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Original scientific paper

BIO-INSPIRED KINETIC STRUCTURES

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Abstract: The goal of this paper is to contribute to the design and study of forms driven by natural forces. The research is based on the application of three disciplines: bionics, kinetics and modular design. The principles of these interdisciplinary studies are applied and verified in the development of a reactive, aerodynamic, wind turbine blade profile. Several variants of nature-inspired shapes and modular kinetic structures are offered, analyzed and tested in order to optimize the design and reach maximum aerodynamics of the blade and the best performance under the influence of wind. The final tests of the blade are conducted using an open-air tunnel. The created blade profile could be applied in various products with possibility of moving under the influence of wind, rain, sea waves, etc. The shape and structure could be used in designing industrial products, architectural and artistic objects, but also in the design of complex engineering solutions.

Key words: aerodynamics; bionic design; kinetic design; modular design; reactive wind turbine blade

БИО-ИНСПИРИРАНИ КИНЕТИЧКИ СТРУКТУРИ

Апстракт: Целта на овој труд е да се даде придонес кон дизајнот и проучувањето на форми кои се движат под дејство на природни сили. Истражувањето е базирано на примена на дисциплините бионика, кинетика и модуларен дизајн. Применетите принципи од овие интердисциплинарни истражувања се применети и верифицирани преку развој на реактивен, аеродинамичен профил на перка на ветерна турбина. Понудени се неколку варијанти на форми и кинетички структури инспирирани од природата, кои потоа се анализирани и тестирани со цел да се оптимизира дизајнот и да се постигне максимална аеродинамичност на перката и најдобри перформанси под дејство на ветерот. Финалните тестирања на перката се извршени со примена на воздушен тунел. Дизајнираниот профил на перката може да биде применет во различни производи со можност за движење под дејство на ветер, дожд, морски бранови итн. Формата и структурата можат да бидат применети во дизајн на индустриски производи, архитектонски и уметнички објекти, но и во дизајн на комплексни инженерски решенија.

Клучни зборови: аеродинамика; бионички дизајн; модуларен дизајн; перка на реактивна ветерна турбина

1. INTRODUCTION

Kinetic design is considered as one of the most important concepts in contemporary art, architecture and design. The works created by following this principle emphasize the dynamics or the fourth dimension in art. The artists that create this type of artistic pieces put their focus on the various visual effects and sensations triggered by the movements of the designed sculptures. Authors Guang-Dah Chen, Chih-Wei Lin, and Hsi-Wen Fan in their paper titled "The History and Evolution of Kinetic Art" [1] provide a thorough explanation of kinetic art. Kinetic art is defined as a "model of dynamic perceivable expression" and has two possible manifestations – using optical illusions with static elements to create a feeling of movement or using actual motion of the elements. Real dynamics in art happened as an appreciation of movements in time and space and were manifested by relying on the natural forces (wind, water) to trigger the motion.

On the other hand, the kinetic approach in product design is based on the connection between movement and energy. Movement uses energy, but movement can also produce energy. Natural forces, such as wind and water movement, are used as renewable energy sources. Industrial designers are significant contributors in expert teams consisted of researches from various scientific and technology fields that in the last decades have been putting their efforts in creating innovations which will improve the use of such renewable energy sources. To achieve this, industrial designers rely on modern methodologies, such as bionics and modularity. The knowledge of 3D modelling and analyzing the geometry of different biological forms play a significant role in developing ingenious products that solve the engineering problem of creating movement triggered by natural forces and using that motion to produce energy.

The main goal of this paper is to contribute to the exploration of forms that can be used in the development of kinetic products moved by natural forces. In this research, bionic principles, modern trends in industrial design and the latest technologies were analyzed in order to create an innovative solu-tion for a modular bionic shape and structure that can be moved by the force of wind. Several variants of bio-inspired structures were given and their characteristics were explored in order to optimize the concepts and suggest the best solution. The idea was to provide a design of a kinetic, aerodynamic wind turbine blade profile that can react to airflow. The developed reactive blade can successsfully convert the energy of air into kinetic energy through rotating motion. The proposed blade profile can be used in the design of industrial design products, architectural objects, or complex engineering solutions. The final design presented in this paper was developed as a prototype and its behaveour was tested using an open-air tunnel.

2. INSPIRATION

Bionics was chosen as the core methodology for finding a new principle to produce energy through a specially designed kinetic, reactive wind turbine with aerodynamic and modular structure inspired from nature. Bionics offers principles for nature-inspired design and it is very popular due to the well-known fact that natural organisms have become the best designers thorough the process of evolution. Creating products by looking at analogous shapes in nature is often a solution to many engineering or design problems. There are many research examples to support this statement.

For instance, the recognized four types of leg movement of insects [2] has been used to offer a 3D model of a robot inspired by six-legged insects; the characteristics of the mechanical and chemical mechanisms of tardigrades are used for the development of biologically motivated artificial adhesive films and robotic systems [3]; the structure of the seahorse skeleton is used for the creation of an ergonomic back-support system [4]; the bionic characteristics of space optimization are applied in the design of a modular, multi-functional storage space [5]; the principles of tensegrity found in spiderwebs are applied in product design in order to achieve equilibrium [6] etc.

Regarding the subject of designing shapes that are responsive to natural forces, researches investigate formations found in nature that offer optimal aerodynamic performances. The characteristics of such bionic examples are commonly transferred in the design of transportation modes, such as aircraft design [7], or the design of engineering renewable-energy technologies where wind power needs to be used as a clean and renewable source of energy [8]. For example, researchers Gavrilović, Rašuo, Dulikravich and Parezanović investigate the wingtip formations of birds and use them as an inspiration to solve the issue with lift induced drag of transport aircrafts [9]. He-Xuan Hu, Bo Tang and Ye Zhang extract the hummingbirds' shape and smooth beak (that provide its' good flying performance) in the development of a bionic train model and by numerical simulation prove that the bionic design helps to reduce the aerodynamic drag and aerodynamic noise [10]. Serson and Meneghini conduct simulations of wavy wings with different wavelengths and amplitudes proving that such wavy wings, as found in nature, have better aerodynamic performance since they reduce the lift-to-drag ratio in comparison with a straight wing [11]. Exploring birds' wings is also a common approach in the design of wind turbine blades. Tian, Yang, Zhang, Wang, Li, Ma and Cong improve the performance of wind turbine blades by designing the airfoil following the morphology of long-eared owls' wings [12]. The results of this bionic process showed increased effective bending of the blades, larger pressure difference between the top and bottom surface, and larger pressure difference between the top and bottom surface at the tip, which all improve the lift.

Similarly, authors Chen, Yao, Wei, Gao and Li, select the best-performing airfoil out of several cross-sections of owls' wings and combine it with the non-smooth shape of the wing in order to design a bionic air turbine blade [13]. As a result, the bionic blade had higher power generation in comparison with standard blades under the same working conditions. This proves the effectiveness of bionic design applied in engineering processes.

In this paper, the study of kinetic forms in nature contributed to a better understanding of reactive kinetic structures, and thus to the identification of an appropriate bionic system that was an inspiration for the wind turbine design process. In addition, it was established that the designed shape of the wind turbine needs to be divided into segments – modules, that can function together as a single system. The modular approach affects the economy of production.

While searching for a suitable bio-system based on the principles of kinetic movement and modularity, the Iridogorgia Octocoral was recognized as a possible solution (Figure 1). By exploring its' characteristics it was noticed that the coral moves by rotating around its' own axis, and changes direction by flexing the body. It was concluded that a similar shape translated into a design can be a suitable solution for a kinetic structure since Nature already developed this shape which is extremely hydrodynamic (Figure 1). Moreover, when a closer view was given, was noticed that the whole coral is composed of one single module which repeats itself in order to build the whole system in a spiral shape (Figure 2).

During an even deeper analysis of the coral it was established that it is build according to the Fibonacci sequence, or the golden spiral (Figure 3). In nature, the golden spiral is very common and designs based on this principle of formation are more effective and have better aesthetic features [14]. The Fibonacci sequence, that is the Fibonacci equation, is a mathematical ration by which the artist Leonardo da Vinci proved that proportions exist in nature, or more precisely, ideal, golden proportions [15]. The ratio of golden proportions is used to achieve visual likeability and an organic appearance of the compositions in design. The golden proportions, commonly referred to as the rule of thirds, helps to direct the eye of the observer to the crucial elements in the design of the product or artistic piece [16]. The golden spiral recognized in the coral is also used as an inspiration in the design of the turbines' appearance.

Fig. 1. Iridogorgia Octocoral [17]

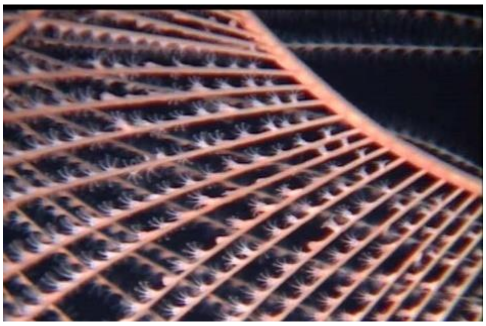

Fig. 2, Recognized modularity in the coral [18]

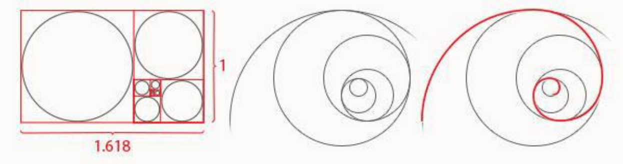

Fig. 3. Graphic representation of the golden spiral [19]

3. DEVELOPMENT OF A SOLUTION FOR A REACTIVE AERODYNAMIC WIND TURBINE

The analysis of the natural phenomenon was a direct inspiration for the development phase of the product. This section of the paper contains a detailed explanation of the process of designing the bio-inspired wind turbine blade profile, from early sketches and rough prototypes to creating the final structure, detailed 3D model, detailed prototype and testing the turbines' performance when exposed to airflow by using an open-air tunnel.

3.1. *Initial sketches*

Starting from the bionic model and the established principles of kinetics, modularity and golden spiral, concepts for the wind turbine were generated. The process started by making a few sketches to get an initial idea of the appearance of this structure. The goal was to make the body a spiral, on which individual blades are placed in the form of a ladder following a geometric rhythm.

Sketch 1. The body is divided to 4× equal segments, that is 4× full rotations of ∢360, with one rotation being divided to 18× individual rods placed at a distance of ∢20 (Figure 4).

Sketch 2. The body is divided to 4× equal segments, that is 4× full rotations of ∢360, with one rotation being divided to 8× individual rods placed at a distance of ∢45 (Figure 5).

Sketch 3. The body is divided to 4x equal segments, that is 4× full rotations of ∢360, with one rotation being divided to 6× individual rods placed at a distance of ∢60 (Figure 6).

At this point, a decision regarding the final segmentation and number of rods was not made. It remained to be established based on prototype development and testing.

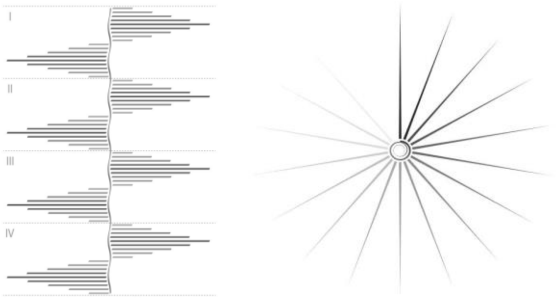

Fig. 4. 4× full rotations of ∢360, 18 individual rods (left – front view, right – top view)

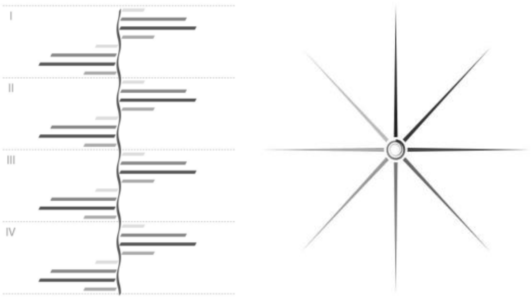

Fig. 5. 4× full rotations of ∢360, 8 individual rods (left – front view, right – top view)

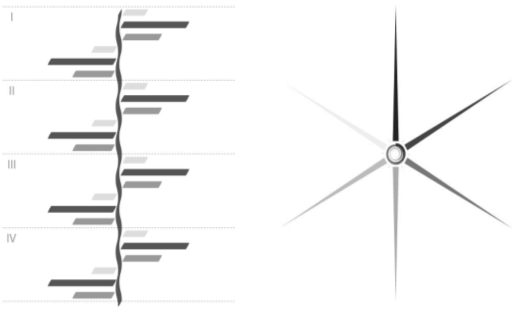

Fig. 6. 4× full rotations of ∢360, 6 individual rods (left – front view, right – top view)

3.2. *Developing prototypes*

Because a three-dimensional shape with complex geometric features was being designed, it was very difficult to capture it only by sketches. Therefore, real prototypes were constructed in order to inspect the shape better.

The basic form of the bio-example (coral) is a comb-like chain. By curling the comb-chain around a central axis spirally, the outer strands are distributed and the whole object becomes similar to the form of an egg. In order to achieve something similar with the prototype it was evident that elastic materials needed to be used. The central body needed to be both flexible to bend in a spiral, but also durable enough to bare the weight of the strands attached to it. The strands also needed to be made of an elastic material in order to bend under their own weight.

3.2.1. *Prototype 1*

The first prototype (Figure 7) imitated the natural phenomenon completely. Exposed to airflow it rotated around the central axis. However, this prototype lacked modularity. The modular composition was achieved in the more advanced stages of the wind turbine development. The prototype maintained the spiral shape by being connected to a metal axis in several points. When hanged on an elastic rope the prototype rotated to airflow. That rotation was interrupted when the rope reached the maximum rotating tension. As a result, it was concluded that to achieve constant rotory motion it was necessary to place a rotary module on which the prototype will be attached. Since the object is hanging, this module needed to have the ability to rotate without interruption regardless of the weight of the prototype. Weight can cause additional friction and prevent the model from moving. The problem was solved by attaching the rotating axis to bearings that have the task to annul the friction created by the weight of the model.

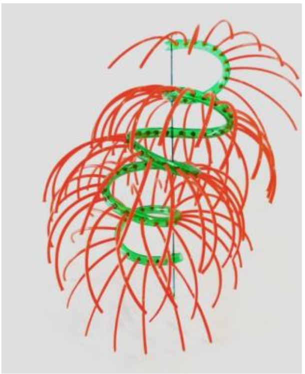

Fig. 7. Prototype 1

3.2.2. *Prototype 2*

By defining the rotory module as the new element that needs to be included in the design a necessity for a new prototype appered and that was the reason for creation of the second prototype with an elastic central axis (Figure 8). Prototype 2 imitated the bionic example to a greater extent and was larger than the first model. It had the comb-like shape which bended under its' own weight in a spiral. The model reacted to even the slightest breeze which proved that the use of the rotory module was successful. In this prototype the modular approach of building the shape and the geometric rhythm were also evident.

Fig. 8. Prototype 2

3.2.3. *Prototype 3*

Since the second prototype also had an elastic and flexible central axis, an attempt was made to use a rigid axis and for this purpose the third prototype was built. Prototype 3 (Figure 9) was made using a wooden rod as the central axis instead of the rubber piper. When the model was attached to the rotary module the prototype oscillates strongly unlike the second model and performed better under the influence of airflow. The problem was identified in the connection between the tip of the fin model and the rotary module. Great tension was present in this spot. This issue was solved by using a universal joint that allows free rotation while eliminating the tension. With the universal joint, the wind turbine, despite having a solid axis, shows solid rotation results in the airflow.

Fig. 9. Prototype 3

3.3. *Design refinement*

When the last two prototypes were compared, the third one seemed more efficient, but did not imitate the bionic example completely. The plastic zip ties used as rods were fulfilling the modular principle of construction, but nor entirely, because the central axis was a separate element. In order for the system to be fully modular, the whole turbine needed to be built by one single element repeated to achieve the spiral shape. This was the most challenging task. In order to provide a suitable solution, inspiration was drawn from nature once more. Snakes' vertebrae and human vertebrae (Figure 10) were considered as examples to withdraw inspiration for building the helix. The vertebrae were great examples to identify how the modular principles of building shapes are used in bionic systems.

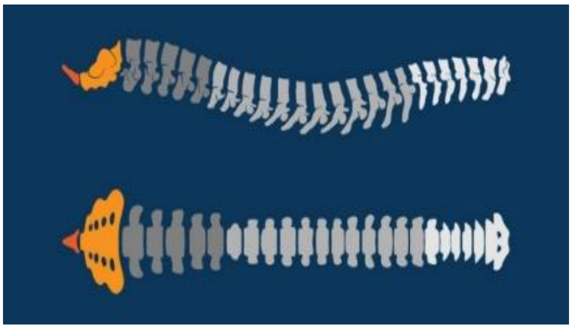

Fig. 10. Human vertebrae as an inspiration for the modular structure [20]

The modular logic of building the spine contributed to the development of the first 3D model – Helix 1 (Figure 11). The model was completely built using a software for 3D modeling. Helix 1 was consisted of a single part, or module, that was gradually upgraded in a geometric rhythm to become a whole spiral that corresponds to the bionic example. The building of the helix was achieved in a simple manner by creating a tooth on one side of the module and a hole with the same dimension as the tooth on the other side. The hole was placed at an angle to allow the rotation of the helix around one imaginary central axis when the modules are stacked one over another.

By establishing the basic principles for the construction of the form in a modular way, Helix 2 was made as a physical prototype. At this stage of development, the way of fixing the individual modules in a single solid form was determined. Lego bricks helped to achieve the desired shape.

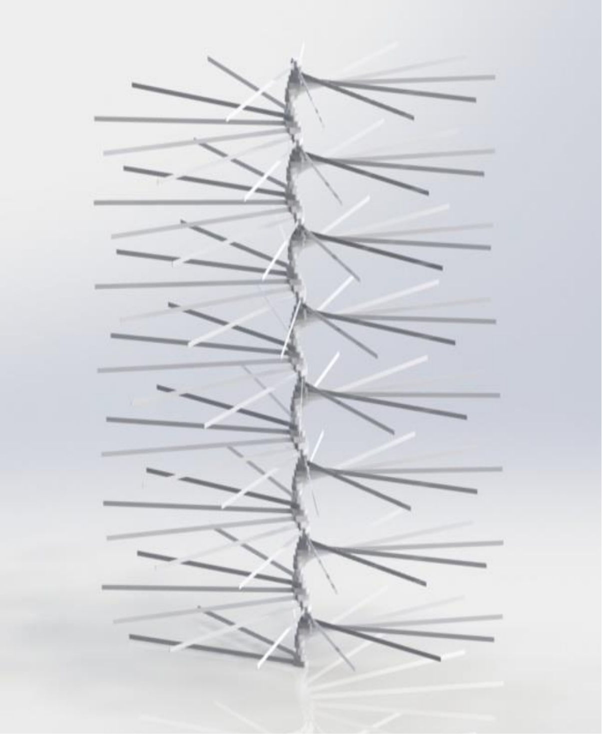

Fig. 11. 3D model of Helix 1

Helix 2 contained 6× degrees in one full rotation (Figure 12). The single module was rotated around an imaginary axis creating a perfect helix. The parts were fastened in 4× contact points which made the construction very firm (Figure 13). At this stage in the wind turbine development process only the logic of connecting individual parts was established. The final appearance of the modular parts was determined in the finishing phase when the details were defined.

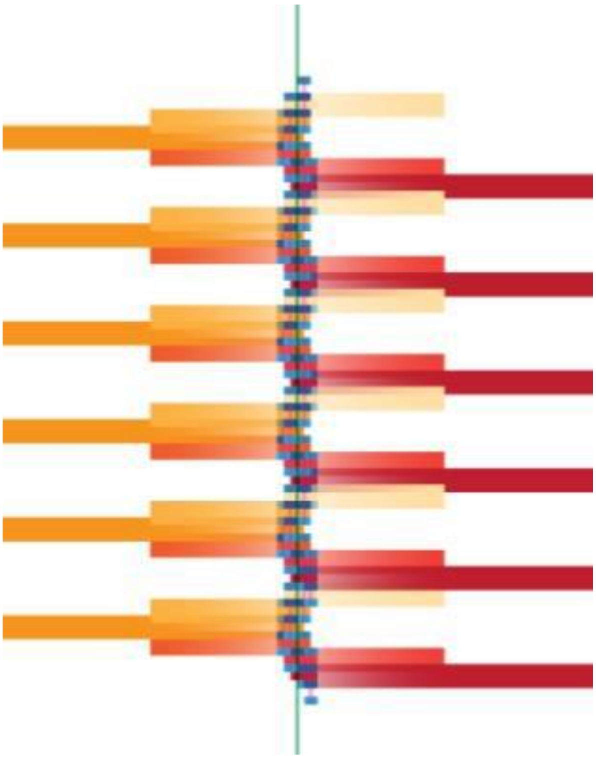

Fig. 12. Graphic representation of Helix 2

Fig. 13. Physical prototype of Helix 2 made from individual hard plastic modules

3.4. *Initial testing*

After defining how the shape will be built, the appearance of the individual blade profiles needed to be defined. For that goal the behavior of the real prototype – Prototype 3 was tested. Through observation of the behavior of the prototype, an analysis of the efficiency of the individual blades of the system exposed to airflow was performed. The test results showed a problem in which the prototype could not maintain a continuous rotation. The problem was detected in: (1) the free movement in two directions of the rotary module and (2) the shape of the object which was geometrically equal, divided into left and right, in each degree of rotation.

Two possible solutions were proposed in order to solve these issues. The first was to adjust the rotary model so that it can move in only one direction (Figure 14). With a mechanical brake on one rotational side the prototype could be forced to move only on one side. At the moment of balancing, the side that had free movement would prevail and start rotating in that side.

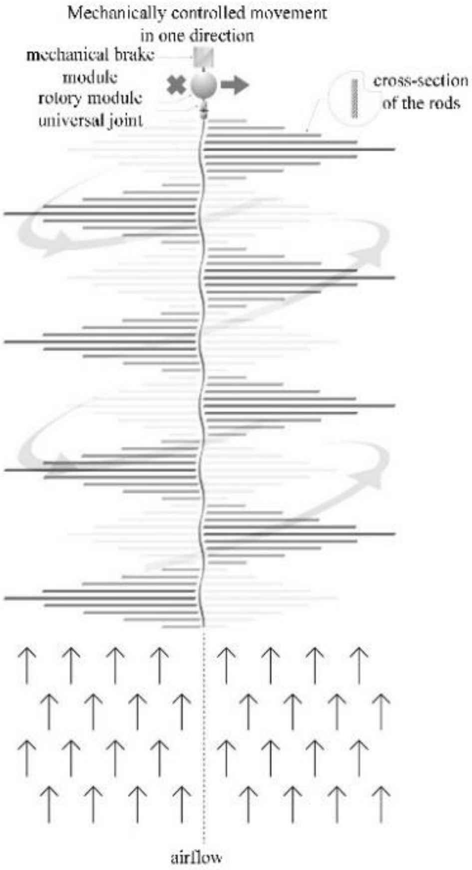

Fig. 14. Mechanically controlled movement in one direction

The second solution was to control the movement using a new aerodynamic of the blade profiles – blades with an equilateral triangle cross-section positioned in a way that one of the sides is parallel to the central axis while the other is positioned with the sloping side in the middle, that is normal to the central axis (Figure 15). When air hit the left side, it could move freely because of the geometry of the rod – its' sharp side. However, when air hit the flat side of the blade there would be a resistance to the movement. This difference could create a tendency to move the whole object only on one side without the need to add mechanical modules for control. This solution was chosen as more effective because it was simpler, more practical and more economic.

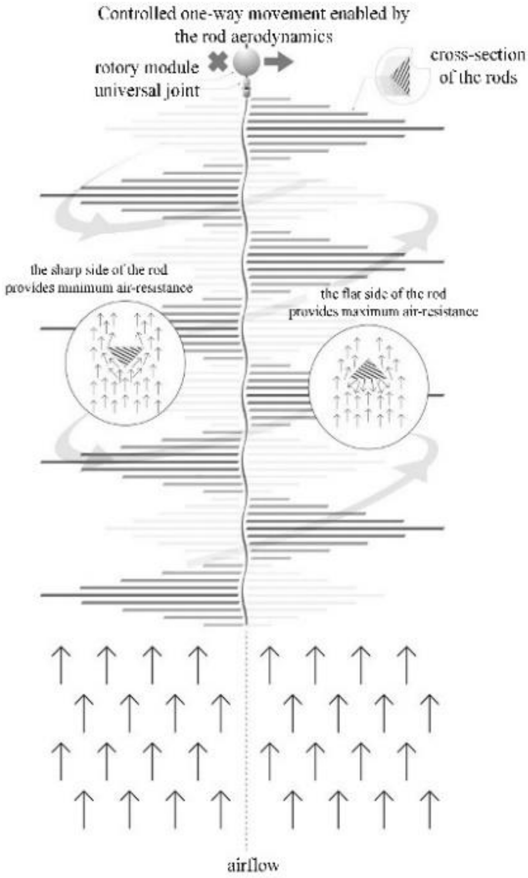

Fig. 15. Controlled one-way movement enabled by the blade profile aerodynamics

3.5. *Detailed development of the model*

With the help of CAD techniques an elaborate 3D model of the established modules, their assemblies, and additional elements such as bearings, bearing housings and the universal joint were built (Figure 16).

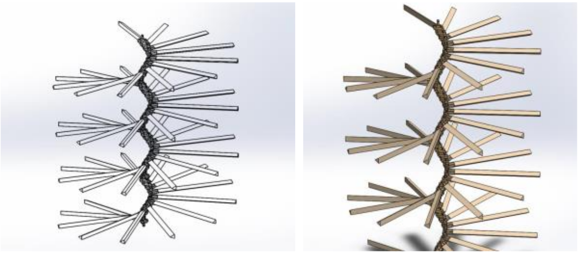

Fig. 16. 3D model of the developed air turbine with modular blades

3.6. *Final testing of the model in an open-air tunnel*

For the purpose of testing, the 3D model underwent changes according to the open-air tunnel specifications. The working surface of the used open-air tunnel has a diameter of 285×285mm and for the testing of the model to be successful it needed to be scaled to a maximum width and height of 150 mm. According to these guidelines, the final model was changed. The final design of the model had 4× full rotations with 48 modules in total. However, the model developed for the open-air tunnel testing was adapted to have 2× full rotations and 24 modules. The new dimension of 150×150 mm was archieved by scaling the main model with a reduction scale factor of 0.4166. There were changes to the length of the rods as well, they were scaled by a length-reduction scale factor of 0.5. The end dimensions of the adapted 3D model were 150×150×150 mm. With all these changes the model was successfully adapted for experiments in the open-air tunnel.

The prototype was manufactured using a 3D-printing technology. For the purpose of this manufacturing technology, the CAD model was divided in two segments: central body and individual blades. The 3D-printed model was made with one of the 3D printer (Prusa MK3) machines at the Faculty of Mechanical Engineering in Skopje that uses Fused Filament Fabrication (FFF) technology (meaning the 3D printer layers melted material over a platform to complete the part). In order to create a prototype was used material polylactic acid (PLA). The individually printed body and blades were than assembled to construct the final prototype used for testing (Figure 17).

Fig. 17. Final 3D-printed model composed of a central body and individual blades connected to an axis

In the Fluid mechanics and hydraulic machinery laboratory at the Faculty of Mechanical Engineering in Skopje the 3D-printed prototype was tested in an open-air tunnel. The testing was done in order to inspect the reactivity of the wind turbine and the rotation it achieves when exposed to a continuous airflow. The speed of rotations that the turbine produces in one minute were measured (rpm) when it is exposed to different airflow velocity (m/s). The air velocity measurement was performed with Prantl-Pito pipe and digital (micromanometer) indicator type MP120 – KIMO, France, while speed of rotation was measured with digital optical tachometer type CT50 – KIMO.

The testing procedure is shown on the following image (Figure 18).

Fig. 18. View of the open-air tunnel in the FME aerodynamics laboratory and reaction of the model exposed to airflow

Exposed to airflow the prototype easily and continuously rotated. This experiment confirmed the reactivity of the model to airflow and its' excellent kinetic and aerodynamic characteristics. The model made rotations only on one side which proved the successful design of the individual blades. The results of the speed of rotation at different airflow velocity are given on Figure 19.

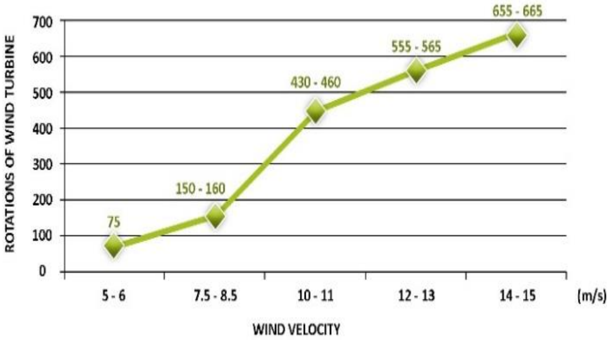

Fig. 19. Speed of rotation at different airflow velocity

According to the results it was concluded that the tested model showed satisfactory reactions to airflow. When the model was exposed to airflow velocity of 5 – 6 m/s, 10 – 11 m/s, 12 – 13 m/s and 14 – 15 m/s it linearly increased the speed of rotation, whereas when it was exposed to airflow of 7.5 – 8.5 m/s to 10 – 11 m/s a fast increase in the speed of rotation was noticed. This means that in that airflow range the model shows the best results.

4. CONCLUSIONS

The presented research is an example of the great importance of the multidisciplinary approach in product design. It is based on the application of the innovative disciplines – bionics, modularity and kinematics in the design of the form of products that generate energy from wind. The recognized principles from these methodologies were applied in the experimental part of the research when solutions for a kinetic, aerodynamic wind turbine driven by the power of wind were explored.

The outcomes confirmed the expectations that gathering inspiration from nature results with designing innovative product functions and aesthetics. The project elaborated in this paper was developed following the Fibonacci sequence, or the golden ratio, recognized in the natural phenomenon – Iridogorgia Octocoral which was the main motive for the design of the product. The natural phenomenon which was analyzed comes from an environment in which it is in a constant movement and changes its' position by rotating around its' central axis. This was a direct inspiration for the appearance and behavior of the designed wind turbine. The concept of modularity commonly found in natural organisms, such as the spine of animals, was also an inspiration as a strategy for building the designed structure in order to make it simple for manufacturing, assembly and therefore more economic. The final product was designed as a composition of a number of subsystems, or modules, which compose the shape when stacked together in a geometric rhythm.

The final kinetic, reactive wind turbine was tested in an open-air tunnel and the results demonstrated that the proposed shape and structure had a very good response to the airflow. The established cross-section of the individual blades allowed a continuous rotation of the turbine in only one direction creating a resistance in the opposite one. This type of modular and responsive structure offers the possibility for multiple applications: in architectural objects, art sculptures, design of mass-produced products or engineering purposes where there is a need for effective wind turbines that produce energy.

Finally, it can be concluded that the interdisciplinary approach in the design of products is more than necessary. The application of innovative techniques and joining the knowledge of experts from various design and engineering fields allows the development of products that incorporate characteristics from various disciplines and as a result they are more successful.

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