A variable twist blade concept for more effective wind generation: design and realization

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ABSTRACT
The increasing utilization of green resources is driving research toward the design and development of new and more efficient energy harvesting systems. As far as the wind energy sector is concerned, aerodynamic design and the definition of new airfoils, specifically devoted to the application of wind rotors, has given a huge impulse in this direction. However, the rigid blade concept is still an important constraint in energy extraction during off-design conditions or start-up phases. In order to cope with this problem, a new system has been developed and manufactured within the specifically funded VENTURAS® (VENTo: Una Risorsa Altamente Sfruttabile or 'wind: a highly exploitable resource') Project. The new system applies morphing to modify blade twisting along the blade span (modifying the pitch angle of some sections) while maintaining the same chord distribution as the design configuration. This innovation offers the possibility of partially adapting the blade configuration to the operating point, thus improving rotor efficiency. Design details mechanisms and deformable skin are discussed. Application to small/micro wind turbines seems the most promising field for such equipment, but its extension to different fields (such as UAV morphing wings) could be of a certain interest as far as energy saving is concerned.

ARTICLE HISTORY
Received 13 April 2016
Accepted 15 May 2016

KEYWORDS
Variable twist; morphing control; wind energy

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§The contribution of the two authors is equivalent.
1. Introduction

The paper presents details on the manufacturing and design of an innovative twist blade variation concept for wind turbine applications.[1] The small and micro wind turbine sector, characterized by dimensions in the 2–4 m of diameter range, has received increasing attention by the entire energy market due to the fact that these turbines are easily transportable, installable and maintainable when used for charging or energy storage purposes. Turbines with diameters ranging from 4 to 9 m are classified in the small turbine class, which is devoted to specific electricity production for residential networks or stand-alone applications. Based on classical procedures, as explained in the following sections and also reported in typical wind rotor design manuals (see for example,[2]), rotor blades are designed for a typical operating point characterized by a defined tip speed ratio. Classical variable pitch can be applied to a typical fixed blade design in order to account for wind variations, but the shape is far from being optimal. From a theoretical point of view, optimal blades should be able to adapt to specific conditions by changing the chord and twist distribution along the span (‘morphing blade configuration.’[3–5]) Several wind turbine efficiency improvement methods have been studied and designed for different rotor configurations. These methods were analyzed by the present research group at the beginning of the activity and during the patent evaluation procedure. They have been explained in detail in several internal VENTURAS Project technical reports. A synthetic summary of these methods is presented here as a preliminary discussion. Integrated trailing edge flaps have been studied and tested in [6] by the SANDIA Labs within the SMART Rotor project. The integrated trailing-edge flaps designed for active control of the rotor aerodynamics have had the following goals: (a) to demonstrate the control capability of the trailing-edge flaps; to evaluate the accuracy of simulation tools in predicting the results of active rotor control; (b) to develop procedures in order to characterize an operating wind turbine with active rotor control. Active load control, utilizing trailing edge flaps or deformable trailing edge geometries, is currently receiving a great deal of attention because of the direct lift control capability of such devices, as reported in [7–9]. A research review has been presented in [10,11] in which several methodologies that can be applied to wind rotor technology have been collected and analyzed. Some of these methodologies have been derived directly as extensions of similar techniques installed on helicopters: (i) Active blade tips, (ii) active twisting and (iii) active flaps have been considered in this area. The active twist concept is basically the same concept as that considered in the VENTURAS project, but is based on actively controlled bending-torsion or tension–tension coupling by means of specific actuators (SMA, PZT, and so on) embedded in the blade structure. An obvious advantage of such a concept is that the overall shape of the blade is maintained during actuation. On the contrary, its scalability for different blade sizes is not so clear. Other methodologies, based on synthetic jets or vortex generators, have been described and evaluated in the same references. An innovative approach devoted to micro/small turbines is presented in this paper with the aim of improving their energy extraction and efficiency by means of an innovative twisting capability design of the blade sections. This morphing capability enables the control system to select the optimum twist law along the blade, even in off-design conditions.[12–15] The design activity has been developed within the VENTURAS(*) Project. The VENTURAS(*) project includes the design and manufacturing of a technological demonstrator which includes the smart blade concept. The demonstrator could be used to evaluate the basic performances and compare them with the numerical expectations. Some preliminary aspects pertaining to the manufacturing and assembling of the demonstrator are presented in the paper. The innovative rotor turbine concept is based on the variation in the blade geometry, according to the operating conditions that influences its efficiency, which is a function of the advance V/ωR ratio (V is the wind speed and ωR is the tip speed). A variable pitch propeller usually has a higher efficiency over a wider advance ratio range than a fixed pitch propeller with the same characteristics. For this reason, an increment in efficiency could be obtained if the blade were designed with specific morphing capability, such as twist variation along the span. The combination of variable pitch and the variable twist law is obtained through a motion system based on servomechanisms which modify the collective pitch and the section blade angles, from the hub to the tip, at several points: smoothness on the blade is obtained through the use of a thin composite skin characterized by high bending stiffness and low torsion stiffness. This solution clearly involves a greater complexity than a conventional wind rotor, and this complication will be evaluated in depth from an economic point of view during the test campaign, to establish whether the gain, in terms of produced energy, justifies the mechanical complication. However, the most important aspect refers not only to the slight efficiency improvement that can be obtained in nominal conditions, but also to the considerable increase in efficiency that can be obtained for off-design wind conditions.

Morphing technologies have been widely investigated in several technological innovation fields and some specific solutions that have been designed for a certain
application have been found to be potentially exploitable in other sectors. The similarity between the blades of large size rotors and the slender wings of aircraft or helicopter blades suggest an interested potential application of these designed concepts.[3] The VENTURAS concept, for example, could be a promising new technology for UAV morphing wings, as shown in [15]. Morphing, in fact, has been shown to be particularly important for large wind turbines, to reduce fatigue loads in order to guarantee continued operation over the lifetime of the turbines.[4] It has in fact been demonstrated that a 20–32% reduction in blade root flap-bending moments can be achieved through the use of active aerodynamic blade control. This allows the turbine blade lengths to be increased, without exceeding the original fatigue damage to the system. It is well known that large-sized turbines have reached a considerable level of development, which (often) leads their technology to be defined as a mature one. However, as far as small size turbines are concerned, it is easy to see that they have not benefited in recent years from a similar degree of attention from the scientific and engineering community. This is at least in part justified by economic reasons: industry, in fact, claims that the production of these turbines is still not sufficiently widespread, with the exception of some micro-turbines, such as those used on boats. Moreover, the small companies that operate in the sector do not have the technical capacity or financial resources to sustain and implement research activities. The design of small turbines is often limited to attempts to scale down large turbines, which has proved to be unsuccessful mainly for two reasons:

- The scaled-down turbines are not highly productive, as they are designed for sites which are far windier than inhabited areas, where mini-wind turbines need to be installed;
- The simple scaling, and the application of control technologies which are not optimized for small size turbines, make these turbines more prone to malfunctions, which therefore introduce the necessity of continuous and expensive maintenance, or even to sudden and irreversible breakage.

According to the state of the art [16] that can be deducted directly from the industry, a fixed pitch configuration is adopted by the majority of commercial small turbines (as it is the cheapest option), while others uses a variable pitch strategy. Other control systems are devoted to avoiding off-design working conditions. However, they can be considered more as braking devices than the control devices. They range from mechanisms that make the blade rotate pitch-wise, which are pulled by masses moved by the centrifugal force (passive change in pitch) or by elastic elements associated with systems that actuate the whole blade, or part of it or extreme equipment such as aerodynamic brakes or by rotation of the whole rotor as in ‘passive lateral yaw or furling.’ The actuation of these mechanisms is based on both the effect of auxiliary surfaces or eccentric masses, and systems that permit vertical yaw (tilting) with overturning of the whole rotor when the wind speed exceeds a certain threshold level. These solutions are usually abandoned when the size of the rotor exceeds 8–10 m, due to the stresses that they may induce and the complexity of the mechanical devices.

2. Innovative blade concept

A synthetic description of the variable twist innovative system is presented in this section. The preliminary design, structural aspects and control equipment are described and detailed/explained in detail on the basis of the results of the VENTURAS project. The VENTURAS concept is patented by the Politecnico di Torino (No. 0001408738, European deposit No. 12791288.9 [17]) with the aim of managing blade twist variation in order to improve the wind rotor performance at different operating points. This effect is achieved by adapting the blade geometry according to the calculated optimal one in function of the global operating data, such as wind speed and rotor speed. In order to explain the reason behind this variable twist blade realization, it is necessary to refer to the well-known map in which the mechanical power obtainable for different tip speed ratios $\chi$ is reported as a function of the rotation a function of the rotation speed. The optimum blade geometry, in terms of chord and twist as functions of the rotor radius (when the airfoil has been chosen as a function of the Reynolds number), is defined and kept constant for a given tip speed ratio.[18] The optimum blade geometry obviously refers to the highest efficiency of the rotor, i.e. the maximum mechanical power achievable. The design point is the point, on the curve characterized by the selected tip speed ratio, which refers to the design wind speed. If the tip speed ratio varies, the whole geometry needs to be modified: if it is not possible to modify the chord, it is necessary to modify the twist law along the radius (not only the overall blade pitch!). This is what has here been done and is reported in Figure 1 for a configuration studied in [12,13]. In generator mode, the speed triangle on the blade does not change if the wind speed varies: the tip speed ratio is constant, the efficiency is also constant and optimum, and the shaft power is at a maximum, but this is not the case of the produced electric power. The electric power depends on the efficiency of the whole electric chain, which means on the efficiency of the generator, rectifier, DC-filter, and inverter.[14] The main contributions to the total efficiency come from turbine (rotor) and generator, but the inverter too has a best functioning
range. This is the reason why the angular speed range is delimited between 267 and 624 RPM in Figure 1 as an example. In this way, more energy (about 7–10%) can be obtained from the black line that operates with constant angular speed for wind speed lower than 7 m/s, instead of $X = 7$ line (see [14], for more details regarding this comparison). How the presented solution deals with the transient, the start-up, and cutoff problems is even more interesting. A suitable optimization program [12,13,18] is needed to define the variation law of the blade geometry along the radius (morphing blade program) for the purpose of always obtaining the maximum useful energy (difference between the electric energy obtained and that used for the internal movement of the blade) and of reaching the optimum operating point for the actual wind speed as quickly as possible. An example of the start-up phase, for a configuration designed with $X = 7$, is given in Figure 2: the blade needs to change in shape by passing through different tip speed ratios $\chi$, starting from a flat blade for an angular speed equal to 0 RPM. The management of the cutoff phase (set, for example, at a wind speed of 14 m/s as in Figure 1) is similar but simpler: In this case, it is possible to simply act on the pitch of the blade to maintain a constant, maximum rotation speed without the need of the best blade shape. The geometry variation control methodology has been developed based in the present research project considering the wind speed and rotation speed. The shape design procedure, as detailed in [18], has been implemented in an ‘in house’ developed program (OPTIWR) that takes into consideration the wind speed advance ratio, as well as the local Reynolds and local airfoil polars for the selection of the optimal blade chord and twist. The program determines the optimal blade geometry for a specific operating condition and the optimal twist variation in an off-design condition in order to identify the maximum actuating loads necessary for the moving system. The moving system follows a specific control procedure, as shown in [12,13]. This control procedure and system can easily be extended to other applications, such as a UAV morphing wing configuration (see [15]) by simply changing the reference inputs: flight speed, accelerations, structural strains, and so on. The VENTURAS configuration has included the classical pitch variation for the blade in order to be able to follow any change in condition. The blade configuration is based on a smart propeller. The smart propeller offers the possibility of following the twist distribution along the blade length according to the design indication for a specific operating point. Some details are reported and presented in the following subsections.

3. Innovative blade configuration: design data and main rotor parameters

The VENTURAS 3-blade rotor has a diameter of 3 m with a design operating point ($X = 6$ and $V = 5$ m/s) of about 1 kW and about 0.48 efficiency (the maximum power is about 6 kW at a wind speed of 14 m/s). Its main design data are reported in Table 1. The rotor is assumed to work at a constant rotation speed ranging from $V = 3$ m/s to $V = 7$ m/s, while the rotor follows the design curve at $X = 6$ for a higher wind speed. From 0 to 3 m/s of wind speed, the rotor is assumed to follow a starting procedure such as that shown in [5,12,13]. In this part of the off design (design curve has $X = 6$) operating regime, the rotor is actuated by changing the local twist according to the maximum reported in Figure 3(a).

3.1. Variable twist concept

The VENTURAS concept requires the blade to be divided into two structural components: (1) the internal supporting structure and (2) an external skin that is able to follow the best twist angle for actual operating conditions. The external skin has to follow the ribs during rotation, but has to be rigid enough to maintain the aerodynamic
Preliminary structural investigation pointed out that a single-cell thin-walled construction could be a good compromise between an increase in stiffness and a reduction in weight. The final configuration was thus that of a circular single-cell structure. The blade was then designed by means of a specific in-house program for optimum shape definition (OPTIWR computer program [18]). The design procedure produces a design configuration and a control strategy. On this basis, the load calculation was established and the preliminary dimensioning of the internal and covering structures was performed. Figure 3(a) presents the maximum twist variation that the blade has to undergo and the selected moving ribs or actuated ones (three in Figure 3(a), while the others are dummy ribs). Figure 3(b) reports a preliminary pictorial view of the rotor in its complete final configuration. The preliminary investigation indicated that three moving ribs were enough for the scope of the project. According to the VENTURAS concept, bending and shear loads are applied to the internal structure, while the covering structure is dedicated to collecting all the aerodynamic pressure that has to be passed to the internal structure by means of the actuated and dummy ribs. The actuating torque is applied directly to the moving ribs in order to rotate the covering structure. As a consequence, the reactions are applied to the internal structure. Starting from an extreme operating condition, it is possible to determine the entity of the applied loads and the actuating couples necessary for the actuation. The preliminary structure was assumed to be made up of CFRP with different layups along the blade span. The typical layup for the internal structure was [0/±452/0]ns up to the defined local thickness. Unidirectional and fabric M46 J/2020 material was assumed for the internal structure, considering the following mechanical properties: $E_1 = 255$ Gpa, $E_2 = 6.6$ Gpa, $G_{12} = 3.9$ Gpa for the UD0 and $E_1 = 123$ Gpa, $E_2 = 114$ Gpa, $G_{12} = 3.7$ Gpa for the fabric. The composite configuration for the internal structure was not used to manufacture the prototype, due to budget and time constraint. A classical aluminum tubular structure was, therefore, used for the prototype. The covering structure was sized in order to have an adequate torsional stiffness for the required twist variation (Figure 3(a)) and which would be consistent with the available actuating torque. The stiffness distribution along the blade was determined to be about $1.7E6$ N mm² for the first part (from the root to the first movable rib) and about $1.3E6$ N mm² for the second part and so on.[15] This first configuration was defined by applying the ‘finger idea’, as described in [15], which consists of an open shell structure closed by a plastic film along the airfoil contour. The maximum twist angle in actuation mode can be determined from Figure 3(a). The chosen configuration was considered too complicated for production and an elastomeric

| Parameter                                      | Value                      |
|-----------------------------------------------|----------------------------|
| Min. rotation speed (rpm) – Max. rotation speed (rpm) | 267.38–534.76              |
| Tip speed ratio ($X = \omega R/V$) (design)     | 6                          |
| Max. wind speed (m/s) – Min. wind speed on design curve (m/s) | 14–7                      |
| Variable blade actuation at constant $\omega$ for wind speed (m/s) | 3–7                       |
| Pitch variation and innovative blade actuation for wind speed (m/s) | 0–3                       |

### Table 1. Main design data for VENTURAS blade.

![Figure 3.](a) VENTURAS maximum twist variation (red squares indicate actuating ribs). (b) Pictorial preliminary view of the complete rotor configuration and a detail of the actuated blade.](image)

The blade also includes a standard variable pitch system in order to complete its capacity to morph.

### 3.2. Structural aspects

The internal structure has been designed as a composite tubular spar with a tapered thickness and layup. A preliminary structural investigation pointed out that a single-cell thin-walled construction could be a good compromise between an increase in stiffness and a reduction in weight. The final configuration was thus that of a circular single-cell structure. The blade was then designed by means of a specific in-house program for optimum shape definition (OPTIWR computer program [18]). The design procedure produces a design configuration and a control strategy. On this basis, the load calculation was established and the preliminary dimensioning of the internal and covering structures was performed. Figure 3(a) presents the maximum twist variation that the blade has to undergo and the selected moving ribs or actuated ones (three in Figure 3(a), while the others are dummy ribs). Figure 3(b) reports a preliminary pictorial view of the rotor in its complete final configuration. The preliminary investigation indicated that three moving ribs were enough for the scope of the project. According to the VENTURAS concept, bending and shear loads are applied to the internal structure, while the covering structure is dedicated to collecting all the aerodynamic pressure that has to be passed to the internal structure by means of the actuated and dummy ribs. The actuating torque is applied directly to the moving ribs in order to rotate the covering structure. As a consequence, the reactions are applied to the internal structure. Starting from an extreme operating condition, it is possible to determine the entity of the applied loads and the actuating couples necessary for the actuation. The preliminary structure was assumed to be made up of CFRP with different layups along the blade span. The typical layup for the internal structure was [0/±452/0]ns up to the defined local thickness. Unidirectional and fabric M46 J/2020 material was assumed for the internal structure, considering the following mechanical properties: $E_1 = 255$ Gpa, $E_2 = 6.6$ Gpa, $G_{12} = 3.9$ Gpa for the UD0 and $E_1 = 123$ Gpa, $E_2 = 114$ Gpa, $G_{12} = 3.7$ Gpa for the fabric. The composite configuration for the internal structure was not used to manufacture the prototype, due to budget and time constraint. A classical aluminum tubular structure was, therefore, used for the prototype. The covering structure was sized in order to have an adequate torsional stiffness for the required twist variation (Figure 3(a)) and which would be consistent with the available actuating torque. The stiffness distribution along the blade was determined to be about $1.7E6$ N mm² for the first part (from the root to the first movable rib) and about $1.3E6$ N mm² for the second part and so on.[15] This first configuration was defined by applying the ‘finger idea’, as described in [15], which consists of an open shell structure closed by a plastic film along the airfoil contour. The maximum twist angle in actuation mode can be determined from Figure 3(a). The chosen configuration was considered too complicated for production and an elastomeric

![Figure 3.](a) VENTURAS maximum twist variation (red squares indicate actuating ribs). (b) Pictorial preliminary view of the complete rotor configuration and a detail of the actuated blade.](image)
skin was, therefore, selected. The preliminary stiffness was evaluated to be about twice that of the first configuration, thus causing higher actuating torques, which were compensated by the adopted mechanism. Some extra ribs (dummy ribs) were introduced into each part of the skin in order to reduce its bending deflection and to keep the airfoil close to the initial one. The global structural behaviour of the blade had been investigated in a previous work [15] by means of FE analysis, and lower von Mises stresses than the reference one had been demonstrated for the materials used for the internal and skin structures. The preliminary dynamic behaviour was also investigated in [15] (Campbell plot) for the VENTURAS rotor, and no critical point was observed within the operating envelope. The results of the FE analysis are discussed in [9] and have not been reported here. Interested readers can refer to the cited reference for more details.

3.3. Actuating equipment and moving configuration

Figure 3(b) presents a schematic view of the actuating system and a pictorial view of the VENTURAS rotor in the final prototype configuration. The moving system is composed of a series of moving ribs plus some dummy ribs that constrain the envelope, so that it is not deflected above a certain admissible variation. Actuation is applied by means of cables that are fixed to wheels and constrained on the moving rib. The cables are actuated by specific equipment that is placed in the rotor hub where an electric motor and a dedicated gear are also located. The system is presented in Figure 4(b). The elastomeric envelope selected for the prototype is shown in Figure 4(a), where the internal structure is visible. The internal tubular structure and the main ribs are presented in Figure 4(b) together with the installed moving system.

3.4. Discussion and comments

Cutting edge technology can play an important role in the diffusion of these systems, which can be considered strategic to expand the production of clean, homegrown energy. The currently available machines would in fact benefit from solutions that enable an efficient energy harvesting over a wider wind speed range. The main objective of the VENTURAS project is to develop and test ‘innovative turbine equipment’ that would be able to increase the working capabilities of turbines in terms of wind speed range, while preventing the deterioration of the efficiency of the whole system, constituted by the turbine and the electric generator.[12] The innovative rotor turbine concept is based on the variation in the blade geometry. A variable pitch propeller usually has a higher efficiency over a wider advance ratio range than a fixed pitch propeller with the same characteristics. The combination of the variable pitch and the variable twist laws is obtained through an actuation system which modifies the global pitch and the section blade angles along the blade span at several points: a thin composite blade skin, characterized by a high bending stiffness and low torsional stiffness, could guarantee the right behaviour for the external surface. This solution clearly involves a greater complexity than a conventional wind turbine propeller.

The active aerodynamic control of large turbines can be achieved through several systems, such as surface blowing/suction, surface heating or changes in section shape through the use of ailerons, smart materials, tabs or segmented blade sections [5] and, as previously described, by a variable twist blade, such as that introduced in the VENTURAS concept. In order to pursue the application of an active control through morphing technologies to small turbines, two main issues must be considered:

- The mechanical devices that actuate the morphing must be small enough to be contained inside the blade and the turbine hub without affecting the aerodynamic and structural characteristics;
- The control action must be limited so as to make the entire solution energetically convenient.

The first issue represents a constraint on the final design rather than a technological challenge, whereas the second
complication is evident and the cost increment, therefore, has to be evaluated. It should be recalled that the benefits obtainable from this solution mainly concern the start-up phase and those phases of operation in which there are sudden changes in the wind speed: in these situations, the control system can optimize the operating principle of the wind turbine, and the machine should then give tangible

Figure 5. (a) Command rod with actuating cables; (b) Actuating ribs; (c) Actuating motors.
5. Conclusions

The main design data of the advanced VENTURAS blade concept is presented with a detailed summary of what the core of the innovation is. The variable twist concept is explained in detail, and the importance of the selection of the twist law (related to specific operating phase or start-up condition) for the maximum energy extraction is pointed out. The main VENTURAS parameters are reported in connection with specific regimes. The maximum variation in twist for each actuated rib is also defined and reported. The structural configuration, control strategy, and actuating system are presented and described together with some details concerning the actuating system architecture and installation. The internal mechanisms are presented in connection to the manufacturing of the technological demonstrator. The new rotor is composed by a central hub hosting all the components for actuation, a main tubular spar for each blade on which the moving and dummy ribs are positioned and a deformable skin. A preliminary assembly of the rotor prototype is also presented. The wind energy harvesting potential of the VENTURAS concept is presented and evaluated at different off-design points. The feasibility of such configuration is demonstrated. It has already been pointed out that a rotor with variable twist blades is mechanically complex and difficult to produce. Nevertheless, a preliminary evaluation of the benefits of this solution, in terms of produced energy in steady conditions, has been carried out and reported. A specific test campaign is under consideration in order to understand whether the proposed concept would be convenient from an economic point of view. Such an extensive test campaign will be arranged for a performance evaluation and comparison with a standard configuration, even in unsteady conditions (variable wind speed and start-up strategy).

Acknowledgments

Special thanks to the ATS WINDY (Temporary Partners Association) committed for VENTURAS project management (VENTo: Una Risorsa Altamente Sfruttabile or ‘wind: a highly exploitable resource’). Special thanks also to Giuseppe Sirigu for some help in the second section.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Ministero dell’Ambiente Italiano (2011–2013).
References

[1] Gili P, Frulla G. Variable twist blade design and realization for a more effective wind generation. Paper presented at: International Conference on Invention ICI-2015; 2015 November 27–30; Sun Moon Lake, Nantou, Taiwan

[2] Martin OL. Hansen. Aerodynamics of wind turbine. Earthscan: London; 2008.

[3] Lachenal X, Daynes S, Weaver PM. Review of morphing concepts and materials for wind turbine blade applications. Wind Energy. 2013;16:283–307.

[4] Berg DE, Wilson DG, Berg JC, et al. The impact of active aerodynamic load control on wind energy capture at low wind speed sites. Paper presented at: European Wind Energy Conference & Exhibition. 2009 March; France.

[5] Loth E, Selig M, Moriarty P. Morphing segmented wind turbine concept. Paper presented at: 28th AIAA Applied Aerodynamics Conference. 2010; June 28–July 1; Chicago, Illinois.

[6] Berg JC, Barone MR, Yoder NC. SMART wind turbine rotor: data analysis and conclusions. Albuquerque. SANDIA National Laboratories; 2014. (SANDIA REPORT SAND 2014-0712).

[7] van Wingerden J-W, Hulskamp AW, Barlas T, et al. On the proof of concept of a ‘Smart’ wind turbine rotor blade for load alleviation. Wind Energy. 2008;11:265–280.

[8] Barlas T, van Wingerden J-W, Hulskamp A, et al. Closed-loop control wind tunnel tests on an adaptive wind turbine blade for load reduction. In: Proceedings of the 46th AIAA/ASME, 2008; Reno, NV, USA.

[9] Trolborg N. Computational study of the Risø B1-18 airfoil with a hinged flap providing variable trailing edge geometry. Wind Eng. 2005;29:89–114.

[10] Barlas TK, van Kuik GAM. Review of state of the art in smart rotor control research for wind turbines. Prog. Aerosp. Sci. 2010;46:1–27.

[11] Schubel PJ, Crossley RJ. Wind turbine blade design. Energies. 2012;5:3425–3449.

[12] Sirigu G., Cassaro M., Battipede M., et al. Innovative blade design for wind generator application. Paper presented at: 6th International Conference on Theoretical and Applied Mechanics: Recent Researches in Mechanical and Transportation Systems. 2015; June 27–29; Salerno, Italy.

[13] Sirigu G, Cassaro M, Battipede M, et al. Wind generator innovative blade design: variable twist and start-up control. Int. J. Mech. 2016;10:53–61.

[14] Vacca M, Ruo Roch M., Masera G., et al. Wind designer: an open tool for analysis and design of wind generators. Paper presented at: International Conference on Clean Electrical Power. 2013; June 11–13. Alghero, Sardinia, Italy.

[15] Frulla G, Cestino E, Gili P, et al. A possible adaptive wing apparatus for new UAV configurations. Paper presented at: SAE 2015 AeroTech Congress & Exhibition: Unmanned Aerial Systems Materials, Structures and Manufacturing. 2015; September 22–24. Seattle, Washington, USA.

[16] International Standard. Wind turbines, part 2: design requirements for small wind turbines. IEC 61400-2. 2nd ed. Geneva, Switzerland: International Electrotechnical Commission; 2006.

[17] Gili P, Frulla G (Inventors). Aerodynamic profile with variable twist. Italian Patent n. TO2011A000981. October 28, 2011. International Patent application n.12791288.9. October 24, 2012. EP 2771238. 2014 September 3.

[18] Frulla G, Gili P, Visone M, et al. A practical engineering approach to the design and manufacturing of a mini kW blade win turbine: definition, optimization and CFD analysis. Fluid Dyn. Mater. Process. 2015;11:257–277.