Geometry optimization of small helicoid VAWT rotor

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Abstract. The exploration of renewable energy sources and energy efficiency are becoming crucial for putting climate change under control. Thanks to large investments in development of technology for transformation of wind energy to useful form of energy, wind energy became one of the most sustainable energy source. According to the fact that horizontal wind turbines (HAWT) are more common, vertical wind turbines (VAWT) are gradually becoming more interesting because of less direction of wind sensitivity that those turbines have. Geometric parameters of rotor, such as aero foil shape, pitch angle, chord length, rotor radius, blades length, number of blades, significantly influence to the helical VAWT rotor performances. In order to be able to do influence analysis of those parameters to the helical VAWT performances, it is necessary to perform huge number of expensive experimental testing. In order to determine optimal number of needed experiments, special attention has to be put on experimental research designing. With correct design of experiment, expenses of helical VAWT rotor development are significantly increased, by using computer simulations tools that are very reliable in those experiment designs and computer simulations can replace preliminary experiment researches. In this paper, by using SolidWorks Flow Simulation tool, the research of influence of pitch angle, chord length, rotor radius and rotor height on the rotor torque, was performed. Design of Experiments and Optimization option, enables defining and performing huge number of computer simulated experiments, where chosen variables are changing their values in the plan range, defined with minimum and maximum, and all according to perform optimal study for more than one variable. Testing on rotor with three blades of NACA 0018 aero profile, with 5 m/s wind velocity, was simulated and presented in this paper.

1. Introduction

Because of the steady increase of energy usage, non-renewable energy sources are becoming less and the negative consequences of their use are increasing. In the world, there is growing awareness that renewable energy sources and energy efficiency are key factor to put climate changes under control. Renewable energy sources provide opportunities for economic development, primarily for developing countries, because they are different from non-renewable sources. Renewable energy sources are available and deployed around the globe so they can provide energy for billions of people still living without modern energy service.

One of the renewable energy sources that has a large available energy potential is wind. Wind is the air masses flow in the atmosphere that is result of uneven Earth's surface warming by solar radiation. Only 2% of solar energy which is "captivated" by Earth's atmosphere per year (1,5x10^{18} kWh) turns into the air masses flow energy. This means that the theoretical annual wind power is approximately about 4x10^{12} kWh, which is one hundred times more than the current total installed energy potential of
all power plants on the planet. This information is worth mentioning even though it is not possible to know how much of that energy can be commercially used. But the fact which tells that exploiting only one percent of the available energy potential of the wind meets the energy needs of the entire planet, clearly indicates why so much resources are being invested in researching new and more efficient ways to exploit wind power.

More recently, wind energy is largely used to produce electricity through wind aggregates. It consists of two basic parts: wind turbine and wind generator (electric generator). In essence, first wind turbine converts the kinetic energy of wind into mechanical energy and then electric generator turns it into electricity. As the part of wind turbine that turns wind energy into mechanical energy has proved as the most important part for its functioning, the term wind turbine has been imposed as the term which is most commonly used when talking about wind power converters in electricity.

There are two basic types of VAWT: drag-type (Savonius) and lift-type (Darrieus). Drag-type turbines have self-starting capability but less efficiency than an lift-type turbines. The self-starting problem with the Darrieus-type turbines is somewhat resolved by the construction of helical blades. The wind turbine performances can be presented through torque and power. Darrieus-type VAWT performances are related to many parameters, such as airfoil shape, pitch angle, chord length, rotary radius, blades length, number of blades etc. Determining the most optimal combination of these parameters is the primary goal of developing new or improving the existing Darrieus-type VAWT. Combinations are made by conducting numerous tests and experiments. In order to reduce the number of expensive experimental studies, it is very important to develop an appropriate design of experiment. A good design of experiment allows to get reliable results with the minimal number of tests.

This paper demonstrates the ability to use the SolidWorks Flow Simulation software package to create a good design of experiment and to compute these experiments. SolidWorks Flow Simulation is used to determine the torque value on the shaft of the non-moving rotor for the different values of pitch angle, chord length, rotor radius and rotor height. Using the Design of Experiments and Optimization option available from the SolidWorks 2017 version, numerous computer-simulated experiments have been defined and computed, where the input parameters have been changed within the defined maximum and minimum range, all in order to determine the optimal combination of these parameters. Numerical simulations were conducted with three NACA 0018 air profiles at air velocity of 5 m/s.

2. Basic geometrical parameters of helicoid VAWT rotor

Of the abovementioned geometrical characteristics of the rotor, which have more or less influence on the wind turbine performances, four characteristics are marked off in this paper: pitch angle, chord length of air profile, rotor radius and rotor height (Figure 1).

In aeronautics, chord refers to the imaginary straight line joining the leading and trailing edges of an aero foil. The chord length $c$ is the distance between the trailing edge and the point on the leading edge where the chord intersects the leading edge. Pitch angle of air profile $\delta$ is the angle between chord and the direction of edge speed of air profile. Rotor Radius $R$ and height $H$ are the characteristics which represent external dimensions of the rotor.

2.1. Creating of 3D CAD model of helicoid VAWT rotor

While creating the 3D CAD model used for parametric analysis, it is necessary to bear in mind the need for automatic adjustment of the model when changing the values of the selected parameters. In our case it was necessary to provide a change of four dimensions. The software for each computer-simulated experiment creates a special configuration of the model with different values of these dimensions.
3. Design of experiment

In the theory of optimization, the experiment presents a series of tests in which variables change depending on the given order, in order to identify the reasons for the changes in the output results.

The purpose of experiments is essentially optimization. The design of experiment, or experimental design, presents techniques that lead to the selection of experiments in order to perform the experiments in the most effective way. Usually, during the experiment, there is an experimental error or noise, and the result of the measurement is significantly affected by this type of error. For this purpose, it is best to analyze data using statistical methods. The basic principles of statistical methods in experiments are mapping, random ordering and rejection.

Duplicating is a repetition of the experiment in a particular order, in order to obtain as precise results as possible, and in order to estimate the experimental error, or standard deviation. Random selection refers to the random order in which we run experiments. In this case, the experimental conditions in one study do not affect the conditions in the previous experiment, nor can we anticipate the conditions in subsequent experiments. Rejection is the isolation of a known systematic influence and thus prevents this influence to prevent other influences to be visible. This is achieved by sorting experiments into groups that are similar to each other. This reduces the source of large deviations and increases the accuracy of the output results.
In order to make a design of experiment, it is necessary to define a problem and select variables, which are called factors or parameters. Also, it is necessary to define the area of the plan or area of interest, which means that the range for each individual variable must be defined. The number of values of variables that can be considered within the design of experiment is limited and, in general, it is a small number of values of each of the variables.

Design of experiment technique and number of levels are chosen regarded to the number of experiments. By the levels we consider the number of different values of variables that can be obtained by discretization. The number of levels is usually the same for all variables. The objective function and the set of experiments that are going to be performed are called the return variable.

3.1. Design of experiments and optimization in SolidWorks Flow Simulation

From the SolidWorks 2017, in section for parametric studies, an additional option Design of Experiments and Optimization appears. This option allows the creation and implementation of particular number of computer simulated experiments in which the values of the selected input variables vary within the defined ranges. On the basis of the obtained results it is possible to implement an optimization study for one or more input variables using the optimization procedure built-in in the software.

Because of the lower cost, the number of different values of input parameters in computer simulated experiments can be higher than in real experiments. However, this number can’t be too large even in this case, because complex computer simulations often require a lot of time and computer resources, and therefore are not cheap. This fact leads to the need for well-designed computer experiments.

The first step is identification of the factors and their ranges, which defines the area of the design of experiment which will be in focus. After that, a suitable design of experiment is selected for the purpose of obtaining as much information as possible about the behavior of the system or process, and with the possibility of performing as few simulations as possible.

Traditional design of experiments techniques used in physical experiments generally explore extremes and, in fewer cases, the center of plan design space. Increasing the difference in the input variables within an experiment makes it easier to determine the effect on the output variables, and the result is that output variables are a subject of random and systematic experimental error, which requires that experiments be repeated sufficiently number of times before statistically valid results are achieved. For computer simulation purposes, experimental design should be space-filling and non-collapsing:

- Space-filling designs – To explore the design space and to capture as much information as possible, the runs should be spread throughout the design space as evenly as possible, that is, the Optimizing the Design experimental design should be space-filling. Hereby we assume that no information about the function underlying the simulation model is available.
- Non-collapsing designs – It is usually not known beforehand which factors are important and which are not. An experimental design is called non-collapsing if, in case one or more factors appear to be unimportant, every run in the design still gives information about the influence of the other factors on the response parameters. In this way, none of the time consuming computer simulations may become useless.

The DoE method developed and implemented for Flow Simulation generates space-filling Latin Hypercube Designs. Such designs are non-collapsing and space-filling.

3.2. Latin Hypercube Sampling

Latin hypercube sampling (LHS) is a statistical method for generating a near-random sample of parameter values from a multidimensional distribution. The sampling method is often used to construct computer experiments or for Monte-Carlo integration.

In the context of statistical sampling, a square grid containing sample positions is a Latin square if (and only if) there is only one sample in each row and each column. A Latin hypercube is the
generalization of this concept to an arbitrary number of dimensions, whereby each sample is the only one in each axis-aligned hyper plane containing it.

When sampling a function of \( N \) variables, the range of each variable is divided into \( M \) equally probable intervals. \( M \) sample points are then placed to satisfy the Latin hypercube requirements; note that this forces the number of divisions, \( M \), to be equal for each variable. Also note that this sampling scheme does not require more samples for more dimensions (variables); this independence is one of the main advantages of this sampling scheme. Another advantage is that random samples can be taken one at a time, remembering which samples were taken so far.

4. Parametric study of vertical wind turbine rotor

First step in parametric study implementation is type of study choice. Flow Simulation offers three types of studies: What If Analysis, Goal Optimization and Design of Experiments and Optimization. In the case of a third type using, it is necessary to select input variables and output parameters, and to create an experiment scenario.

4.1. Variable parameters used for design of experiments and optimization

Variable parameters used as input variables are grouped into three groups: simulation parameters, dimensional parameters and design table parameters. In the first group are next parameters:

- parameters specified in the General Settings as physical features characteristics or as default parameters (default wall temperature, default wall roughness) or as ambient conditions for external analyses (pressure, density, temperature, velocity),
- parameters specified as the Boundary Condition (velocity, mass/volume flow rate, pressure, temperature, etc.),
- parameters specified at the model surfaces and in the solid components as conditions of the engineering device models (see Input Data - Overview for a list of currently available engineering devices),
- parameters specified as characteristics of the Global Mesh and the Local Meshes.

In our case, all four input parameters belong to a group of dimensional parameters. Figure 3 gives an overview of these parameters and the design of experiment space, that are the defined ranges for each individual variable.

![Figure 3. Variable parameters used for design of experiments and optimization.](image)

The pitch angle actually changes in the range of \(-10^\circ\) to \(10^\circ\). The software does not allow defining negative angles so the angle \(-10^\circ\) corresponds to the angle \(0^\circ\) and the angle \(10^\circ\) to the angle \(20^\circ\).

The parameter of interest that represents the objective function of our study is the torque of the rotor shaft. This parameter must be defined within the preparatory actions for the parametric study.

4.2. Experiments scenario

As already mentioned, the number of different values of input variables that can be considered within the design of experiment is limited and in general this number is small. The extreme and mean values of the observed parameter are most commonly used. In computer simulated experiments, using only
three different values of input variables, it is not possible to complete the requirement that the design of experiment be space-filling. That number should be higher.

The number of different values of the input variable, using the Latin hypercube sampling method, is determined by the number of experiments. In our study for the number of experiments, number 27 was determined, because it is a recommended representative number of experiments according to Taguchi's method, which is used for experiments with four parameters at three and more levels. Based on the selected number of experiments, the software has created the scenario shown in Table 1.

**Table 1.** Design of experiment for 27 different values of four input variables.

| Exp. 1 | Exp. 2 | Exp. 3 | Exp. 4 | Exp. 5 | Exp. 6 | Exp. 7 | Exp. 8 | Exp. 9 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Chord Length [m] | 0,219231 | 0,257692 | 0,246154 | 0,284615 | 0,234615 | 0,207692 | 0,226923 | 0,269231 | 0,288462 |
| Pitch Angle [°] | 6,923077 | 3,846154 | 0 | 17,692308 | 14,615385 | 3,076923 | 18,461538 | 1,538462 | 10,769231 |
| Rotor Radius [m] | 0,315385 | 0,323077 | 0,430769 | 0,453846 | 0,5 | 0,361538 | 0,4 | 0,461538 | 0,307692 |
| Rotor Height [m] | 1,138462 | 0,846154 | 0,892308 | 0,907692 | 0,923077 | 0,953846 | 0,861538 | 1,092308 | 1,046154 |

Figure 4 shows that for each of the six combinations of input parameters, the condition, where in each column and row there is only one value, is satisfied. Also, it can be noticed that the values are satisfactorily scattered and they are not grouped around the diagonal.
4.3. Display of results of performed experiments

After the design of experiment was created, computer simulations were performed with 27 different combinations of four input parameters. The obtained values are shown in Table 2 and graphically presented in Figure 5. As can be seen, the smallest torque value is 0.179 Nm and it was obtained during the second experiment, while the highest value was 0.558 Nm and it was obtained during the sixteenth experiment.

| Exp. | Torque [Nm] |
|------|-------------|
| Exp. 1 | 0.231852 |
| Exp. 2 | 0.179424 |
| Exp. 3 | 0.405166 |
| Exp. 4 | 0.391711 |
| Exp. 5 | 0.398875 |
| Exp. 6 | 0.260500 |
| Exp. 7 | 0.261224 |
| Exp. 8 | 0.494536 |
| Exp. 9 | 0.230666 |
| Exp. 10 | 0.449164 |
| Exp. 11 | 0.364470 |
| Exp. 12 | 0.520686 |
| Exp. 13 | 0.188215 |
| Exp. 14 | 0.321111 |
| Exp. 15 | 0.338919 |
| Exp. 16 | 0.557989 |
| Exp. 17 | 0.439297 |
| Exp. 18 | 0.384939 |
| Exp. 19 | 0.435731 |
| Exp. 20 | 0.340516 |
| Exp. 21 | 0.246439 |
| Exp. 22 | 0.275538 |
| Exp. 23 | 0.290357 |
| Exp. 24 | 0.235917 |
| Exp. 25 | 0.234261 |
| Exp. 26 | 0.295269 |
| Exp. 27 | 0.394453 |
4.4. Rotor optimization on basis of obtained experiments results

The minimum and maximum torque values obtained during the performance of the experiments are most likely not the actual extreme values of the observed parameter. In order to determine the combinations of four input parameters that provide the minimum, maximum, or some other target value of the observed parameter, the optimization procedure is required. The Design of Experiments and Optimization option enables the optimization study to be performed after the experiments are performed, in order to determine the optimal combination of input variables in order to obtain the desired value of the output parameter.

In this paper, the Design of Experiments and Optimization option was used to create an optimal combination of pitch angle, chord length, radius and height of the rotor, in order to obtain the minimum and maximum torque of the VAWT rotor shaft, and in order to obtain a torque equal to 0.5 Nm. Table 3 shows the results of performed optimization.

Table 3. Values of optimal combinations of input variables and values of assumed and calculated output parameter.

| Parameters            | Objective Function |
|-----------------------|--------------------|
|                       | Minimize | Maximize | Target   |
| Chord Length [m]      | 0.3       | 0.3      | 0.230015 |
| Pitch Angle [°]       | 0         | 0        | 1.981078 |
| Rotor Radius [m]      | 0.3       | 0.5      | 0.499999 |
| Rotor Height [m]      | 0.8       | 1.2      | 1.018870 |
| Torque [Nm]           |           |          |          |
| Assumed               | 0.098912  | 0.713232 | 0.5      |
| Calculated            | 0.126700  | 0.636602 | 0.497533 |

For optimal combinations of input variables, the software assumes torque values. Computer simulated experiments were created and conducted for the offered combinations. The results of these simulations indicate that the goals of optimization have been achieved, although not in way that the software assumed it. Thus, the value of the torque at the rotor, optimized to obtain the maximum value, is greater than the highest value obtained within the 27 experiments, but still less than the assumed. A similar scenario is with minimizing of torque. Assumption was consistent with the obtained results only with the target torque value of 0.5 Nm.
5. Conclusion
The value of the rotor shaft torque is one of the basic performances indicators of the Darrieus-type VAWT. Its value is influenced by numerous parameters, such as airfoil shape, pitch angle, chord length, rotor radius, blade length, number of blades etc. In this paper, SolidWorks Flow Simulation Design of Experiments and Optimization option, was used to create design of experiment and to perform computer simulated experiments in order to determine the optimal combination of chord length, pitch angle, and radius and height of the rotor. The simulations were performed to obtain the minimum and maximum torque on the VAWT rotor shaft. The results obtained showed that this tool, which is available from the SolidWorks 2017 version, can be used for the preliminary determination of the optimal combination of variable factors.

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