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Spectral Analyses of an Optimized Ducted Wind Turbine Using Hot-wire Anemometry

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Abstract

The use of ducted wind turbines is developing, and various scientists are investigating the performance, economic analysis, and energy production by these types of turbines at a lower cost. In this work, the ratio of wind speed increment related to free stream wind speed and turbulence rate in a pre-designed duct used for a horizontal three-blade wind turbine is evaluated using a hot-wire anemometer sensor and the data analysis methods. The duct installed in the University of Tehran Aerospace Faculty wind tunnel and flow characterization is performed using the CTA apparatus in order to measure and evaluate the wind flow turbulence in the throat section of the duct, where the wind turbine has been installed. The wind speed analysis is carried out at different speeds of the wind tunnel test section, showing that in the throat section of the duct, the wind speed increases with a constant slope, and in more analysis, it is found the wind speed in the duct throat can be increased to 2.5 up to 3 times of the free stream flow speed at a different wind speed of the wind tunnel test section. Fast Fourier transform is used in order to evaluate the frequency content of the measured signals, and it is shown that the frequency level decreases by any decrease in the wind flow speed and its energy level. From the spectral analysis, it is found that only a few peaks are included in the extracted frequency, showing that from a low turbulence inside the duct, it can be concluded that the flow disturbances will not have a significant impact on the performance of the wind turbine placed inside the duct throat.

Keywords: *Ducted Wind Turbine, Optimization, Spectral analysis, Hot-Wire.*

1. Introduction

Increasing the wind speed inside the pre-designed ducts, which leads to an increase in the available wind power for extracting its energy by wind turbines has been the focus of the researchers in their studies. Allaei [1] has introduced Invelox as a new type of ducted wind turbine, reporting that the output energy increases about 72% for the wind turbines used. Han [2] has introduced a horizontal shrouded wind turbine, reporting that the output power of a wind turbine can be increased to 2.4 times by their designed shroud and lobed ejector. Chaudhari [3] has designed another shroud for the horizontal wind turbines, and their CFD analysis has shown that the average wind speed can be increased to 1.75 times of free-flow stream, while the maximum wind speed can reach 2.5 times the free streamflow.

The researchers have used various methods in order to evaluate the ducted wind turbines and their performance to introduce them as low-cost wind turbines that harvest energy from low speed wind. A more detail about the ducted wind turbines has been introduced by Taghinezhad [4]. In this work, we used the Fast Fourier Transform (FFT) algorithm in order to process the hot-wire signal and analyze the turbulence of the flow. The increase in the wind speed flow through the throat section of a designed duct is studied in a wind tunnel test, and the results obtained are reported.

2. Materials and methods

2.1. Investigation of speed and turbulence of flow using hot-wire sensor

A ducted wind turbine was designed and fabricated based on the Morel [5] design criteria. The empirical tests were carried out in the University of Tehran Aerospace Faculty wind tunnel lab. The wind tunnel flow stream speed was calibrated by the pitot method. A schematic representation of the experimental work is shown in figure 1. First of all, a hot-wire anemometer sensor was installed in the middle of the test section of the wind tunnel to be calibrated by the flow stream of the wind tunnel (1). Then the designed duct was installed in the test section of the wind tunnel, and the calibrated hot-wire sensor was fixed in the throat section of the duct in order to measure the wind speed at this point (2). Then a BNC connector with its related wire was used in order to connect the sensor to a Constant Temperature Anemometer (CTA) (3). CTA, located outside the wind tunnel, is shown with four numbers that change the temperature to the voltage signals (4). Then the collected data was moved to a desktop computer A/D card (5). At the end, the software designed by Tabrizian [6] was used to extract the data from the A/D card.

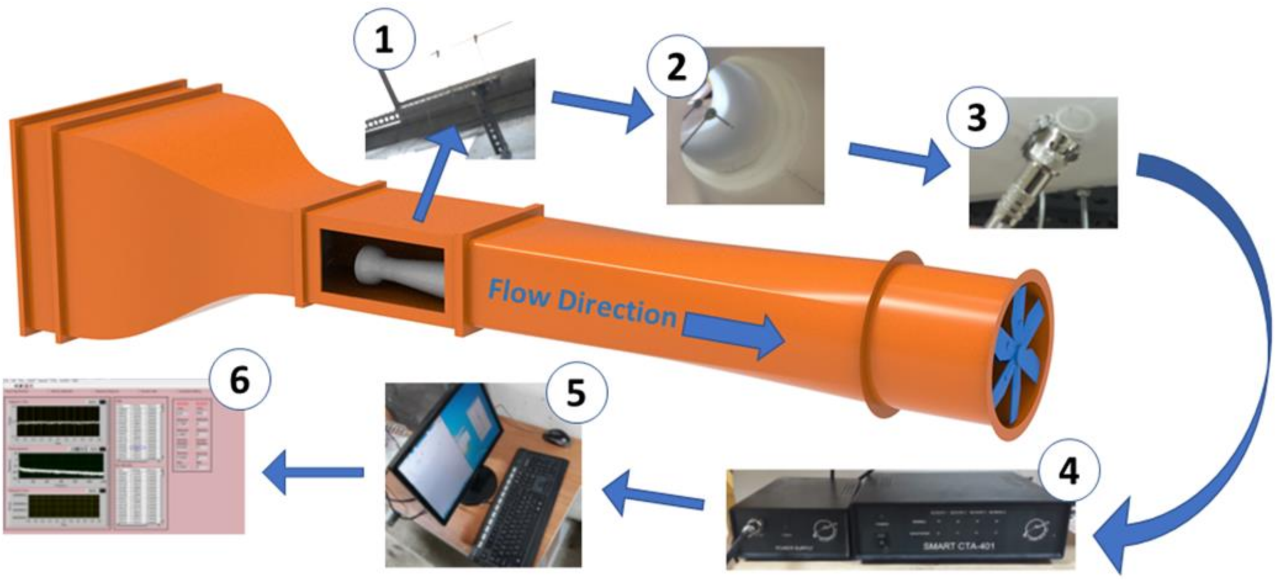


Figure 1. Apparatus arranged to measure turbulence of the duct located in wind tunnel.

3. Results and Discussion

3.1. Investigation of flow turbulence in throat section

Using the calibration data for the hot-wire sensor, the calibration equation can be derived. In order to measure the flow turbulence, the hot-wire sensor was located at the throat section of the duct. The measured output voltage from the sensor located in the throat section of the duct at the wind speed of 10 m/s is shown in figure 2.

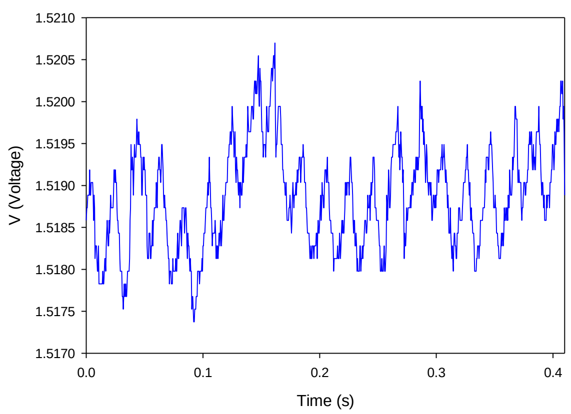


Figure 2. Measured voltage from the duct throat at 10 m/s free stream flow.

In order to show an increased rate of the wind speed through the duct throat section, the estimated wind speed in the throat section and in the test section of the wind tunnel was drawn with area graphs using the wind tunnel speed as the graph index (Figure 3). The area plot shows the difference between the wind speed in the duct throat section and the wind tunnel test section. The wind speed in the duct throat section increased significantly. By increasing the wind speed in the test section, more increment in the duct throat section was seen, while it seems that the slope of this increment is a constant value.

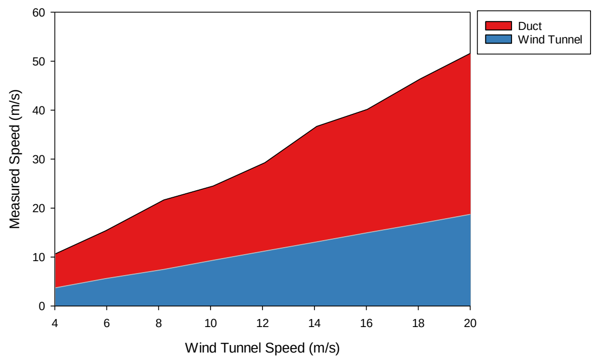


Figure 2. A comparison between the wind speed at duct throat section and the wind tunnel.

In order to have a better study, the wind speed was increased at the throat section of the duct. The ratio of the wind speed in the throat section of the duct to the wind speed at the test section of the wind tunnel was plotted in different wind speeds of the wind tunnel test section (Figure 4). The error bars show the deviation for the repeated tests at the same wind speed. The increased wind speed ratio at the throat section of the duct at different flow speeds of test sections are valued between 2.5 to 3 times.

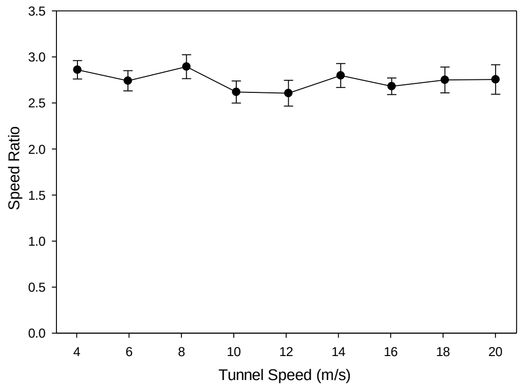
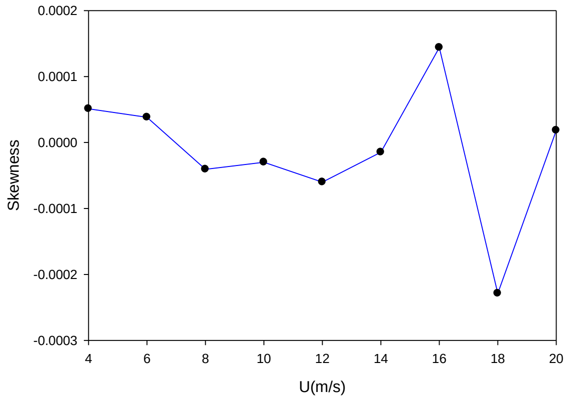


Figure 4. Increased ratio of wind speed in the throat section of the duct.

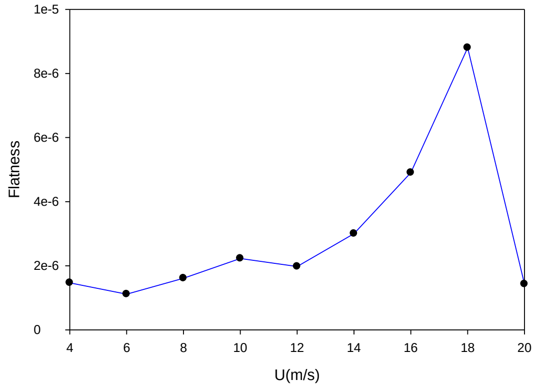
The deviation from the Gaussian distribution function can be investigated using the skewness and Kurtosis. This is because the relationship between the number of degrees of freedom in space and time decreases locally. Skewness is a criterion for examining the symmetry, or more precisely, asymmetry of the data. Kurtosis or flatness is a parameter that indicates that the measured data is more or less sharper than the normal distribution at the maximum sharp point.

Figure 5 shows the skewness and Kurtosis changes, respectively, at different wind velocities across the duct throat section. The skewness for the normal distribution is zero, and any symmetric skewness data is close to zero. The plotted line in figure 5(A) shows that the absolute value of skewness for all velocities is very close to zero. It means that the extracted data has a normal distribution. The measured skewness represents both the negative and positive values, which means that the skewness of the data is close to the normal distribution.

Figure 5(B) shows the amount of kurtosis or flatness for the signals at all the throat cross-section velocities. The flatness measured the tail weight (normal distribution peak point) to the sharpness of the distribution. The positive kurtosis indicates the peak distribution, and the negative kurtosis indicates a smooth distribution. Figure 5(B) shows that this data has heavy-tailed distributions.



(A)



(B)

Figure 5. Skewness (A) and Kurtosis changes at different wind speeds at the throat section.

Figure 6 shows the turbulence intensity at the duct throat section at different wind tunnel velocities; according to the Bardal & Sætran [7] research work, the turbulence intensity above 10% significantly reduced the wind turbine output power. As it can be seen, the measured values for the turbulence intensity at all wind speeds of 4-20 m/s are a maximum of 0.65%, which is far below 10%, and does not disturb the performance of the wind turbine installed at the throat section.

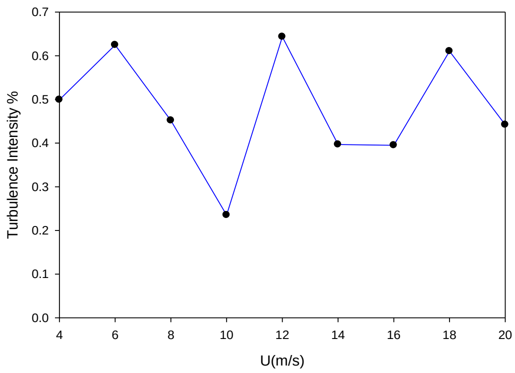


Figure 3. Turbulence intensity of throat sections at different wind tunnel speeds.

3.2. Spectral analysis of flow velocity

Fast Fourier transform (FFT) and power spectrum distribution were performed in order to investigate the content of the airflow rate signal. To measure the velocity signal, a hot wire sensor was placed at the center of the duct throat section. FFT was used in order to measure the frequency content of the fixed or transient signals and simulating the mean frequency content of the signal at all data points. In order to investigate the energy content of the signal, the power spectrum distribution was calculated and plotted. Figure 7 shows the distribution of the power spectrum at the speeds of 6 m/s, 10 m/s, and 14 m/s.

It is obvious that by decreasing the flow rate at the duct inlet, the power spectrum amplitude decreases, indicating a decrease in the flow energy content at all frequencies. Two main peaks are shown in figure 7 with this regard that the duct is located inside the wind tunnel and is mounted on the floor of the wind tunnel test section, and then the vibrations of the tunnel wall affecting the duct and the low-frequency peak could be attributed to these vibrations. The second peak occurred at a frequency of 32 Hz, which was due to the instabilities associated with the wind flow contraction at the inlet and the Gartler vortex at the turning point of the contraction section [8]. These frequencies indicate the instability in the boundary layer of the duct wall, which is one of the factors affecting the intensity of the turbulence in the duct. The absence of more peaks or lower altitudes of higher frequencies indicates a low degree of turbulence within the duct, and it can be said that it will not have a significant impact on the performance of the wind turbine placed inside the duct.

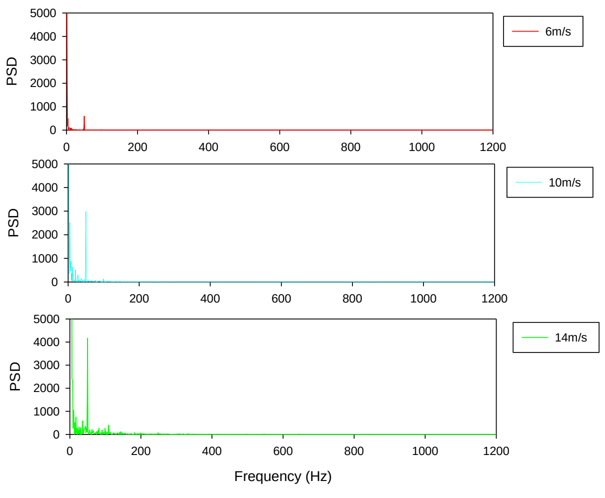


Figure 4. PSD of velocity signal at the throat section at different wind tunnel flow rates.

4. Conclusions

In this work, a parametric study on the convergent-divergent duct was conducted in order to evaluate the optimized duct in the empirical tests. Then a prototype of the duct was fabricated, and the experimental tests were performed in order to validate the analysis. The experimental tests reached good results, and the following conclusions could be obtained:

1) The flow intensity at the throat section was investigated using a hot-wire sensor. The speed measurements showed to be between 2.5 and 3 times the duct section relative to the free flow.

2) Examination of the skewness and kurtosis of the collected data by the hot-wire sensor shows the normal and acceptable distribution of the data at different speeds.

3) The measured turbulence intensity shows values near zero (maximum of 0.65%) at different velocities from 2m/s to 20m/s; this variable indicates the uniformity of the flow inserted to the contraction input and delivered to the duct throat section.

4) Using the fast Fourier transform, the frequency content of the measured signals was investigated, and it was shown that with decrease in the wind speed in the freestream flow, the energy level decreased at all frequencies.

Examination of the power spectrum distribution revealed a few peaks, indicating a low turbulence inside the duct, and it can be concluded that the flow disturbances will not have a significant impact on the performance of the wind turbine placed inside the duct throat.

5. Acknowledgment

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