ANALYSIS AND INITIAL ASSESSMENTS OF THE AIRON VARIABLE GEOMETRY WIND TURBINE AND POSSIBLE APPLICATIONS

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Abstract

This work introduces the AIRON wind turbine, an innovative solution in the small wind sector characterized by a variable geometry system. This system allows dual rotation: the main structure rotates on the vertical axis, while each blade rotates individually between 0° and 90°, thus optimizing wind capture regardless of its direction. Patented under number 202022000000065, AIRON uses multiple propellers with double blades on a horizontal axis mounted on a vertical pole, ensuring high energy efficiency. The prototype, made with composite materials such as aluminum, fiberglass, and carbon fiber, was tested under real conditions on a building in a hilly area. The tests demonstrated the turbine's ability to start and maintain rotation even with very weak winds, below 2 m/s, and to produce up to 600 W with winds of about 16 m/s, values competitive for domestic use and small agricultural or nautical settlements. In addition, AIRON stands out for its low noise, provided by the damping system and the variable movement of the blades, and for a dynamic balance that limits vibrations and wear. From a technological point of view, optimized versions are being developed with ball and magnetic bearings to reduce friction and maintenance, dedicated electric generators to maximize efficiency, and scalable models from 1 kW to 6 kW for domestic, rural, and small-scale industrial applications. The robust and modular structure and the variable geometry system make AIRON versatile for residential, agricultural, nautical, marine, and river environments, with an efficiency up to six times higher compared to Savonius turbines of equivalent size, thanks to significantly greater power and driving torque. This turbine represents a significant step forward for micro wind power, combining efficiency, quietness, and versatility of use.

Keywords:
Variable geometry wind turbine; Vertical axis wind turbine; Micro wind energy; Dual rotation system; Low wind speed operation; Distributed renewable generation.

1. Introduction

The wind energy sector traditionally includes horizontal-axis turbines (HAWT) and vertical-axis turbines (VAWT), each with specific operational characteristics, advantages, and limitations. Among the most common vertical-axis configurations are Savonius turbines, which rely mainly on aerodynamic drag forces, and Darrieus and H-Rotor turbines, which instead exploit lift forces. Despite their prevalence, these solutions present issues related to energy efficiency and dependence on wind direction. In particular, in traditional vertical turbines, the continuous variation of the angle of attack relative to the airflow leads to phases of the cycle in which the blade produces negative torque or contributes only marginally to power generation.

A further limitation of conventional configurations concerns the need for relatively high support structures to intercept more stable and intense winds, resulting in increased installation and maintenance costs. In this context comes the AIRON turbine, conceived as an innovative variable-geometry solution, capable of overcoming these constraints through a mechanical system that coordinates the movement of the main rotor and the individual blades. The objective is to maximize the effective surface exposed to the wind during production phases and minimize aerodynamic losses during passive phases, thus improving the overall efficiency of the system even in conditions of variable and turbulent wind.

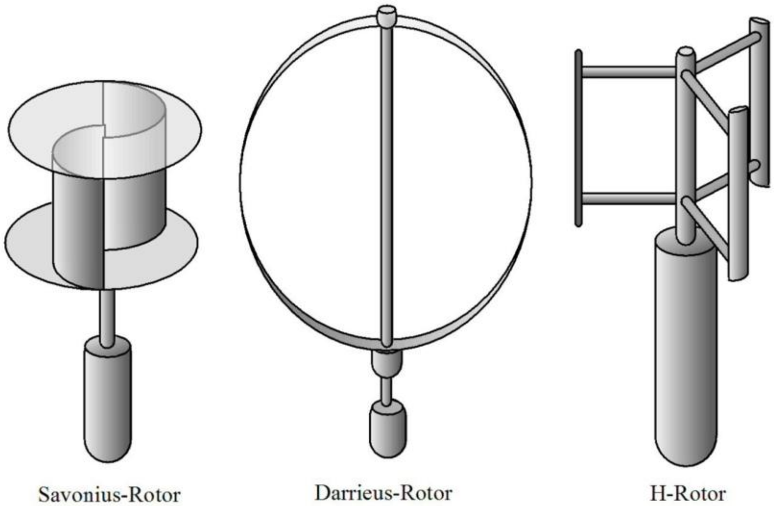


Figure 1: *Savonius and Darrieus turbine*

2. Description of the AIRON Variable Geometry System

The distinctive element of the AIRON turbine lies in the principle of double rotation. The entire structure rotates around the main vertical axis, while each blade is free to rotate around its own longitudinal axis within an angular range of 0° to 90°. This synchronized movement allows continuous dynamic adaptation to the wind direction. When a blade is in a vertical position and presents the maximum surface to the flow, generating driving torque, the opposite blade is positioned almost horizontally, significantly reducing aerodynamic resistance and braking torque. The system is equipped with a cushioned stop mechanism that limits and controls the extreme rotation angles of the blades, reducing mechanical stress, vibrations, and noise. The modular configuration involves multiple propellers installed along a central cylindrical shaft, with pairs of blades staggered by 90° from each other. This arrangement improves the continuity of the delivered torque, reducing the fluctuations typical of traditional vertical turbines and increasing overall dynamic stability. The design was supported by CAD modeling and the production of 3D-printed components, such as the hemispherical coupling elements between the blades and the drive shaft. These components allowed for the optimization of geometric accuracy, assembly repeatability, and torque transfer efficiency, while also facilitating the prototyping and functional validation phase.

***Figure 2:** Blade mold and blades molded in carbon fiber.*

Figure 3: *3D-printed CAD hemispherical elements for coupling blades on the drive shaft.*

3. Prototyping and Experimental Testing

The first prototype of the AIRON wind turbine was built using a construction configuration focused on simplicity, modularity, and speed of assembly, with the primary aim of validating the innovative principle of variable geometry. The main supporting structure was made of aluminum, a material chosen for its favorable strength-to-weight ratio, good workability, and natural resistance to corrosion. The use of aluminum profiles and components allowed for a frame that was sufficiently rigid, yet at the same time lightweight, reducing the rotating masses and facilitating the assembly and transport operations of the prototype. The rotation systems were made using high-strength steel bearings, selected to ensure smooth movement, reduced friction, and long-term reliability. The correct choice of bearings proved essential to guarantee the free rotation of both the main shaft and the individual blades, a key element for the proper functioning of the dual-rotation mechanism. In the initial prototyping phase, the blades were made of PVC, an inexpensive material that is easily shapeable and suitable for quickly checking the aerodynamic and structural response of the system. This initial configuration allowed for testing the kinematics of the variable movement, assessing the dynamic stability of the assembly, and identifying any mechanical issues before moving on to more advanced solutions. Subsequently, in order to improve performance in terms of lightness, structural stiffness, and dimensional accuracy, dedicated molds were designed and produced for the manufacturing of blades in composite materials, particularly fiberglass and carbon fiber. These materials are known for their high specific mechanical strength and low weight, characteristics essential for optimizing aerodynamic efficiency and limiting stresses on the drive shaft. The use of composites also made it possible to achieve more geometrically accurate profiles, improving surface quality and the repeatability of the production process. In the final evolutionary phase, the project was further refined by adopting shaped aluminum blades and a supporting structure made of AISI 316 stainless steel. This choice represented an optimal compromise between robustness, durability, and resistance to atmospheric agents, making the system suitable even for installations in particularly harsh environments, such as coastal areas or high-humidity zones. In fact, AISI 316 stainless steel ensures excellent anti-corrosion properties, increasing the service life of the device and reducing the need for maintenance.

The electric generator integrated into the prototype is a standard commercial device designed to operate effectively at low rotational speeds, around 60 rpm, consistent with the kinematic characteristics of the AIRON turbine. During experimental tests, the system demonstrated the ability to reach a maximum power of about 600 W at wind speeds of 16 m/s, a value particularly significant in relation to the compact size of the turbine. In addition, a good starting capability was observed even with winds below 2 m/s, highlighting the high sensitivity of the system and the effectiveness of the variable geometry in maximizing energy conversion even in unfavorable aerodynamic conditions and low flow intensity.

3.1 Detailed Experimental Methodology

The experimental tests were conducted by installing the AIRON turbine prototype on the roof of a private house located in a hilly area, chosen for the presence of naturally variable wind conditions both in terms of intensity and direction. This context represented a particularly significant test bench, as it allowed for the evaluation of the system's behavior in real and uncontrolled conditions, characterized by turbulence, sudden gusts, and changes in direction typical of complex orographic environments. The installation at height also partially reduced the shielding effects due to surrounding buildings and obstacles, ensuring exposure to the airflow more representative of actual operating conditions.

The prototype was fixed using a support structure rigidly anchored to the roof, in order to ensure mechanical stability and safety during testing, even in the presence of strong wind. Particular attention was paid to the alignment of the vertical axis and the proper leveling of the system, in order to avoid misalignments that could affect performance measurements or generate abnormal stresses on the bearings and transmission components. During the experimental campaign, precision measuring instruments were used to continuously and reliably acquire the main operating parameters. In particular, a **digital anemometer** was used, positioned near the turbine and at a height comparable to that of the rotor, to monitor wind speed and direction in real time. This instrument made it possible to directly correlate environmental conditions with the system's dynamic and electrical response, providing fundamental information for performance analysis. Regarding electrical production, a **high-precision digital multimeter and a data logging** system capable of continuously recording voltage, current, and instantaneous power delivered by the generator were used. The data were acquired with sampling frequencies suitable to capture even rapid variations due to wind gusts or dynamic transients of the rotor. In addition to instantaneous power, the cumulative energy produced over time was also monitored, a parameter useful for evaluating the device's overall yield on an hourly and daily basis. The rotor's rotational speed was measured using **optical sensors** installed on the main shaft, capable of detecting the number of revolutions per minute (rpm) with high accuracy. This data proved essential for analyzing the relationship between wind speed, rotational regime, and power generated, as well as for verifying consistency with the characteristic curves of the adopted electric generator. The integration of measurement systems allowed the construction of a complete experimental database, including environmental, mechanical, and electrical variables. The collected data set made it possible to trace realistic operating profiles of the device under actual working conditions, highlighting the behavior of the turbine during start-up, in steady-state operation, and in the presence of sudden changes in wind. The analysis of the measured quantities allowed for the evaluation of the overall system efficiency, rotational stability, continuity of energy production, and adaptability of the variable geometry to different wind conditions, providing a solid experimental framework for the technical validation of the AIRON solution.

3.2 Performance and Reliability Results

Experimental results have clearly confirmed the effectiveness of the variable-geometry concept underlying the AIRON turbine. In particular, it was observed that the system is capable of starting autonomously and reaching a stable rotational speed even in the presence of very light winds, below 2 m/s. This cut-in speed value is particularly significant when compared with many micro wind turbines currently available on the market, which generally require higher wind speeds, often ranging between 2.5 and 4 m/s, to overcome friction losses and the initial inertia of the rotor. The ability to start at low speeds is mainly attributed to the dual-rotation configuration, which allows for maximizing the useful surface exposed to the wind during the propulsive phase while simultaneously reducing aerodynamic resistance during the blade's return phase. During field tests, the dynamic behavior of the turbine showed a progressive and regular response to increasing wind speed. Within the range of average winds, up to about 16 m/s, energy production remained at particularly favorable levels, reaching a maximum instantaneous power of about 600 W. This result appears significant in relation to the compact size of the prototype and its modular configuration. The power output remained stable even in the presence of moderate wind speed fluctuations, demonstrating good system adaptability and continuity of energy production. This level of performance makes the AIRON turbine suitable for applications in domestic, rural, and marine environments, particularly for low to medium energy demand usage, such as lighting, battery charging systems, small appliances, or remote monitoring equipment.

Another notable aspect emerging from the experiments concerns the reduction of noise pollution, a parameter often critical for the social acceptance of small-scale wind installations. Traditional turbines, especially those with a horizontal axis or fixed-pitch blades, frequently generate aerodynamic noise due to the continuous passage of the blades through the air and the formation of tip vortices. In the case of the AIRON turbine, the cushioned end-stop system and the dynamic variation of the blade angle have contributed to significantly limiting the typical 'whooshing' associated with high-speed rotation. The controlled movement of the blades indeed reduces sudden variations in aerodynamic load and impulsive stresses, resulting in an attenuation of noise emissions.

From a mechanical point of view, the dynamic balancing achieved through the use of adjustable counterweights played a fundamental role in improving the overall stability of the system. The correct distribution of masses along the rotating shaft made it possible to minimize unwanted vibrations and oscillations, especially in gusty or turbulent wind conditions. This resulted in a reduction of cyclic stresses on the bearings and transmission components, helping to limit early wear phenomena and potential malfunctions. Overall, the results obtained demonstrate that the AIRON solution not only ensures good energy performance but also offers significant advantages in terms of quietness, stability, and operational reliability.

3.3 Technological Development Prospects

Currently, the AIRON project is the subject of further research and development activities aimed at improving overall efficiency, long-term reliability, and industrial competitiveness of the system. One of the main optimization lines concerns the adoption of next-generation ball bearings and, prospectively, induction magnetic bearings. The latter, by eliminating direct mechanical contact between the rotating parts, would allow a drastic reduction of friction, mechanical losses, and the need for periodic maintenance. The decrease in internal resistances would also result in a lower minimum starting speed and an increase in overall energy efficiency. At the same time, the development of electric generators specifically designed for the characteristic rotation speed of the AIRON turbine, about 60 rpm, is underway. The use of electric machines at low speeds would allow maximizing electromechanical efficiency, improving the power factor, and increasing operational lifetime, reducing thermal and mechanical stresses on the windings. A further development concerns the design of scalable models, with nominal powers ranging from 1 kW to 6 kW, intended for different market segments: domestic applications, isolated rural contexts, small agricultural or craft activities, up to small-scale industrial uses. The modularity of the system represents a key element to adapt the technology to different energy needs. Finally, advanced variable-geometry control systems are under study, to optimize in real time the orientation of the blades according to wind conditions. These solutions are relevant for installations in marine and river environments, where wind variability requires high adaptability and robustness.

Figure 4: AIRON prototype with modular elements; comparison between system with and without semi-spheres.

Finally, the configuration of the AIRON turbine. The supporting structure has a hexagonal cross-section, with the possibility of 3 or 6 blades distributed over multiple planes to avoid mechanical interference. The blades are equipped with fixed or adjustable counterweights and damping systems (jacks and valves) to reduce noise and ensure precise stops between 0° and 90°.

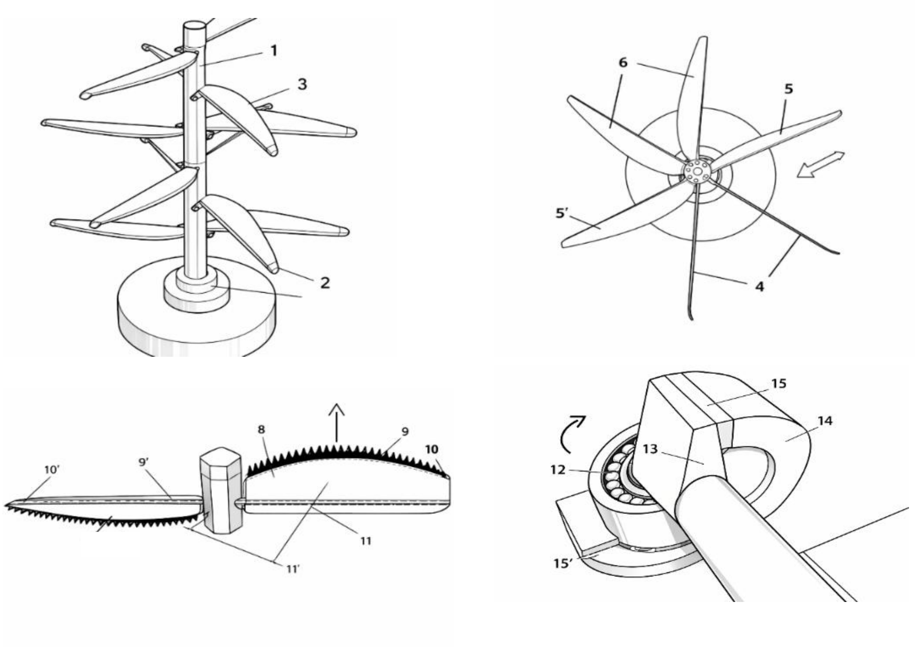


Figure 5: *Series of axonometric views of the main components of the AIRON system [adapted from patented documents: vertical support (1), rotating base (2), blades/propellers (3), blades in vertical positions (4), blades in intermediate rotation positions (5) (5'), blades in horizontal positions (6), circular section rod (8), blades opposed at 90° (9) (9'), deflector curvature at the end of the blades (10) and (10'), counterweight systems (11) (11'), ball bearing (12), striking tab (13). locking element (14), striking elements (15)]*

4. Comparative Performance Analysis

Comparative dynamic analyses were conducted in order to quantitatively evaluate the performance of the AIRON turbine compared to a traditional Savonius turbine of the same geometric dimensions, both characterized by a radius of 0.5 m and a height of 1.5 m, subjected to a constant wind speed of 20 m/s. This comparison was set up by keeping the boundary conditions unchanged, in order to isolate the effect of the different aerodynamic and kinematic configuration of the two systems. The Savonius turbine, known for its construction simplicity and high starting torque, indeed represents one of the main references in the field of vertical-axis turbines based on drag forces.

- The results obtained highlight how AIRON has a starting torque approximately double that of the Savonius under the same operating conditions. This aspect is particularly significant during startup, as a higher initial torque allows the system to more easily overcome the inertia and friction losses in the bearings and the electric generator. In practical terms, this translates into a greater starting capability even in the presence of very weak winds, improving the number of actual operating hours per year and, consequently, the overall energy producibility of the plant;
- Another distinctive element that emerged from the dynamic analysis concerns the torque behavior as the rotor's angular speed increases. In the case of the Savonius turbine, the characteristic curve shows a relatively rapid decrease in torque with the increase in rotational speed, a phenomenon typical of systems primarily based on aerodynamic drag forces. In contrast, AIRON exhibits a less pronounced and more gradual decrease in torque, thanks to the variable geometry that allows for optimizing the blade exposure angle throughout the entire rotation cycle. This behavior ensures greater stability of the torque delivered over a wider range of angular speeds, improving the system's operational flexibility;
- • From the point of view of converted mechanical power, the comparison is even more significant. With the same size and wind conditions, AIRON is capable of delivering about six times more power

compared to the classic Savonius turbine. This increase is attributable to the higher overall aerodynamic efficiency of the system, which reduces the passive phases and losses due to braking torque. The analysis of the power graphs as a function of angular velocity indeed highlights how AIRON maintains high and relatively constant values over a wide operating range, while the Savonius shows a more limited peak and a rapid drop beyond the point of maximum efficiency;

- • The greater consistency of the power curve represents an additional strategic advantage, as it facilitates the regulation and coupling with the electric generator. A more linear and stable trend indeed allows for optimizing the operating point of the electric machine, reducing load fluctuations and improving overall electromechanical efficiency. In conclusion, dynamic analyses show that AIRON not only surpasses the Savonius in terms of recoverable power, but also offers better controllability, a wider operating window, and greater overall system efficiency.

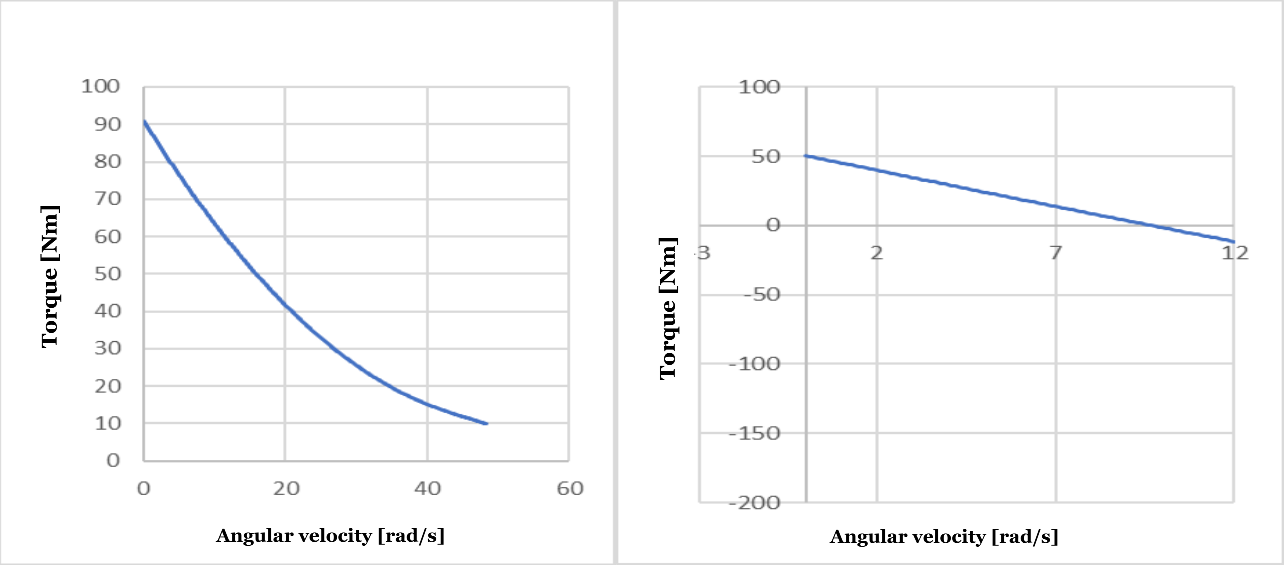


Figure 6: *Torque vs angular velocity graph. AIRON vs Savonius.*

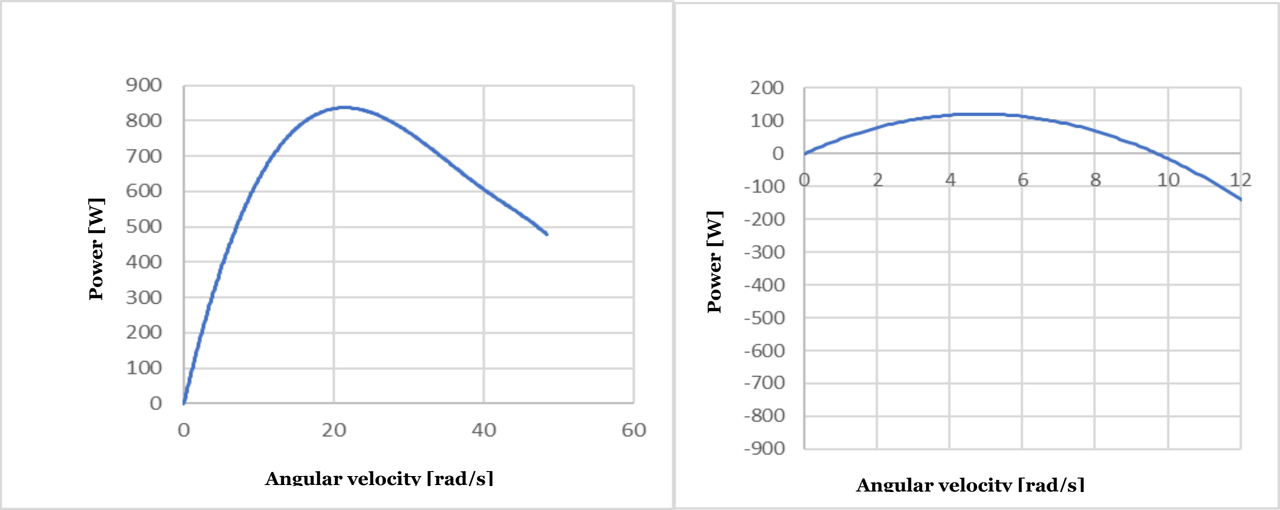


Figure 7: *Power vs angular velocity graph. AIRON vs Savonius.*

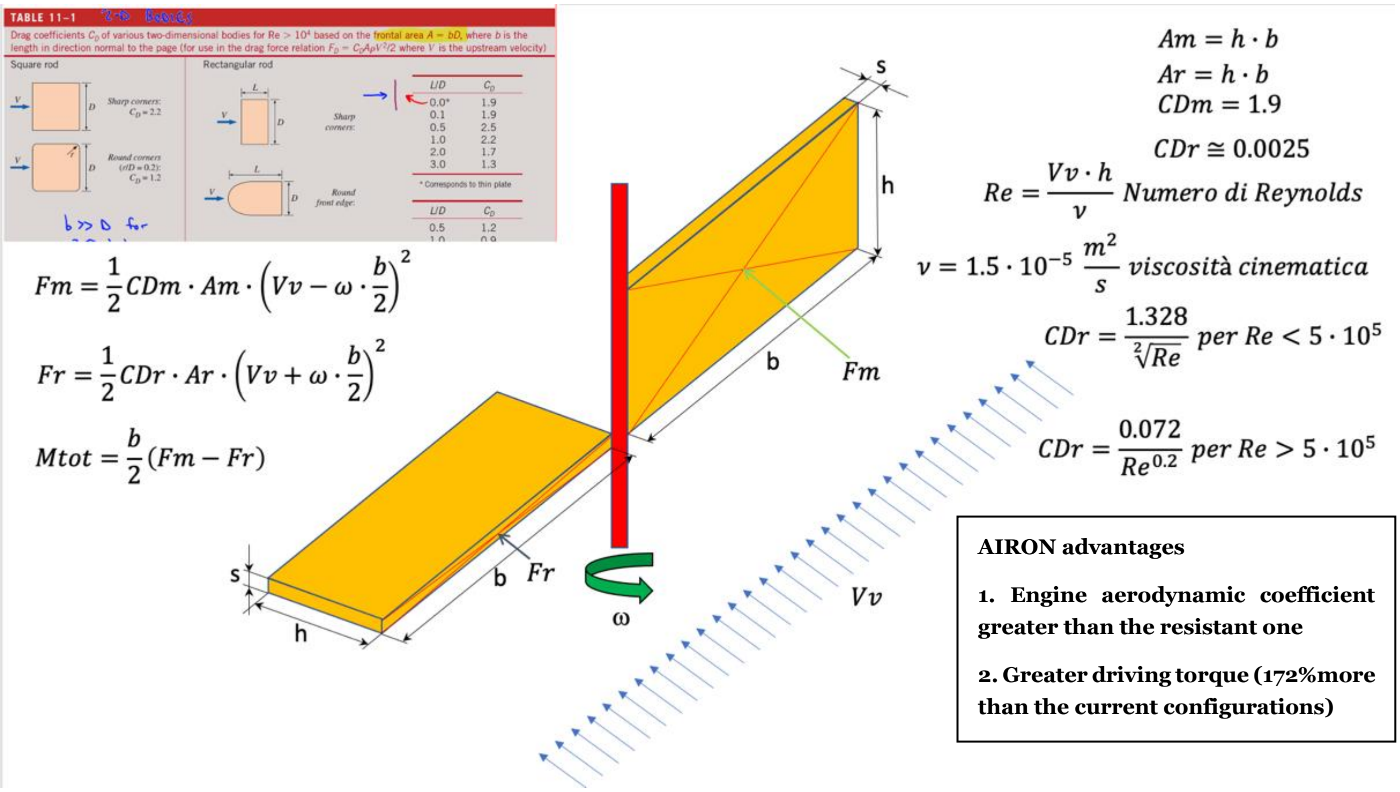


TABLE 11–1 2-D Bodies

Drag coefficients C_D of various two-dimensional bodies for Re > 10^4 based on the frontal area $A = bD$, where b is the length in direction normal to the page (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Square rod

Sharp corners: $C_D = 2.2$

Round corners ($r/D = 0.2$): $C_D = 1.2$

b >> D for

Rectangular rod

Sharp corners:

L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

* Corresponds to thin plate

Round front edge:

L/D	C_D
0.5	1.2
1.0	0.9

$$Fm = \frac{1}{2} CDm \cdot Am \cdot \left(Vv - \omega \cdot \frac{b}{2}\right)^2$$

$$Fr = \frac{1}{2} CDr \cdot Ar \cdot \left(Vv + \omega \cdot \frac{b}{2}\right)^2$$

$$Mtot = \frac{b}{2}(Fm - Fr)$$

$$Am = h \cdot b$$

$$Ar = h \cdot b$$

$$CDm = 1.9$$

$$CDr \cong 0.0025$$

$$Re = \frac{Vv \cdot h}{\nu} \; Numero\ di\ Reynolds$$

$$\nu = 1.5 \cdot 10^{-5} \, \frac{m^2}{s} \; viscosità\ cinematica$$

$$CDr = \frac{1.328}{\sqrt[2]{Re}} \; per\ Re < 5 \cdot 10^5$$

$$CDr = \frac{0.072}{Re^{0.2}} \; per\ Re > 5 \cdot 10^5$$

AIRON advantages

1. Engine aerodynamic coefficient greater than the resistant one

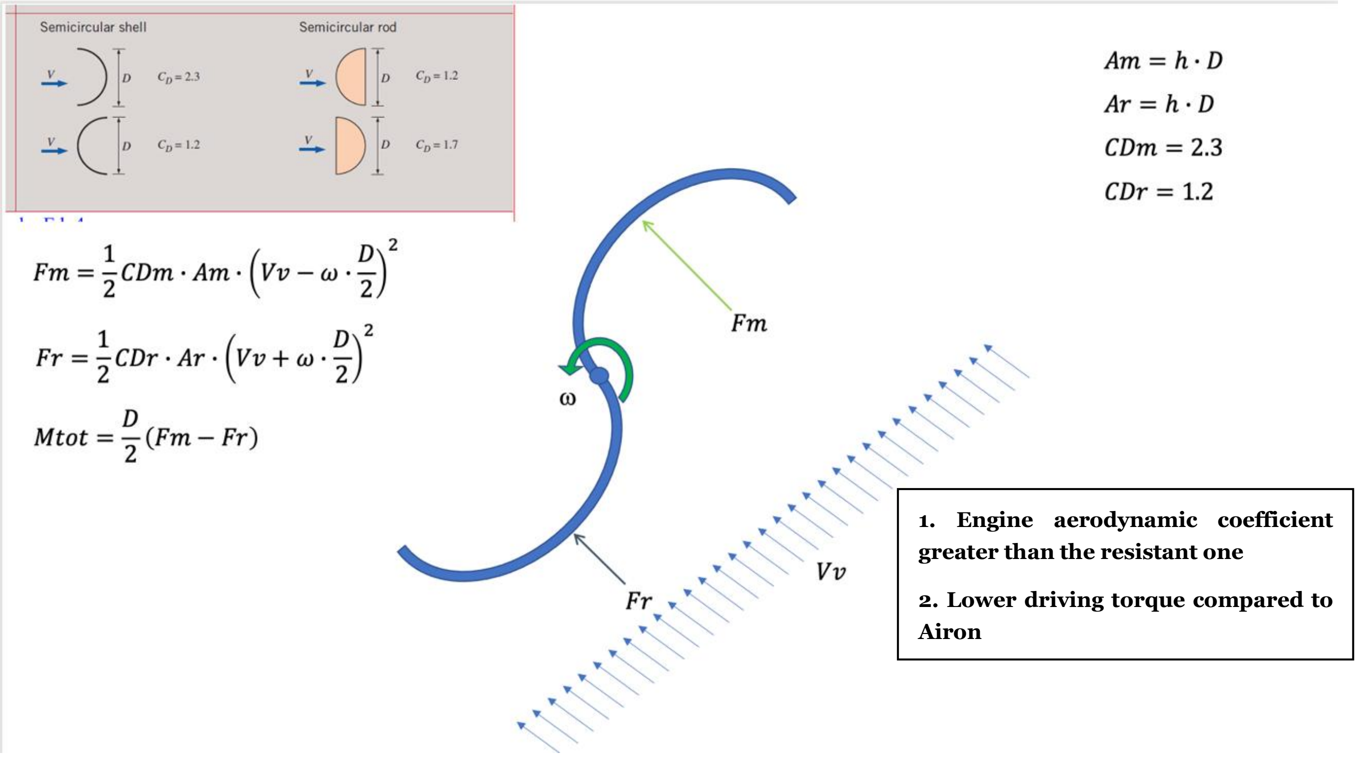
2. Greater driving torque (172%more than the current configurations)

Figure 8: *Drag and Lift coefficient*

5. Advantages and Applications

The main advantages of the AIRON turbine are:

- *High starting torque*: the variable-geometry configuration and the double rotation of the blades allow maximizing the active surface exposed to the wind in the initial phases, generating a driving torque significantly higher than traditional vertical turbines of the same size.
- *Low cut-in speed*: the reduced overall inertia and the optimization of the blade incidence angle allow the system to start even with wind speeds below 2 m/s, increasing the annual hours of actual operation.
- *Elimination of assisted starting systems*: thanks to the high initial torque, auxiliary electric motors or mechanical devices to support starting are not necessary, resulting in reduced plant complexity, costs, and maintenance.
- *Higher aerodynamic efficiency* compared to traditional Savonius: the reduction of passive phases and braking torque allows a significant increase in recoverable power with the same intercepted area and wind conditions.
- *Greater stability of the torque and power curve*: the less marked decay of torque as angular velocity increases ensures a wider operating range and better adaptability to different wind regimes



$$Am = h \cdot D$$
$$Ar = h \cdot D$$
$$CDm = 2.3$$
$$CDr = 1.2$$

$$Fm = \frac{1}{2} CDm \cdot Am \cdot \left(Vv - \omega \cdot \frac{D}{2}\right)^2$$
$$Fr = \frac{1}{2} CDr \cdot Ar \cdot \left(Vv + \omega \cdot \frac{D}{2}\right)^2$$
$$Mtot = \frac{D}{2}(Fm - Fr)$$

1. Engine aerodynamic coefficient greater than the resistant one

2. Lower driving torque compared to Airon

Figure 9: *Torque comparison*

- *Utilization of wind from any direction*: being a vertical-axis turbine, AIRON does not require yaw or active orientation systems; the rotor maintains continuous unidirectional rotation regardless of the direction of the flow.
- *Reduced operational noise*: the controlled movement of the blades and the cushioned end-stop system limit vibrations and turbulence, reducing the acoustic impact compared to many conventional turbines.
- *Structural simplicity and modularity*: the mechanical structure is composed of repeatable and easily assembled elements, favoring scalable production, easy maintenance, and adaptability to different nominal powers.
- *Reduced vertical footprint*: compared to other wind solutions, AIRON does not require very tall towers, facilitating installation in urban or residential areas.
- *Application versatility*: the system is suitable for use in domestic, agricultural, nautical, and off-grid installations, with potential developments for marine and river environments thanks to structural robustness and corrosion resistance.

Conclusions

The conducted activity allowed for the systematic and experimental validation of the AIRON wind turbine with variable geometry, clearly highlighting its differences and advantages compared to conventional mini-wind solutions currently available on the market. The integration of the double synchronized rotation of the blades, careful design of the kinematics, and progressive optimization of the materials used has led to significant performance results. In particular, the adopted configuration allows for high starting torque, facilitating startup even in very low wind conditions. Indeed, appreciable electricity generation was observed already at speeds below 2 m/s, a factor that affects the increase in the effective annual operating hours. Furthermore, the reduced-scale prototype reached power outputs up to 600 W, with performance that, for the same geometric footprint, is up to six times higher compared to a traditional Savonius turbine.

The results obtained indicate that AIRON is able to effectively combine aerodynamic efficiency, simplicity of construction, and low noise impact. The reduction of vibrations and turbulence associated with blade motion, combined with the cushioned end-of-stroke system, helps to limit operational noise, making the technology particularly suitable for residential and peri-urban contexts. At the same time, the ability to operate in variable and turbulent wind conditions opens up interesting prospects for applications in rural, agricultural, and nautical settings, where wind conditions are often irregular and not optimal for traditional horizontal-axis turbines. Dynamic analyses also highlighted more regular torque and power curves, less prone to sudden drops as rotational speed increases. This “flat” behavior facilitates the regulation of the electric generator, improves the stability of the operating point, and makes integration into hybrid wind–photovoltaic systems with storage easier, which are increasingly common in distributed micro-generation. From a scientific point of view, the work provides an initial quantitative framework of the behavior of multi-blade variable-geometry turbines, offering an experimental basis useful for the validation of CFD numerical models and multibody models dedicated to coupled aero-structural analysis. However, further investigations are still necessary, including wind tunnel test campaigns on different geometric configurations and pitch angles, structural fatigue analysis in the presence of long-term turbulence, and more in-depth studies on electromechanical coupling with generators optimized for low rotational speeds. In the future, the modular evolution of the AIRON concept towards nominal powers ranging from 1 to 6 kW, together with the introduction of ultra-low friction bearings, magnetic supports, and active geometry control systems, could consolidate the role of this technology as a competitive alternative for micro-generation in complex sites, including marine and river environments. These developments will allow for a more in-depth assessment of the economic and environmental sustainability of the system, promoting the definition of design guidelines and specific performance standards for variable-geometry wind turbines.

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