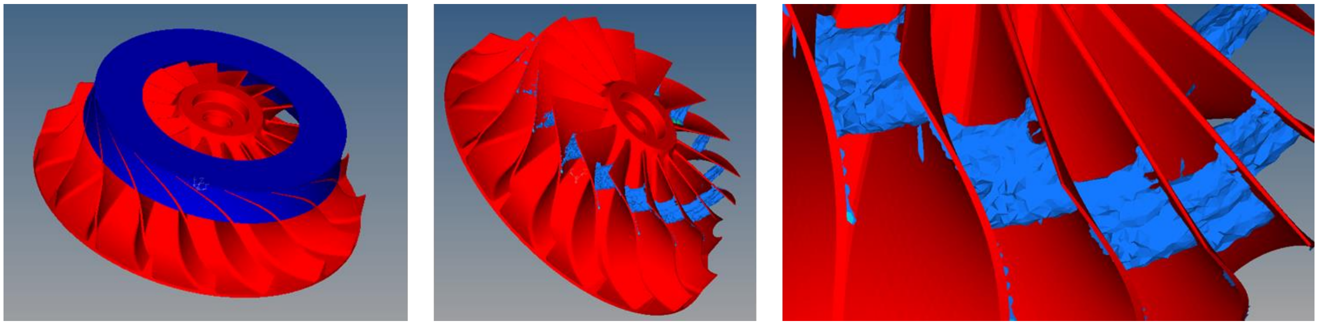


Figure 21 – Modal Optimization applied to an open impeller

A series of reinforcements have been built between two consecutives blades, to improve the stiffness and increase the mode frequency. The design of the reinforcements is very effective to fulfill the scope of the optimization. In fact, the ribs connect the two closes areas of two consecutives blades and not the same areas of each blade. This has the effect of adding the least quantity of material necessary to improve the stiffness and to connect parts that have different modal displacement. In fact, if the same regions had been connected, the results would have been only to reduce the frequencies of the modes, as it would have been added mass without improving the structure stiffness.

In Figure 22 the increase in frequencies of the impeller modes are reported. For the blade modes at high Harmonic Index it has been observed a very high increase in frequency, almost two times the baseline frequencies. It is also worth to highlight that in the new design, the modes frequency is now depending on the Harmonic Index of the modes, increasing toward the right of the chart. This is a clear indication that the structures behave as single part, comprising also the blades.

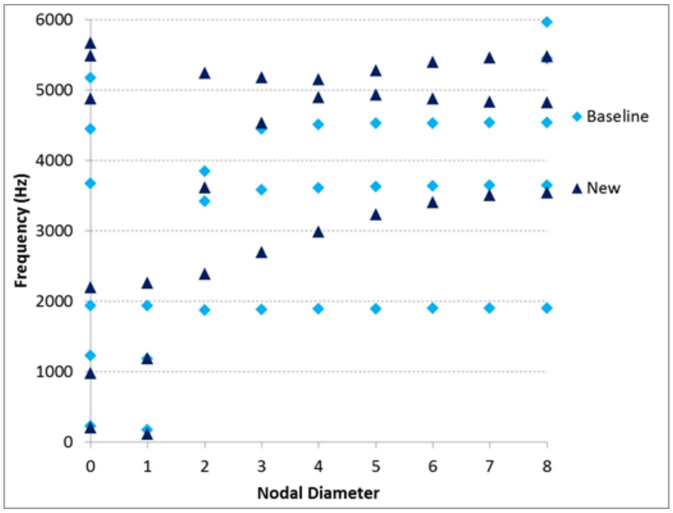


Figure 22 – Frequency comparison of new design vs baseline open impellers.

Case study

The OEM has produced several impellers trough Additive Manufacturing. The methodology used is the DMLM. It is an additive manufacturing process that uses lasers to melt ultra-thin layers of metal powder to build a three-dimensional object. Objects are built directly from an .stl file generated from CAD (computer-aided design) data. The use of a laser to selectively melt thin layers of tiny particles yields objects exhibiting fine, dense and homogeneous characteristics.

The DMLM process begins with a roller spreading a thin layer of metal powder on the print bed. Next, an .stl file directs a laser to create a cross-section of the object by completely melting metal particles. The print bed is then lowered so the process can be repeated to create the next object layer. After all layers are printed, the excess unmelted powder is brushed, blown or blasted away. The object typically requires little, if any, finishing. High-precision DMLM parts possess exceptional surface characteristics along with mechanical properties equivalent to those found in traditional wrought materials. Surface quality and minimal porosity are two key advantages of the DMLM process. Since it is possible to move the print bed in as little as 20-micron increments, objects exhibit a smooth surface quality that minimizes the need for post-production finishing. The DMLM process minimizes the porosity common with sintering. In fact, it is possible to achieve close to 100 percent density. DMLM offers short lead times ideal in situations where repeated testing of functional metal prototypes is necessary. Where traditional production times are often measured weeks, the DMLM process only requires hours or days.

Pumps
The OEM has the capability to build pump impellers up to 9”. Comparing to traditional lead time to produce one impeller, the required time has been brought down 33%.

The process studied and implemented to produce the test case is as follow:

- Machine selection: EOS M280/290.
- Material selection: IN718.
- Deposition and melting of metal powder as per DMLM process.
- Heat treatment of the part produced to achieve the required material properties.
- Removal of the internal support, needed to sustain overhang structures at angle above 45°.
- Final machining to achieve the desired external geometry
- Finishing process to reduce the final roughness in the flow path region.

The impeller has been produced and installed in the field in 2015.

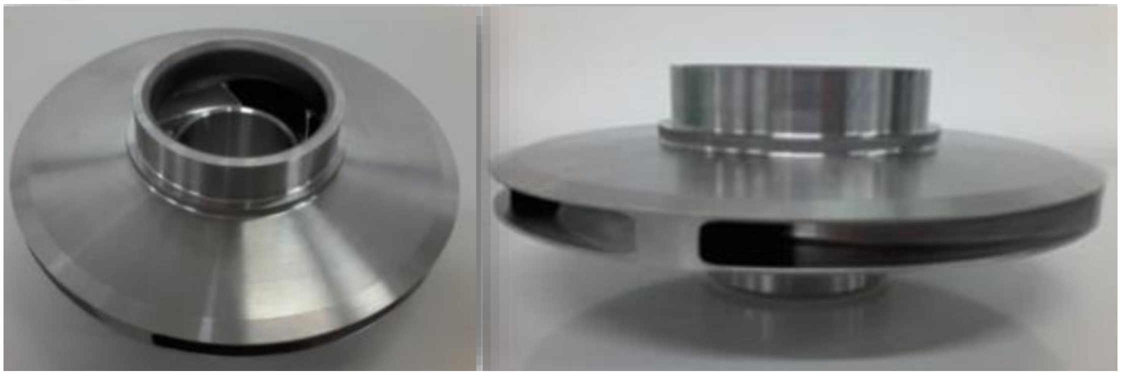


Figure 23 – Pump Impeller by DMLM produced in 2015

Compressors

Pump impellers can be considered easier to be manufactured compared to compressor impellers. In fact, the number of blade is usually not high and the channel height usually allow for an easy movement of the tools. Furthermore, pumps are less sensitive to imprecision in the final geometry of the rotating components and can withstand higher deviation from the nominal design.

On contrary, compressor impellers have a more complex geometry of the gas channel, especially in the tridimensional cases, and can be particularly challenging to be produced with traditional one-piece technologies, such as full milling or Electro Discharge Machining (EDM).

Tridimensional impeller designed at low flow coefficient (below 0.0600) and bidimensional impeller at very low flow coefficient (below 0.0100) present very narrow blade passages that are impossible to be manufactured with industrialized methodologies. For those geometries, Additive Manufacturing is a powerful technology to enable the production in a single piece process.

The OEM has performed a series of trials to individuate the optimal machine settings to produce 3D and 2D impellers in Aluminum and IN718. The machine used is a EOS M400, with a volume capability of 400 mm x 400 mm x 400 mm. The manufacturing steps are the same described in chapter related to pump impellers.

In Figure 24 and 25 are shown the impeller produced during the trials. A 3D impeller and a 2D impeller of 390 mm of external diameter have been realized in aluminum; the same 2D impeller has been produced in IN718.

The final geometries were within the requested dimensional and geometrical tolerances, with a final roughness achieved through abrasion flow machining. The parameters that were found outside the requested tolerances are reported in Table 9. The main differences are measured on the hub and shroud thickness at the exit region; however, it is possible to machine the external part of the to achieve the required dimensions.

For the above reasons, we believe, the manufacturing technology is ready to be used on production units.

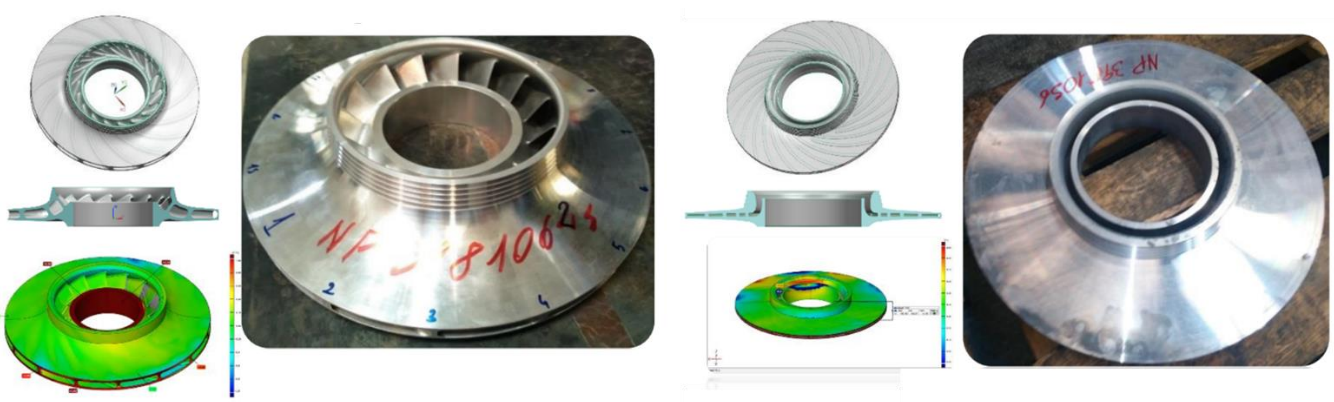


Figure 24 – Compressor Impellers produced in Aluminum

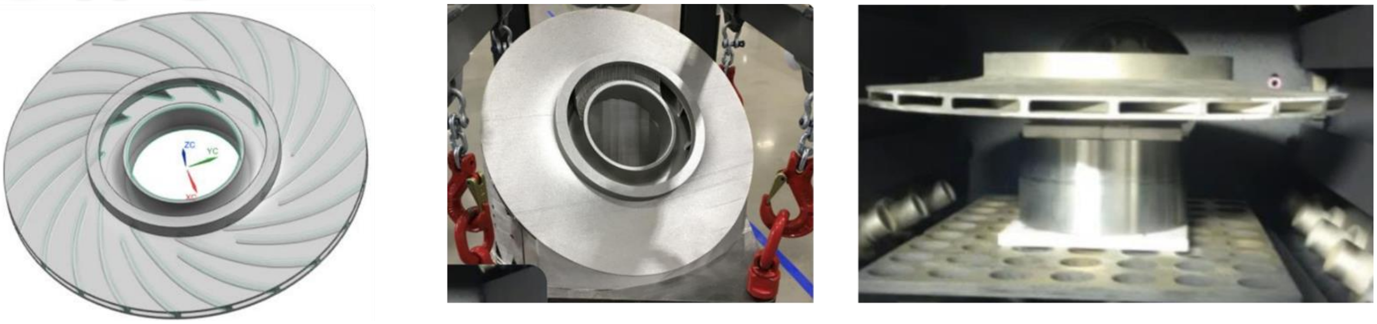


Figure 25 – Compressor Impeller produced in IN718

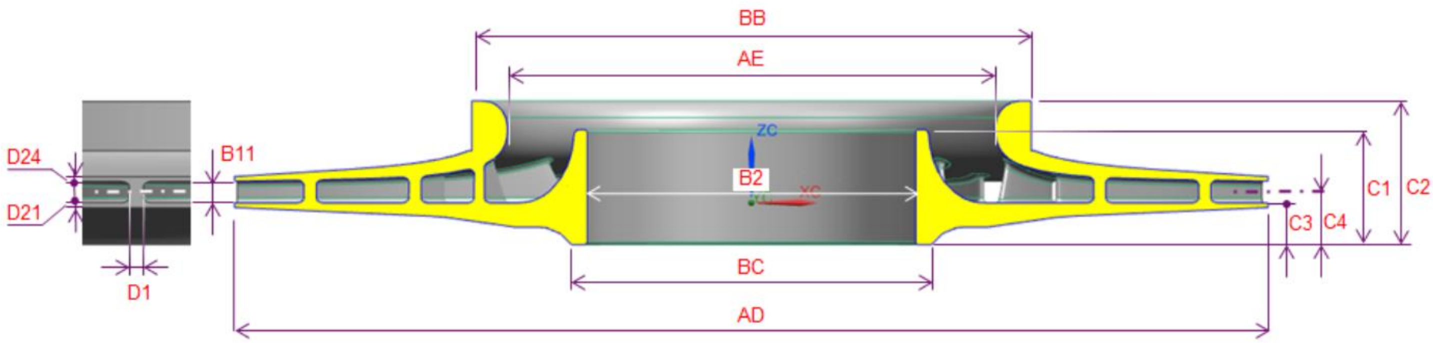


Figure 26 – Dimension definition for geometrical control.

Parameter	Description	Difference vs nominal
B3	Inner Diameter	-0.01%
C1	Foot length	2.27%
C2	Total length	1.38%
BB	Seal diameter	-0.03%
B11	average exit width	-3.86%
D21	Average Disk thickness at exit	11.11%
D24	Average Shroud thickness at exit	52.78%

Table 9 – Impeller dimensions outside requested tolerances.

CONCLUSIONS

Along this paper an introduction to innovative manufacturing process and related design approaches have been presented highlighting the strength and the weakness of both and showing how the printing techniques shall be though not just as an alternative to conventional processes but as a new technology enabler generating geometries that couldn't be neither imagined before.

New geometry optimization tools such as lattice filled volumes and topological optimization are required to generate geometries that can't be easily generated with convectional design approach.

A deep and complete understanding of the whole design process is required to fully take advantage of the multidisciplinary design techniques available today, shaping the design space boundaries to reach the best design solution.

Definition of the design space is critical for the optimization of the shape without affecting the interfaces and the fluid dynamic functionality of the component.

The results reported show how topological optimization gives promising results in terms of mass reduction, stress optimization dynamic response of the structure and that many design space constraints can be removed if coupled with additive manufacturing techniques. Significant improvements in terms of mechanical performance have been achieved: the stresses values and the radial displacements of the interference zone have been reduced if compared to traditional design, decreasing the impeller weight as well. The resulting structure is lighter and satisfies all design constraints. This aspect has allowed to raise rotational velocity and then the machine efficiency.

The best configuration of constraints and objective functions to obtain new components structures was defined. The best strategy to obtain promising results is minimizing the total compliance, with constraints on local stress, displacement and volume fractions. The "ready to print geometry" can be produced by a rendering process, after each optimization to create a smooth 3D model for the manufacturing.

Additive manufacturing techniques has been widely investigated within the company in relation to the process stability for final tolerances and material characteristics repeatability. Once set up the printing parameters the most challenging aspect has been the reduction of the surface roughness that is very poor at the end of the printing process if compared to subtractive manufacturing techniques.

Some printing results have been presented focusing on impeller for different products such as pumps, compressors and expanders and the process capability have been shown with good correspondence between the desired and actual dimension highlighting that, currently, a final re-machining is required, but that the raw material lead time is reduced to almost zero, obtaining similar strength properties with respect to the forged material. The slightly strength reduction is not a concern because of the high average tensile properties of the selected material a because the design made with topological optimization allows a large stress reduction of the final components covering the gap.

Current design development direction of the OEM is aiming to join aero-thermal-mechanical and dynamic optimization including transient effects to the whole system composed by rotor with impellers, bearings and casings using the whole capability of multiphysics design tools coupled with additive manufacturing.

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