The Oretical and Experimental Aspects of Building a Model of the Self-Oscillatory Wave Wind Turbine

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Abstract. The article presents an overview of the work on the creation of a mathematical model of self-oscillating systems for converting the energy of the moving flow of the medium. The principle of their work and their inherent advantages are described. The method of measurement and processing of the array of kinematical data during the operation of the wind turbine is considered. The evaluation of the efficiency of self-oscillating wind turbines is given.

1. Introduction

One can witness a steady growth in the use of renewable sources of energy in the world. These growth rates are particularly high in solar and wind power engineering.

According to the Renewables Global Status Report published by the international organization REN21, commercial wind power activities were carried out in over 90 countries as of the end of 2017. In 2017, wind power engineering accounted for more than 29% of the installed renewable energy capacity, whereas the wind power capacity growth exceeded 52 GW. Thus, the aggregate capacity increased by nearly 11% reaching 539 GW \cite{1}.

A modern wind power plant fleet is based on wind turbines using lift force (lift machines) for motion. Nowadays, more than 90% of the wind power plants in operation use horizontal axial repeller wind turbines as a drive, although they exhibit a number of drawbacks: they need a tower of 50 m or more in height (installing such wind turbines is expensive and laborious); the wind turbine efficiency is inhibited by the large repeller diameter due to the wind flow speed variations along the vertical blade diameter; if the wind is too strong, a wind protection mechanism is needed; the generator is connected to the wind turbine via a multistage multiplier, which loses some of the generated energy; it is problematic to perform power transfer from the generator rotating together with the nacelle to consumer terminals located on the ground; repeller wind turbine blades are difficult and expensive to manufacture; high-power repeller wind turbines use a sophisticated automatic servo drive for wind orientation. Blade wind turbines cause environmental problems and, in addition, may create electromagnetic interference to radio communication.

Orthogonal wind turbines with a rotation axis perpendicular to the flow and using both lift force (lift machines) and aerodynamic resistance force (drag machines) are also applied in wind power plants with small and medium capacity. These wind power plants have a number of advantages: their operation does not depend on the wind flow direction (so there is no need in wind orientation systems, and the structural dynamics is simplified); the generator and multiplier can be placed on the plant foundation (installation and operation are simplified, support strength and rigidity requirements are decreased, and generated power transmission is simplified); the blades of orthogonal wind engines are...
simpler and cheaper; vertical axial wind power plants have a lower linear speed of blade movement and a lower aerodynamic noise level (the noise propagation diagram is directed upwards and downwards along the rotor rotation axis); they have a low electromagnetic interference level [8], [9], [10].

The main reason for the limited use of orthogonal wind power plants is typically their lower wind energy efficiency and lower unit capacity, as drag machine working blades cannot move quicker than the wind (as opposed to repeller wind turbine blades). This does not allow them to develop a high rate of rotation. Besides, the area of the airflow part used by orthogonal wind turbines is generally smaller than that of the wind wheel. As a result, their weight and size characteristics per one unit of installed capacity are higher than those of repeller wind turbines. Furthermore, the rotation of vertical axial wind turbines is noticeably uneven, as the wind load alternates between the blades [2], [12], [13].

Therefore, no ideal wind turbine exists. The search for the best wind turbine is going on. New wind turbine designs have been proposed, which are different from those which have become conventional. They can operate without the use of standard wind turbine forces and their operating elements may not rotate at all. Such wind turbines may be referred to as innovative ones. They may have advantages which will open up areas of applications to make their use potentially beneficial.

Such innovative wind turbines include auto-oscillating wave wind turbines. Being the legal successor of the USSR, Russia is their country of origin. The first patent for this type of wind turbines was issued to S.D. Strekalov in the USSR in 1984 (A. c. 1240949 USSR MPK F03D5. Wind engine / Strekalov S.D. //Registered on 30.06.86. Bulletin No. 24). A few more patents were obtained later, and wind turbine models with a similar operating principle were built.

2. Results and Discussion

A wave wind turbine represents an auto-oscillating system to convert the wind and water flow energy. The wing (or wings) performing auto-oscillation due to the oncoming medium flow is the operating element of such wind engines. In addition, their motion trajectories are similar to that of a body floating at the borderline between the liquid and gaseous media, but in the case of an auto-oscillating wind turbine, the oscillations occur inside the flow rather than at the interface of the media. The power generation capabilities and parameters of these oscillations are determined by the amount of energy conducted through the flow and the parameters of the self-oscillating system itself.

When modelling the interaction processes involving Lagrange vortex methods for a viscous medium taking into consideration the diffusion vortex shift, one can refer to well-known methods. In the random walk method [3], an accidental shift with the Gauss probability distribution is added to the convective shift. The concept of diffusion speed simulated as attraction and repulsion of vortexes was introduced in [4]. The vortex approaches to the solution of related tasks based on the meshless numerical method of viscous vortex domains (VVD) make it possible to simulate the body movement and the movement of the continuous viscous medium within a single set of equations and obtain justified solutions with random inertia data of the rotor and wind-receiving surfaces, including vanishingly small ones [5, 6].

The moving elements of wave auto-oscillating wind turbines perform reciprocating (oscillating) motions [7]. Intermediate transmission devices, such as linear generators, piston pumps and compressors, may be used as operating devices in such systems.

Other advantages of auto-oscillating wind turbines are that they start operating at a rather low wind speed and their energy converters can be placed at the base of the plant.

The designs of auto-oscillating wind turbines eliminate the main drawback of rotor wind turbines, i.e. the noise in the low and super-low frequency zone, which is particularly important for small and medium capacity wind turbines, as they are often located in close proximity to areas containing people. Moreover, the vertical dimensions of auto-oscillating wind turbines are small, which allows using low-height support trusses for their installation and locating the turbines themselves on elevations and roofs of buildings.
It has been reported recently that similar wind turbines have been under study in a number of countries, including the USA, where Eng. Gene Kelly obtained a patent for an adaptable flow-driven energy capture system (Gene Kelly, US patent 20070040389 A1), featuring a similar auto-oscillating wind turbine. In the UK, Heath Evdemon from Nottingham Trent University has built an auto-oscillating wind turbine called the Wind Harvester. In Tunisia, Anis Aouini created a similar auto-oscillating TYER Wind turbine—an innovative startup wind power engineering project. The project is a private initiative and is supported by Pakistani and Algerian investors. Thus, it should be noted that there has been an increased interest in wind turbines using wings which perform repetitive motions as their operating element.

An auto-oscillating system is a system which is capable of producing sustained oscillations for an indefinitely long time due to an energy source located in the immediate vicinity of the auto-oscillating system. The periodic process in these systems is created with the help of a non-periodic energy source. The oscillation parameters do not depend on initial conditions there and are determined only by the properties of the auto-oscillating system itself.

During auto-oscillations, the auto-oscillating system itself creates an internal periodic force which acts on it, thus leading to auto-oscillations. For this to be achieved, it is necessary to have a special feedback mechanism in the auto-oscillating system, which will regulate the periodic energy input after each period of oscillations to compensate for its loss caused by energy dissipation.

The input of the compensatory energy portion has to follow a certain law. If there is no proper input energy synchronization and self-oscillation, it is impossible for auto-oscillations to exist.

The auto-oscillating processes were studied on the basis of a wind turbine model whose kinematic scheme is shown in Fig. 1. It is a system comprising the rocker arm AB and the lever OD, which are connected to each other by means of the joint BD. A load having the mass \( m \) is located below the joint. Two wing-shaped panels are installed in the rocker arm AB, increasing the amount of energy extracted from the flow. The wing on the lever OD functions as an element controlling the wind turbine operation ensuring the feedback function together with the joint BD.

The second Lagrange equations were applied to the wind turbine model

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\alpha}} \right) - \frac{\partial T}{\partial \alpha} - \frac{\partial U}{\partial \alpha} - \frac{\partial \Phi}{\partial \alpha} + Q(t),
\]

where the \( \alpha \) coordinate is the angle of deviation of the rocker arm where the wings were installed from the equilibrium position, \( T, U \) are the kinetic and potential energies of the oscillating system, \( \Phi = \beta (\dot{\alpha})^2/2 \) is the Rayleigh dissipation function taking into account the energy dissipation caused by the presence of internal and viscous friction forces, and \( Q(t) \) is the time-dependent generalized force acting inside the oscillating system.

As a result, it was shown that its solution is the second-order differential equation looking like

\[
\ddot{\alpha} + 2h \dot{\alpha} + \omega_0^2 \alpha = A \cdot Q(t),
\]

where \( \ddot{\alpha}, \dot{\alpha}, \alpha \) are the coordinate, velocity and acceleration of model elements, \( h \) and \( \omega_0 \) are coefficients, whereby auto-oscillations are possible in the system if \( h < 0, \omega_0^2 > h^2 \).

Applying this solution to a specific wind turbine requires determining values of the constituent coefficients \( 2h \) and \( \omega_0^2 \), as well as the type of the generalized exciting force \( Q(t) \), which are extremely difficult to calculate in practice. That is why their values were determined experimentally, which was achieved by the digital processing of data obtained from the ADXL 345 sensor based on the Arduino computational platform.
The ADXL 345 sensor [11] is a micropower triaxial micromechanical accelerometer with high resolution (13 bits and acceleration measurement range ±16 g) and an event detector from ADI. The measurement results are retrieved through the SPI or 12C interfaces as 16-bit data. The sensor has a 32-level FIFO buffer. The ADXL 345 allows differentiating high-frequency movements (for example oscillations having a frequency of 1000 Hz). The sensor is well-suited for measuring low frequency vibrations, static acceleration and deviation angles (less than 1°). Its standard areas of application are navigation, robotics, security systems, personnel safety monitoring systems, protection of mechatronic devices during falls, controlling energy consumption of portable equipment, building a spatial measurement picture, controlling freight integrity, measuring physical load intensity, and photography equipment.

It has also become possible to use the ADXL 345 for measuring kinematic values for research and engineering purposes. When researching the operation of the wind turbine, the data obtained from the sensor attached to the wind turbine rocker arm were transmitted to an evaluation board providing an interface for inputting and recording data via a USB port to a personal computer. The data were further exported to EXCEL, where they were finally processed.

The data array represents acceleration and angular velocity values with a pitch of 10^2 sec, which are measured along three coordinate axes. Subsequently, of practical importance was the angular velocity array obtained in the motion plane of the oscillating wind turbine element.

The array was processed in EXCEL by calibrating the obtained data against the initial sensor position at rest (accounting for the displacement error) and calibrating magnitude (accounting for the measurement scale). The final calibrated angular velocity array was differentiated and integrated in EXCEL and, therefore, angular acceleration and angular coordinate arrays corresponding to the angular velocity array were obtained. Based on the array data, it is possible to build characteristic curves $\alpha = \alpha(t)$, $\omega = \omega(t)$, $\varepsilon = \varepsilon(t)$, where: $\alpha$ is the angular coordinate, $\omega = \dot{\alpha}$ is the angular velocity, and $\varepsilon = \dot{\omega}$ is the angular acceleration. The results obtained for the operation mode 30-5-1.1 are shown in Fig. 2, 3 and 4.

The obtained data arrays make it possible to calculate coefficient values and the system oscillation period and present the final form of the equation (2). For this purpose, the equations of auto-

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**Figure 1.** Auto-oscillating wind turbine kinematic scheme.
oscillations were presented in the form of a set of equations. Then the angular acceleration and velocity values for two consecutive close points of time in the areas of monotonically increasing (decreasing) function values were taken for the solution of this set of equations.

A number of computations were made for different time intervals of the mode under consideration. As a result, the calculated mean wave period \( T=0.883 \) s correlated well with the oscillation period which can be determined directly from the graphs and is equal to \( T=0.877 \) s.

Using the calculated coefficient values in the equation (2) resulted in the following:

\[
\dot{\alpha} - 4.35h \dot{\alpha} + 52.5 \alpha = 3.7 \cdot Q(t),
\]

(3)

It is easy to notice that the coefficient values resulting from the measurements were in keeping with the requirements to the equation coefficients needed for the auto-oscillation mode \( h<0, \omega_0^2>h^2 \) to exist.

The question related to the generalized force type \( Q(t) \) is of the utmost importance. It was suggested that the generalized force acting in the auto-oscillating system is a function of its velocity of motion.

To verify this hypothesis in respect of the existing arrays \( \alpha, \omega, \varepsilon \) and the calculated value \( A \), a data array of the exciting force \( Q = Q(t) \) was calculated in EXCEL and a graph of its time dependency was built (Fig. 5).

In addition, a curve showing the relationship between the generalized exciting force acting in the oscillating system and the rocker arm angular velocity within the period was built in EXCEL (Fig. 6). The trend line built on the same graph, which shows what the relationship would be like in the ‘ideal situation’, pointed to a direct proportional relationship between the generalized force and the angular velocity in the form of:

\[
Q(t) = Q(\dot{\alpha}) = -k\dot{\alpha},
\]

(4)

where \( \dot{\alpha} \) is the rocker arm angular velocity in the oscillation plane; \( k=1.1 \ kg\cdot m^2/s \) is the proportionality factor.

The described method also makes it possible to determine the oscillation power during the operation of the wind turbine despite the fact that its kinematic parameters change continuously.

The instantaneous power of an auto-oscillating wind turbine at any time can be presented as the product of the generalized exciting force acting on the rocker arm and its angular velocity. For the measurement mode 30-5-1.1, an area within the oscillation period was selected and further calculations were made for that area. The generalized exciting force graph within the period is presented in Fig. 7. The graph shows that the systematic errors which occur during the calculation of angles and angular acceleration values also affect the exciting force array calculation results, making its visual graphical perception more difficult, too. The curve was ‘smoothed’, and the ‘smoothed’ curve is also shown in Fig. 7.

Fig. 8 shows the angular velocity and smoothed generalized exciting force graphs on one coordinate plane.

The average oscillation power was calculated in EXCEL directly by averaging the sum of instantaneous power values for \( n \) – measurements over the period:

\[
N_{av} = \frac{\sum_{i=1}^{n} Q_i \cdot \omega_i}{n},
\]

(5)

The graph of the mechanical oscillation instantaneous power over the period for the ‘smoothed’ exciting force is shown in Fig. 9.

The instantaneous power graph for the ‘unsmoothed’ exciting force is given in Fig. 10.

The average mechanical power of oscillations for the full measurement time was also calculated (\( \tau = 12 \) sec, \( n = 1200 \) measurements). The relative deviation of the average power values from each other was within 1%.

On the basis of the obtained results, it is possible to conclude that it is not necessary to perform the ‘smoothing’ operation for the arrays of calculated values when calculating the oscillation power,
because the accumulated systematic errors cancel out during the averaging operation. The ‘smoothing’ procedure contributes only to a better visual representation of the graph showing the result. Given considerable data volumes, it makes the calculation procedure significantly less laborious.

3. Conclusions

1. One can witness a steady growth in the use of renewable sources of energy in the world.
2. Wind power engineering is one of the most rapidly developing renewable energy sectors.
3. No ideal wind turbine design exists. Innovative wind turbine designs are different from conventional ones. Innovative wind turbines may display significant advantages which make their application potentially beneficial.
4. Auto-oscillating wave wind turbines, which are essentially auto-oscillating systems converting the wind and water flow energy, may also be considered as innovative wind turbines.
5. Auto-oscillating wind turbines are characterized by the following advantages: environmental friendliness, ability to operate at a low wind speed, a convenient design, and a high wind energy utilization ratio.
6. The digital processing method applied to data obtained from the ADXL 345 sensor makes it possible to determine the oscillation parameters of the auto-oscillating wind turbines in the mode of constantly varying motion parameters.
7. The systematic errors which occur in the process cancel each other out and do not affect the final result. This makes calculations less labor-intensive if the data volume is considerable.
8. The fact that it is possible to use data arrays over the entire measurement time without having to select values for a strictly defined oscillation period also contributes to shorter processing periods.

Figure 2. Wind turbine rocker arm oscillation angular coordinate $\alpha = \alpha(t)$ graph for the operation mode 30-5-1.1.
Figure 3. Wind turbine rocker arm oscillation angular velocity $\omega = \omega(t)$ graph for the operation mode 30-5-1.1.

Figure 4. Wind turbine rocker arm oscillation angular acceleration $\varepsilon = \varepsilon(t)$ for the operation mode 30-5-1.1.

Figure 5. Graph showing the generalized exciting force $Q=Q(t)$ acting on the wind turbine rocker arm during oscillation for the operation mode 30-5-1.1.
Figure 6. Graph showing the relationship between the force acting on the rocker arm in the auto-oscillating system and its angular motion velocity (red), and the trend line (black).

Figure 7. Graph showing the generalized exciting force acting in the oscillating system $Q=Q(t)$ (blue) (the ‘smoothed’ data are purple) within the oscillation period for the measurement zone 30-5-1.1.
Figure 8. Graph showing the angular velocity $\omega = \omega(t)$ (green) and the ‘smoothed’ generalized exciting force $Q=Q(t)$ (purple) within the oscillation period for the measurement zone 30-5-1.1.

Figure 9. Graph showing changes in the mechanical oscillation power for the ‘smoothed’ exciting force within the oscillation period for the measurement zone 30-5-1.1.
Figure 10. Graph showing changes in the mechanical oscillation power for the ‘unsmoothed’ exciting force within the oscillation period for the measurement zone 30-5-1.1.

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