Design for Additive Manufacturing of a Horizontal Axis Wind Turbine

Simone Cantarelli, Daniela Francia, Alfredo Liverani, Leonardo Frizziero
Department of Industrial Engineering
Alma Mater Studiorum University of Bologna
Bologna, v.le Risorgimento, 2 - 40136, Italy
simone.cantarelli@studio.unibo.it, d.francia@unibo.it, alfredo.liverani@unibo.it, leonardo.frizziero@unibo.it

Abstract

This paper aims to provide the study of a design strategy for 3D printing production process, given its recent development, as well as that of high-performance materials. In particular, we focus on the blade of a wind generator by evaluating new construction methods deriving from new design approaches. The strategies used for the present study are described as follows: firstly, it was necessary to proceed to redesign the blade, by CAD software in order to menage a 3D model for the study and to initialize the whole project; then, the FEM analysis to validate the study. Finally, the AM (Additive Manufacturing) theorization and simulation for both a scaled blade and a full-sized one. The motivation behind this paper draws on the predominance and the constant evolution of the 3D printing in recent years, as well as the continuous research on both development and improvement of costs and performance of composite materials used.

Keywords
Wind-turbine, Design for Additive Manufacturing, Composite Materials, Finite Element Analysis

1. Introduction

This study aims to develop a Design for Additive Manufacturing method in order to provide a guideline for further more specific studies. More in detail, a blade of a wind generator will be analysed, redesigned, and tested to be 3D printing compliant through Additive Layer Manufacturing (ALM) methods; in the end, its practical realisation will be hypothesised. Firstly, the methods nowadays used in three-dimensional printing will be included, thus highlighting the strengths and weaknesses of each of them. Investigations upon materials currently in use on wind turbines will be carried out. Subsequently, the geometry of the wind turbine will be considered, drawing it as faithful as possible to the original; then, changes will be made with all appropriate load cases to provide for the criticalities due to three-dimensional printing. The setting and use of tools such as the Finite Element Analysis (FEA) will then define the conditions of use of the wind generator. At that point, some hypothesis about the realization of the scale model will be presented, evaluating the printer's volume first and after the positioning, timing, and quantity of the material used as well as any supporting fillings.

The paper aims to highlight the possible strategies to maintain a high quality standard and reduce the costs of such a technology at the same time. Indeed, this case study aspires to give contribution to a general improvement of 3D printing not only in the renewable energy field but also in any possible industry and in some other field as the biomedical where the surgical simulation is raising and improving (Frizziero et al, 2019, 1317 - Frizziero et al, 2020, 5181).

2. Literature Review

2.1 Design for Additive Manufacturing

Hällgren, Pejryd, and Ekengren (2016) define two methods of Design for Additive Manufacturing (DfAM):

- Process-driven shape

- Designer-driven shape.

In the Process-driven shape, numerical methods are used for a topological optimization to maximize the shape of the object and performance improvements. For this reason, it may be possible to prevent any waste of material and, hence, guarantee cost reductions. However, the disadvantage of such a method lies in the geometry: the more complex it is, the more complex calculations will be (Hällgren, Pejryd & Ekengren, 2016).

In the Designer-driven shape, the experience of both the designer and the operators of the object is needed, as well as knowledge of the properties of materials, accuracy of the machinery, and related costs. Furthermore, several steps are necessary to proceed with the present method:

- choice of print direction (for example, reduction of heights, better filling of the build chamber);
- addition of extra material on the surfaces to be machined
- geometry change in order to:
  - obtain self-supporting geometries during the print phase, so as to avoid supports;
  - integrate two or more reciprocal motionless parts of the same material into a single one;
  - reduce volumes to lower the production time (*ibid.*).

For the present case the Additive Layer Manufacturing (ALM) method is used, illustrated by Salonitis & Al Zarban (2015), which consists of dividing the piece to be printed into several very thick layers (a tenth of a millimeter) and overlapping them, thus to reproduce the object (Figure 1). There are two reasons why the layers must fulfill these characteristics: the conservation of a sufficient surface finish and the technological limit of not allowing the deposit of a greater amount of material.

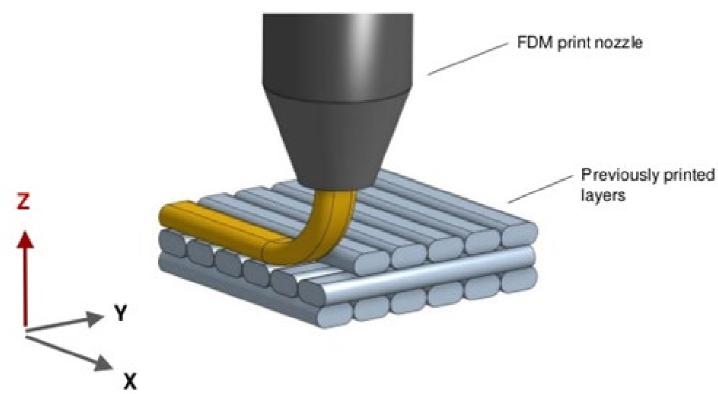

Figure 1: Illustration of ALM method

Another printing method is constituted by the so-called Selective Laser Melting (SLM). It works with the progressive stratification of powder material, which is gradually fused with a laser beam before proceeding with the addition of the next layer. This method is the most versatile Additive Manufacturing process, as it can process a wide range of metallic powder, such as aluminum, titanium, steel, copper, and their alloys. The process is relatively slow, compared to the ALM process. However, it is possible to improve the building rate through the introduction of a multiple laser source (Gokuldoss et al, 2017, p. 3).

2.2 Stress analysis

In the first instance, it is necessary to be familiar with the main stresses that a wind turbine undergoes during its use. Therefore, a correct analysis of the loads needs to be carried out. In this terms, Schubel & Crossley (2012) propose the idea of including the worst situation possible for a turbine to operate, in order to obtain a good simulation. This concept is named “worst case scenario” (Schubel & Crossley, 2012, p. 3441).

Furthermore, it must be considered that the mass of the blades is notable for generators with a diameter of more than 70 meters and, therefore, the centrifugal effect is important. In this regard, both the studies of Schubel & Crossley (2012) and Cox & Echtermeyer (2012) introduce the test of the 50 years of storm in stop conditions, i.e. a turbine with flat pitch blades is continuously hit by a storm for half a century. Therefore, both the operative and the worst case scenarios require a study of the different types of load that weigh on the turbine behavior. The present work relies on Schubel & Crossley (2012, p. 3441), which considers the following loads:

- aerodynamic;
- gravitational;
- centrifugal;
- gyroscopic;
- operational.

Among these, the most important stress is the aerodynamic one as it is necessary for the functioning of the blade. On the contrary, the centrifugal and gravitational ones are only deleterious. The gyroscopic effect is mild, if assuming that the rotation axis remains constant. In the end, the operating loads derive from the pitch and from the misalignment of the axis, with respect to the wind and braking forces.

In addition to the aerodynamic forces, the centrifugal force effect must be taken into account, as it directly depends on the mass of the blade, the rotation speed, and the radius.

2.3 Finite Element Analysis (FEA)

FEA analysis is usually used for the study and the application of these stresses, especially aerodynamic and centrifugal, considering the preliminary nature of this study. This methodology identifies solutions to differential equations, often linear, which approximate the physical problem. Not being able to work on the continuum, it is necessary to discretize the object of the study by introducing reticular structures (*mesh*) that can have the basic element of various shapes (triangle, square, polygon). Of course, the more the mesh is faithful to the geometry, the more complex it will be, as well as its equations. The choice of a quite small element for the mesh will lead to highly accurate results, but this may cause a longer computing time (Liu, 2013, p.2).

3. Methodology

The case study follows the guidelines mentioned above with some peculiar precautions. The present work is divided into four steps:

1. analysis of the specifications, loads and production materials for the object;
2. redesign, following some basic principles (for example, maximum strength, minimum weight and/or stiffness), and subsequent FEA test;
3. identification of any production criteria, more specifically the correct machine to use, minimum layer thicknesses, the speed of nozzle, and the inspection of any non-self-supporting structures;
4. evaluation and validation of the project, thus defining the object as a whole. (Salonitis & Al Zarban, 2015).

3.1 Materials

After some evaluations upon the material to opt for, carbon fiber in epoxy matrix (as in Figure 2) was selected, whose characteristics are explained in Tuberosa (2012). More specifically, there are two possible types of carbon suitable for this application: H.T. carbon with particularly high breakdown voltage (about 390 [GPa]) and H.M. carbon with very high Young's modulus (higher than 300 [GPa]). However, the use of these fibers is subject to the application of an epoxy matrix, which is composed of a resin to which a catalyst has been added with the purpose of causing polymerization, thus hardening the resin.

In more detail, the selected carbon will have the following characteristics:

- Tensile breaking strength: 420 [MPa];
- Elastic modulus: 54 [MPa];
- Poisson's ratio: 0.045;
- Density: 1,450 [kg/m^3].

Nevertheless, this material presents three disadvantages. Firstly, its cost is much higher than that of glass fiber or kevlar. At the same time, its compressive strength is much lower than the one of those materials mentioned before and, in the end, this carbon possesses high sensitivity to local defects, as shown in Mishnaevsky Jr. et al. (2017, p, 18).

Figure 2: Example of a blade turbine realized with composite materials.

3.2 Geometry and Redesign of the blade

The series of profiles composing the blade constitute the most crucial element of the system (Figure 3), as they allow the maximization of the rotation power. Particularly important for its correct design is the power coefficient (Cp), which is the quotient of the ratio of the electrical power to the wind energy. The other necessary parameter is the coefficient λ, called tip-speed ratio, which is the ratio of the related blade speed to that of the wind.

The profiles used for the present case study are taken from Neto et al. (2018). They are the result of the study on a wind turbine based on a metaheuristic optimization. The final sequence of profiles belongs to the DU category, i.e. created by Delft University, which are developed especially for the wind sector. However, a lack of precise information upon these profiles suggested their substitution with NACA profiles (National Advisory Committee for Aeronautics), since they were found to be quite similar to each other.

The list of profiles with their substitutes is shown below:

1. DU 00-W-401 is replaced with: FX77-w-343 (Grasso, 2012b, p. 12)
2. DU 00-W-350 is replaced with: FX77-w-343 (Grasso, 2012b, p. 12)
3. DU 97-W-300 is replaced with: NACA 63-412 (from personal study)

4. DU 91-W-250 is replaced with: NACA 63-412 (from personal study)
5. DU 00-W-212 is replaced with: FFA W3-241 (Palmer et al., 2018, p. 126)
6. DU 96-W-180 is replaced with: NACA 4418 (Grasso, 2012a, p. 639).

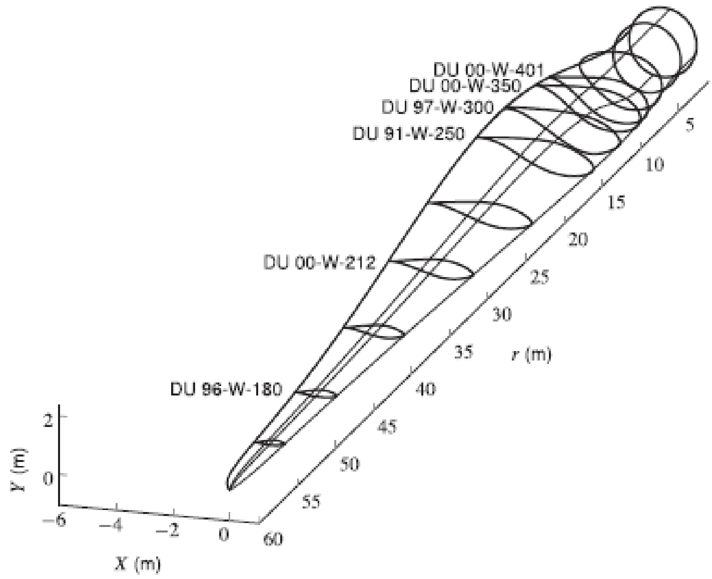

Figure 3: Wire-frame of the blade (Neto et al., 2018, p. 656, fig. 12).

The blade wire-frame in Neto et al. (2018, p. 651) was taken as a model for the first draft of the present blade shape. In more detail, a grid was created to locate the points of the leading edge of each profile. Consequently, it was possible to calculate their positions through proportions and, hence, to deduce the complete leading edge profile.

Secondly, it was necessary to calculate the chord lines of the related profiles by using the same method, thus defining the positioning and the length of each profile. Finally, the height of the profile was quantified, so that all data useful for the design were available.

In this way, the complete geometry was obtained. After this, a test was necessary to verify if the criterion assumed for the blade redesign was correct. Since the study was still preliminary, the criterion of maximum strength constituted the most adequate option, as there is still no precise knowledge of the material.

3.2.1 Reference standards for validating and testing wind turbines

There are two reference standards for validations and tests of wind turbines: the international IEC-61400-23 and the English ISO17025, in which the areas to be tested to validate the project are defined. These are: stresses, deformations, fatigue, and resonance frequency. Their evaluation requires some methods of static and dynamic type that work on one or more axes to better simulate loads and stresses.

Cox & Echtemeyer (2012, p.197) illustrate the Failure Criteria, which are divided into three parts to be verified after the FEA analysis:

- bending, especially for the final portion of the blade;
- material tension, paying attention to the combined stresses;
- buckling verification.

For the first point, a maximum bending of 30% is set in relation to the blade-tower distance during the turbine functioning and of 5% in case of stop. As regards the material, it is necessary to use a coefficient to guarantee a minimum of safety. Lastly, the buckling requires the evaluation of the worst case and then the calculation of the safety factor. Typical values from various studies are reported in Table 1.

Table 1: Typical values of a generic wind turbine blade.

	Younsi et al.	Kong, Bang, Sugiyama	Cox & Echtermeyer	Griffith & Ashwill
Material	/	Glass fiber	Carbon fiber	Glass fiber
Blade length (m)	14	23	70	100
Bending strain (%)	7.29	8.6	12	13.4
Safety factor	/	1.77	2.977	2.205
Peak load coefficient	/	3.43	1.634	2.042

3.3 Finite Element Analysis

3.3.1 Bending

Stresses that cause bending are aerodynamic, whose effects have been assumed in a load of 10 [kN] applied in the blade's center of gravity. The resulting deformation is therefore 2.882 meters, that is 4.8% (Figure 4). Such a value is rather low if compared to the other studies, but this may depend on the approximation made.

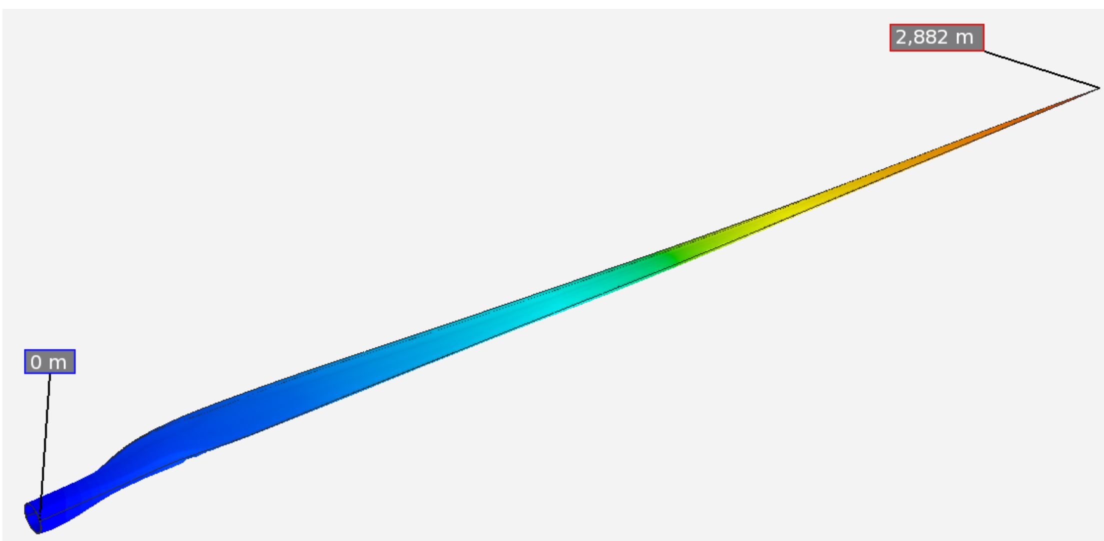

Figure 4: Expected deformation after FEA analysis.

3.3.2 Material tensions

Tensions constitute the result of aerodynamic and centrifugal stresses, which are the most prevalent compared to the others acting on a moving blade. Furthermore, the effects of gravitational loads have not been taken into consideration for the sake of simplicity, and consequently, buckling will not be discussed. The tensions obtained reach the peak in the root of the blade with $3.11x10^8$ [Pa], obtaining a safety factor of 1.35, in conformity with the other studies.

The results shown before confirm the validity of the present study, despite all the necessary improvements. As a consequence, the next step can be theorized, that is the printing of the blade scale model and in real size.

3.4 Scale 3D printing

For the printing of the scale model, it was assumed to use a large generic printer with a printing area of 6x2.3x1.8 meters, which would allow the model to be reproduced on a 1:10 scale. As regards the printing simulation, one of the many software on the market was chosen, as long as it managed to import the file in .stl format, i.e. the most used one for the definition of the mesh. At this point, the overall dimensions were defined and simulations were carried out to find the optimal positioning to avoid any material waste and, at the same time, render the production as fast as possible.

3.4.1 Printing with the leading edge facing down

For this printing method, the main problem that can be encountered is due to the printing area that is not wide enough, thus increasing the possibility of having stresses during the printing phase. The merits, however, are remarkable in this case. Indeed, the support material is minimized and it is also possible to keep the inside of the blade empty thanks to its teardrop-shaped geometry, thus limiting the waste of material (Figure5).

Another flaw is the so-called staircase effect that is naturally formed with the overlapping of the layers. However, it is common to all positioning and for this reason a subsequent surface finishing process is always provided. In terms of time and quantity of material, this printing mode allows for significant savings, since the piece would be produced in 221 hours and with the use of only 774 meters, much lower than the other process.

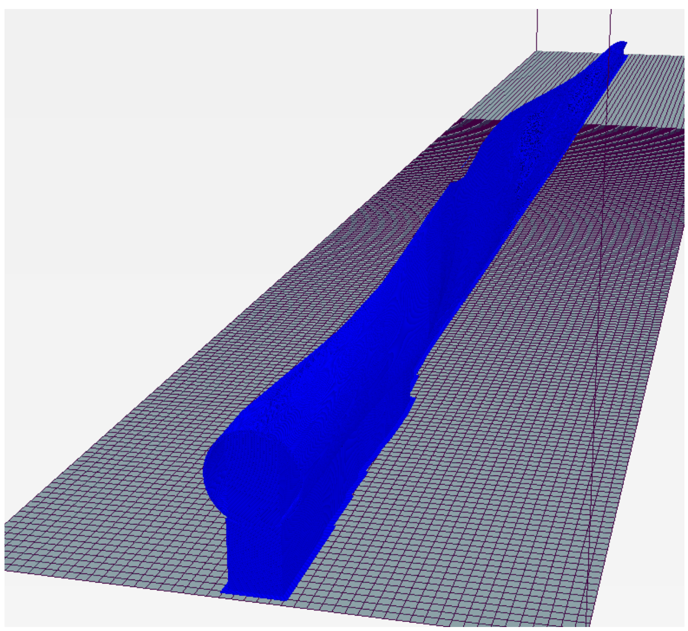

Figure 5: Model of the blade, with the leading edge facing down.

3.4.2 Full Size Blade 3D printing

As far as full-size printing is concerned, only hypotheses will be made, given that the manufacture would involve the creation of an *ad hoc* printer.

First of all, it was assumed to create a core in easily workable material with good thermal stability, such as PVC foam. This material would first be processed in such a way as to have the same shape as the blade and, if necessary, it could be deleted after the printing's completion. On the other hand, the printer was supposed to have four axes, i.e. the three movements of the extruder in order to cover every position plus an axis of rotation of the piece. These vertical and horizontal translations would allow the extruder to deposit the material in every point.

The combination of translation and rotation movements is demanded for two reasons. The first is to allow the extruder to always work perpendicular to the surface on which it deposits the material, while the second lies in the need to intersect carbon fibers at 90° to compensate for the material anisotropy. In addition, the present method should guarantee the best possible surface finish, given the working conditions of the extruder. The second advantage is that the final welding would no longer be necessary. Indeed, the two parts of a wind turbine are currently made by molding two half-shells later glued together (Figure 6), which usually constitutes the weak point of the structure in the long run. Instead, the method described in this study would propose the realization of a blade as a single structure, thus avoiding any gluing process.

Figure 61: wind blade turbine separated in two parts, produced with classic mode.

5. Conclusion

The present study had the purpose to outline a methodology for a 3D printing system for complex structured objects using a wind turbine as the case study. More in detail, the selected guideline to redesign the blade was acquired from Neto et al. (2018), so that its geometry resulted similar to the one in the reference study. In these terms, FEM led to the creation of a stress-simulation model on the component in line with those presented in literature. As a consequence, the method allowed the calculation of the most relevant values for the current project, i.e. bending, material tension, and buckling. Instead, deformations were not quantitatively significant, probably due to the preliminary nature of the study. At a later stage, the printing simulation of a 1:20 scale model demonstrated the project's feasibility, given the short printing time and the affordable cost. On the other hand, the theorizing of a full-size blade printing still deserves a more in-depth study for a complete validation.

Generally, the study proved to be valid as the data correspond to expectations and overall trends in the field of wind turbines. Furthermore, the method proposed could give some basis to further research on 3D printing's technological development through Design for Additive Manufacturing, in any scientific sector. Indeed, the method is already employed in the creation of more complex objects optimized for 3D printing in an effective way.

References

Cox, K. & Echtermeyer, A. (2012). Structural design and analysis of a 10MW wind turbine blade. *Energy Procedia*, *24*, 194-201.

Frizziero, L., Santi, G.M., Liverani, A., ...Maredi, E., Stilli, S. (2019). Paediatric orthopaedic surgery with 3D printing: Improvements and cost reduction. *Symmetry, 11(10),* 1317.

Frizziero, L., Santi, G.M., Liverani, A., ...Stilli, S., Trisolino, G. (2020). Computer-aided surgical simulation for correcting complex limb deformities in children. *Applied Sciences (Switzerland),10(15),* 5181.

Gokuldoss, P. K., Kolla, S. & Eckert, J. (2017). Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting—Selection Guidelines. *Materials*, *10*, 672.
Grasso, F. (2012). Design and Optimization of Tidal turbine Airfoil. *Journal of Aircraft*, *49*, pp. 636-643.
Grasso, F. (2012). *Design of Thick Airfoils for Wind Turbines* [PowerPoint slides]. ECN.
Griffith, D.T. & Johanns, W. (2013). Carbon Design Studies for Large Blades: Performance and Cost Tradeoffs for the Sandia 100-meter Wind Turbine Blade. In *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, pp. 1-12. Boston, 8-11 April 2013.
Hällgren, S., Pejryd, L. & Ekengren, J. (2016). (Re)Design for Additive Manufacturing. *Procedia CIRP*, *50*, 246-251.
Kong, C., Bang, J. & Sugiyama, Y. (2005). Structural investigation of composite wind turbine blade considering various load cases and fatigue life. *Energy*, *30*, 2101-2114.
Liu, Y. (2013), Effects of Mesh Density on Finite Element Analysis. *SAE Technical Paper*, 2, 1375.
Mishnaevsky Jr. L., Branner K., Petersen H., Beauson, J., McGugan, M., & Sørensen, B. (2017). Materials for Wind Turbine Blades: An Overview. *Materials*, *10*, 1285.
Neto, J.X.V., Junior, E.J.G., Moreno, S.R., Ayala, H.V.H., Mariani, V.C. & Coelho, L.d.S. (2018). Wind turbine blade geometry design based on multi-objective optimization using metaheuristics. *Energy*, *162*, 645-658.
Palmer, F.S., Donisi, L., Pindado, S., Ortega, O.G., Gutiérrez, M.O. (2018). Towards an Airfoil Catalogue for Wind Turbine Blades at IDR/UPM Institute with OpenFOAM. *Journal of Aerospace Engineering and Mechanics.*
Salonitis, K. & Al Zarban, S. (2015). Redesign Optimization for Manufacturing Using Additive Layer Techniques. *Procedia CIRP*, *36*, 193-198.
Schubel, P.J. & Crossley, R.J. (2012). Wind Turbine Blade Design. *Energies*, *5*, 3425-3449.
Tuberosa, B. (2012). *Proprietà meccaniche a trazione di compositi polimerici rinforzati con fibre lunghe di carbonio di interesse per il settore automotive*. [Laurea], Università di Bologna, Corso di Studio in Ingegneria meccanica.
Younsi, R., El-Batanony, I., Tritsch, J.-B., Naji, H. & Landjerit, B. (2000). Dynamic study of a wind turbine blade with horizontal axis. *Eur. J. Mech. A/Solids*, *20*, 241–252.

Biography

Simone Cantarelli graduated from Alma Mater Studiorum - University of Bologna in 2020. He earned a bachelor's degree in Mechanical Engineering with a thesis on Design for Additive Manufacturing. During his academic studies, he participated in projects related to the innovation of urban means design.

Daniela Francia got a PhD degree in 2008 discussing a final thesis titled "Modeling and simulation of mechanical systems with a high number of degrees of freedom by means of non-conventional methods and CAD systems ". Since 2005, she owned courses at the I and II Faculty of Engineering of Bologna as a tutor for the subjects of Computer Aided Design & Construction Aviation, and later as teacher in Industrial Technical Drawing. In 2010 she became Assistant Professor at the Faculty of Engineering, University of Bologna, in the field of Design and Methods of Industrial Engineering, SSD ING-IND/15. She is involved in several projects and research activities in collaboration with research institutions and private companies. Research interest for Rapid Prototyping, Design and Manufacturing, conventional and not conventional Optimization Methods for industrial applications, numerical and experimental Analysis of bio-mechanical and environment friendly components, Interaction Methods by Virtual Reality applications. The focus research activities are centered on innovative methodologies just like QFD, TRIZ, Design for Assembly, Design for Disassembly, Design for Additive Manufacturing, Design for Six Sigma, Bench Marking. She attended numerous national and international conferences and is author of scientific publications of national and international relevance.

Alfredo Liverani is a member of CbEM (Computer-based Engineering Methodologies) research group and he is involved in several activities related to Computer Aided Design (CAD), Computer Graphics, Virtual and Augmented Reality. In detail he focuses on real-time visualization and interaction with particular attention to mechanical, aeronautical applications and Industrial Design. Surface modelling, reverse engineering, mesh generation (FEM) and manipulation, virtual prototyping and live simulations are fields investigated in the several publications available at http://diem1.ing.unibo.it/personale/liverani.

Leonardo Frizziero is engineer, married, father of three children, Leonardo Frizziero got the diploma at Scientific High School "A. Sabin" and graduated at the Faculty of Engineering of the University of Bologna. In academic field, he promotes the scientific issues related to the Mechanical Design and Industrial Design Methods (CAD 2D, 3D, Advanced Design, QFD, TRIZ, DFSS, DFD, DFA, etc.). In 2005, he was recruited by Ferrari Spa, as Team Planner of new Ferrari cars projects. In 2009 he came back to University, obtained the Ph.D. degree and started collaborating with the Design and Methods Research Group of Industrial Engineering becoming Junior Assistant Professor in February 2013 at DIN of AMS University of Bologna. He teaches and follows research in the design fields, participating at various competitive regional, national and international research projects. Since 2018 he has been a Senior Assistant Professor. Since 2017 he is qualified Associate Professor of Design and Methods of Industrial Engineering (ING-IND/15). Prior to the role of university professor, he held relevant positions for some industrial companies.