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Design of low noise wind turbine blades using Betz and Joukowski concepts

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Abstract. This paper presents the aerodynamic design of low noise wind turbine blades using Betz and Joukowski concepts. The aerodynamic model is based on Blade Element Momentum theory whereas the aeroacoustic prediction model is based on the BPM model. The investigation is started with a 3MW baseline/reference turbine rotor with a diameter of 80 m. To reduce the noise emission from the baseline rotor, the rotor is reconstructed with the low noise CQU-DTU-LN1 series of airfoils which has been tested in the acoustic wind tunnel located at Virginia Tech. Finally, 3MW low noise turbine rotors are designed using the concepts of Betz and Joukowski, and the CQU-DTU-LN1 series of airfoils. Performance analysis shows that the newly designed turbine rotors can achieve an overall noise reduction of 6 dB and 1.5 dB(A) with a similar power output as compared to the reference rotor.

1. Introduction
Wind energy is developing very fast in the world. To reduce CO_2 emission from fossil energy and alleviate global warming, governmental targets in developing wind energy are very ambitious in most countries. For example, in Denmark, electricity production is forecasted to reach 50% from wind energy in 2020 [1] and 100% from renewable energy in 2050 [2]. This means there will be important installations of both onshore and offshore wind turbines in the near future. As it is known, noise from wind turbines is an important issue for future development of onshore wind energy. To overcome the noise problem, the present paper focuses on design of low noise wind turbine blades.

The design of horizontal axis wind turbine blades is nowadays a standardized procedure. Most of the wind turbine manufacturers are using the Glauert concept based on Blade Element Momentum (BEM) theory [3] with existing airfoils that were developed in the aeronautic industry for enhancing aerodynamic performance and therefore not optimized regarding to noise. In our previous work, low noise CQU-DTU-LN1 series of airfoils were designed and tested in acoustic wind tunnel located in Virginia Tech [4]. The design objectives of the low noise airfoils are high lift, high lift-drag ratio, low noise and low roughness sensitivity. Since the main noise sources of a wind turbine are located in the outer part of the blades, the airfoils (especially the airfoils with thickness of 15%-21%) used for constructing that part should be designed optimal for both aerodynamic and aeroacoustic performances. As a consequence, these low noise airfoils will be used in the present design of low noise wind turbine blades.

To investigate different design concepts, the concepts of Betz and Joukowski were considered in [5]. The former concept is based on the analytic solution of the Goldstein circulation distribution of the screw wake and the latter is based on constant blade circulation. In the present paper, the developed Betz and Joukowski concepts in [5] will be further used for designing low noise wind turbine rotors.

To start our investigation, we choose an 80 m 3MW commercial onshore turbine rotor as the baseline rotor. The 3 blades of the reference rotor are constructed with NACA634XX airfoils and have a thickness of around 18% at a radial position of 90% rotor radii. The twist and chord distribution is shown later in Figure 6. The noise emission from the reference rotor will be analysed using the semi-empirical model developed in [6-8] which is based on the BPM model [9]. In order to reduce the noise from the reference rotor, the rotor is constructed with the CQU-DTU-LN1 airfoils [4]. Finally, 80 m 3MW wind turbine rotors using the concepts of Betz and Joukowski are designed. The aerodynamic performance and noise emission from the 4 turbine rotors are compared and analysed at wind speeds of 6.1 and 10.5 m/s.

2. Jowkowski and Betz concepts

In [5] two concepts of optimal rotors with a finite number of blades N_b of radius R were considered: (1) Joukowski rotor with constant Γ circulation and constant azimuth averaging induction factors $a = N_b \Gamma / 2\pi l$ along blade; and (2) Betz rotor with circulation given by Goldstein's function $G(r,l) = N_b \Gamma(r,l) / 2\pi l \, w U_\infty$ along blade r. The parameter l denotes a helical pitch of tip vortices in the first case and helical sheets leaving the blades with a constant velocity w in the second case. The rotor optimizations were made with the unique parameter a or w in each case for a fixed helical pitch l. A correlation of operating regimes of the both rotors was recognized by an equal value of tip speed ratio defined by the following relationship, respectively

$$\lambda_0 \equiv \frac{\Omega_0 R}{U_\infty} = \frac{R}{l}\left(1 - \frac{a}{2}\left(1 + \frac{\varepsilon}{R}\right)\right) \text{ and } \lambda_0 \equiv \frac{\Omega_0 R}{U_\infty} = \frac{R}{l}\left(1 - \frac{w}{2}\right), \tag{1}$$

where U_∞ is wind speed and Ω_0 is angular speed of the rotor. In [5] for the Betz model an expression for the axial interference factor was obtained

$$a = w \int_0^1 G(x,l) dx \,. \tag{2}$$

For an identical operating conditions (1) after which the Joukowski model gives a by a direct calculation and the Betz one by using (2) the chord distribution in the radial direction has been calculated by the same formulas

$$c(r) C_n = \frac{8\pi R a r \sin^2 \phi}{\lambda_0 (1-a) N_b}, \tag{3}$$

where the flow angle ϕ should be defined like a by different ways for both rotor concepts. In the case of Betz after definition of the optimum value of w the formula takes a very simple from

$$\text{tg}\phi = \frac{R\left(1 - \frac{1}{2} w\right)}{\lambda_0 r}. \tag{4}$$

In the case of the rotor by Joukowski the original formulation for the flow angle is used

$$\mathrm{tg}\phi = \frac{U_\infty - \frac{1}{2}u_z}{\Omega_0 r + \frac{1}{2}u_\theta}, \tag{5}$$

in which the induction velocity on the blade directly depends on the optimal induction factor *a* namely

$$u_z(r) = a\left(\begin{Bmatrix} N_b \\ 0 \end{Bmatrix} + \frac{\sqrt[4]{l^2+R^2}}{\sqrt[4]{l^2+r^2}}\sum_{n=1}^{N_b}\mathrm{Re}\left[\frac{\pm e^{i\chi_n}}{e^{\mp\xi}-e^{i\chi_n}} + \frac{l}{24}\left(\frac{3r^2-2l^2}{(l^2+r^2)^{3/2}} + \frac{9R^2+2l^2}{(l^2+R^2)^{3/2}}\right)\ln\left(1-e^{\xi+i\chi_n}\right)\right]\right) \tag{6}$$

$$u_\theta(r) = \frac{al}{r}\left(\begin{Bmatrix} 0 \\ N_b \end{Bmatrix} - \frac{\sqrt[4]{l^2+R^2}}{\sqrt[4]{l^2+r^2}}\sum_{n=1}^{N_b}\mathrm{Re}\left[\frac{\pm e^{i\chi_n}}{e^{\mp\xi}-e^{i\chi_n}} + \frac{l}{24}\left(\frac{3r^2-2l^2}{(l^2+r^2)^{3/2}} + \frac{9R^2+2l^2}{(l^2+R^2)^{3/2}}\right)\ln\left(1-e^{\xi+i\chi_n}\right)\right]\right) \tag{7}$$

where $e^{\xi} = \frac{r\left(1+\sqrt{1+R^2/l^2}\right)\exp\left(\sqrt{1+r^2/l^2}\right)}{R\left(1+\sqrt{1+r^2/l^2}\right)\exp\left(\sqrt{1+R^2/l^2}\right)}$ and $\chi_n = \frac{2\pi(n-1)}{N_b}$.

3. Summary of the employed numerical tools

In this section, we present briefly the numerical models used for analysing both aerodynamic and aero-acoustic performance of wind turbine rotors.

3.1. Aerodynamic model

The aerodynamic model is based on the blade element momentum theory (BEM) with Shen's tip loss correction [10, 11]. The principle is based on the axial and tangential momentum balance with the axial and tangential force acting on the blades. The final equations are

$$\frac{aF(1-aF)}{(1-a)^2} = \frac{\sigma C_n F_1}{4\sin^2\phi} \tag{8}$$

$$\frac{a'F(1-aF)}{(1+a')(1-a)} = \frac{\sigma C_t F_1}{4\sin\phi\cos\phi} \tag{9}$$

where *a* and *a'* are the axial and tangential induction factors on blade, σ is the local solidity, ϕ is the flow angle, and Cn and Ct are the normal and tangential force coefficients obtained with 2D airfoil data corrected for rotational effects. The tip loss functions F and F_1 are

$$F = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-\frac{B(R-r)}{2r\sin\phi}\right)\right] \tag{10}$$

$$F_1 = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-g\frac{B(R-r)^n}{2r^n\sin\phi}\right)\right] \tag{11}$$

$$g = \exp\left(-\frac{0.125(B\lambda-21)}{1-2\min(dc/dr)}\right) + 0.1 \tag{12}$$

where dc/dr is the gradient of the chord distribution in the radial direction in the tip region and the exponent *n* is

$$n = 1 + 0.5\min(dc/dr) \tag{13}$$

The 2D airfoil data was obtained with the XFOIL code [12] using the e^N envelope transition model (N = 9) for the clean case and fixed transition at 5% and 10% chords on the suction and pressure sides for the rough case.

3.2. Aeroacoustic model

The aeroacoustic model used here is a semi-empirical model based on the BPM model [9] which is developed in our previous works [6-8]. The main development is the use of actual boundary layer quantities of the airfoils used in the design of the blades, the extension for high Reynolds number flows and the modification of trailing edge bluntness noise using CAA computations. The emphasis is put on reduction of airfoil-self noise since inflow noise is intrinsic to the atmospheric conditions and cannot be controlled in the design step. More details can be found in [6-8].

4. Results

In this section, we first present the aerodynamic and aeroacoustic performance of the reference wind turbine rotor and its modifications. Second, we present the performance of the designed Betz and Joukowski rotors. The reference wind turbine has a rated electrical power of 3MW and a diameter of 80 m. As a consequence, we will use the same rotor size and rated power for the subsequent design of other rotors.

4.1. Performance of the reference rotor

To get an idea of noise emission from a commercial wind turbine, we chose the 3MW wind turbine as the reference wind turbine. To reduce the noise emission of the reference wind turbine, the rotor is redesigned with the low noise CQU-DTU-LN1 series of airfoils; the NACA airfoils on the reference blade were replaced with the LN1 airfoils with the same relative thickness, and the chord and twist distributions were kept the same. For further noise reduction, the reference and the modified turbines are pitched with 3 deg for comparison. In Figure 1 (left), the power performance of the turbines is plotted. The reference turbine has a rated mechanical power of 3MW which should give an electrical power of 2.75 MW. A similar power will be obtained for the redesigned turbines. From the figure it is noted that the reference turbine with 3 deg pitch gives a heavy power reduction. The thrust of the turbines is plotted in Figure 1 (right). As the LN1 series is a series of high lift airfoils, the thrust of the modified rotor is higher than the reference one.

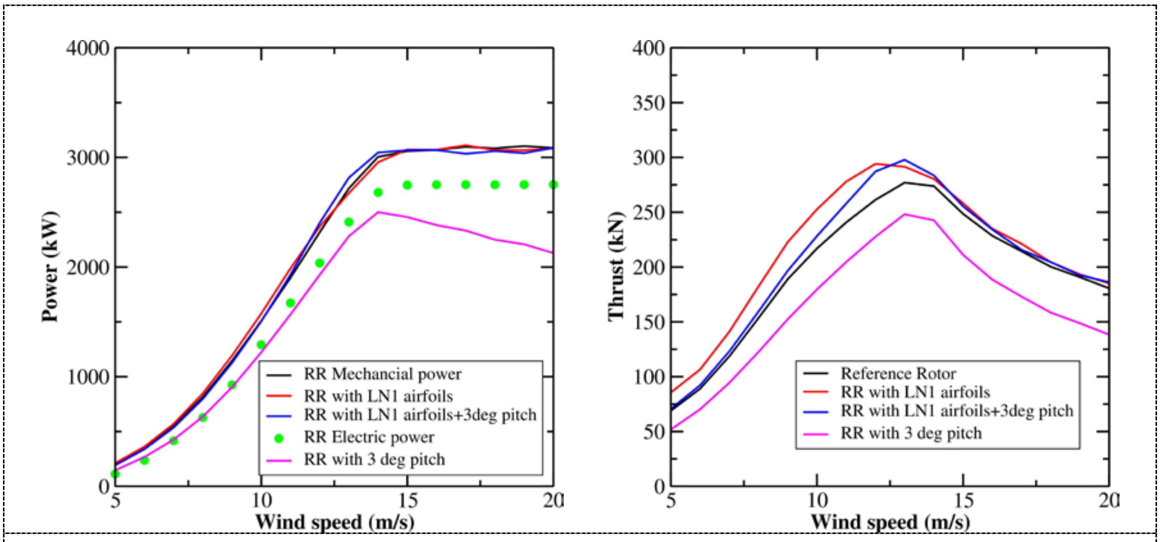

Figure 1. Power and thrust of the 3MW reference turbine and its modification.

Noise emission of the turbines at a wind speed of 6.1 m/s and an inflow turbulence intensity of 3% is plotted in Figure 2. The reference turbine is designed to be a variable speed and variable pitch turbine. The rotor speed at 6.1 m/s is 12.3 RPM. It is considered that the turbine in the beginning operates in clean conditions and after 5 years in service due to surface deterioration and soiling, the turbine operates in rough conditions (which were simulated by tripping the boundary layer in XFOIL calculations). From the clean case, the noise emission of the modified turbine with the LN1 airfoils is slightly less than the reference one while it is much smaller in the rough case. By increasing the pitch angle it is seen that noise reduces gradually in the two cases. The reference turbine in the “pitched” clean case is performing better that the modified one, but again in the rough case the modified turbine is better. The greatest noise decrease of the modified turbine comes from the reduction of the trailing edge noise of the turbulent boundary layer. It should be noted that the LN1 airfoils have higher lift than the original airfoils and therefore a pitch angle should be used for the modified turbine in order to obtain a similar aerodynamic performance as the reference turbine.

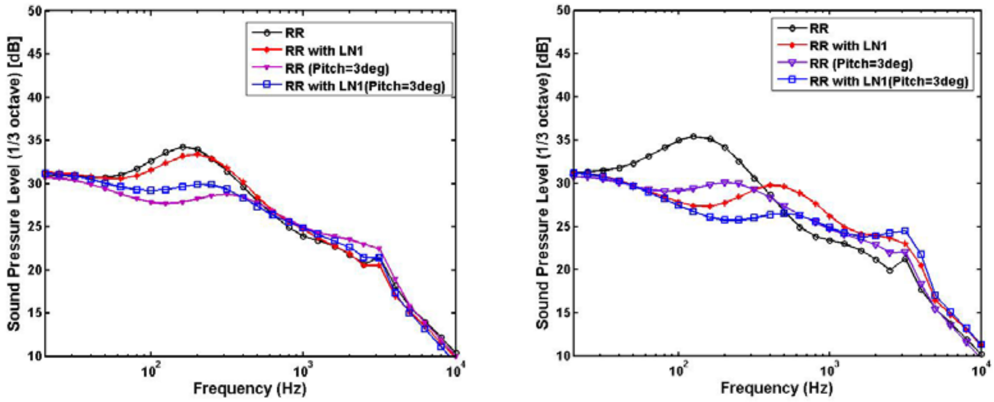

Figure 2. Noise emission of the 2.75 MW reference turbine and its modification with a rotor speed of 12.3 RPM at a wind speed of 6.1 m/s, inflow turbulence intensity of 3%. Clean surface (left) and rough surface (right).

4.2. Betz and Joukowski rotors

The Betz and Joukowski rotors constructed with the LN1 airfoils for a design angle of 7 degrees and a pitch angle of 0 degrees are plotted against the reference wind turbine in Figure 3. From the figure, it is seen that the Betz and Joukowski rotors have a smaller chord distribution but a bigger twist angle distribution. The power and thrust performance is plotted in Figure 4. It is seen that similar power curves are obtained but thrust is higher than that of the reference rotor.

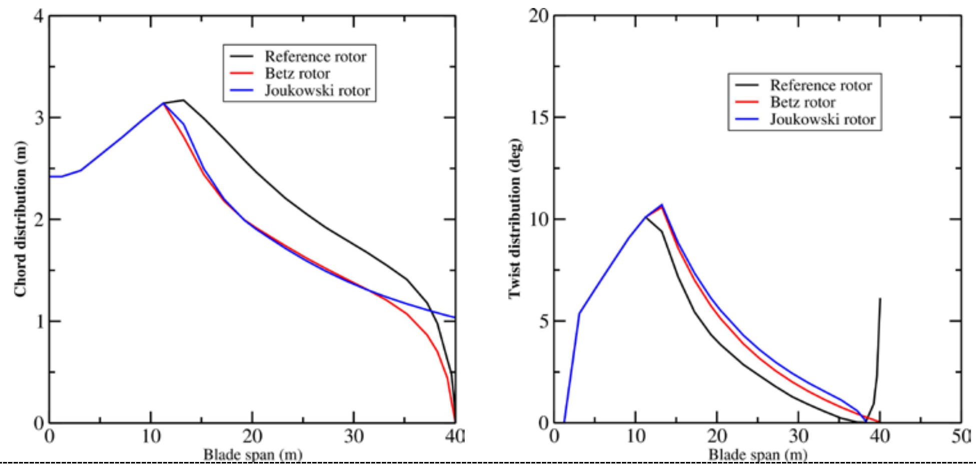

Figure 3. Chord (left) and twist (right) distributions of the reference, Betz and Joukowski rotors.

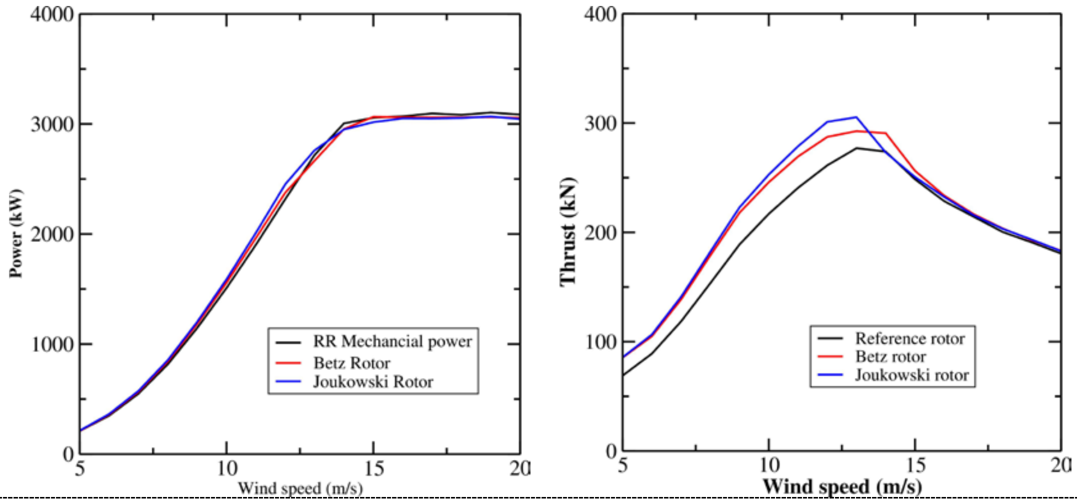

Figure 4. Power and thrust of the 3 MW Betz and Joukowski rotors.

Noise emission of the Betz and Joukowski rotors is plotted in Figure 5. In the clean case, noise is seen increasing while only slight decrease is seen in the rough case.

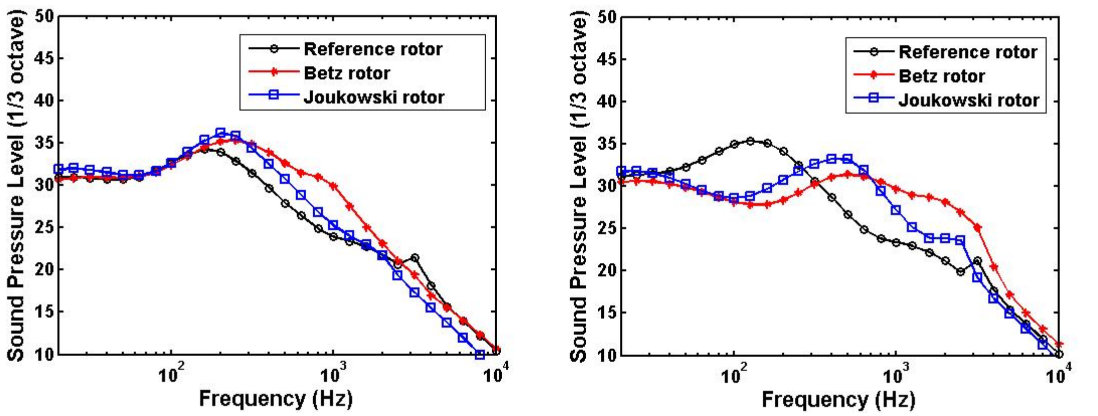

Figure 5. Noise emission of the 3 MW Betz and Joukowski rotors with a rotor speed of 12.3 RPM at a wind speed of 6.1 m/s, inflow turbulence intensity of 3%. Clean surface (left) and rough surface (right).

4.3. Redesigned Betz and Joukowski rotors

In order to reduce noise of the Betz and Joukowski rotors, the rotors (still with LN1 airfoils) are redesigned for a design angle of attack of 4 deg and a pitch angle of 4 deg. The chord and twist distributions are plotted in Figure 6 which shows almost same chord distribution as the reference rotor. The power and thrust performance of the redesigned rotors is also similar to that of the reference rotor (Figure 7). Figure 8 shows the noise emission of the redesigned Betz and Joukowski rotors and reference rotor with and without pitch. Very good performance of the new rotors is seen which gives a noise reduction of 6 dB and 1.5 dB(A) with similar power output as compared to the reference wind turbine rotor.

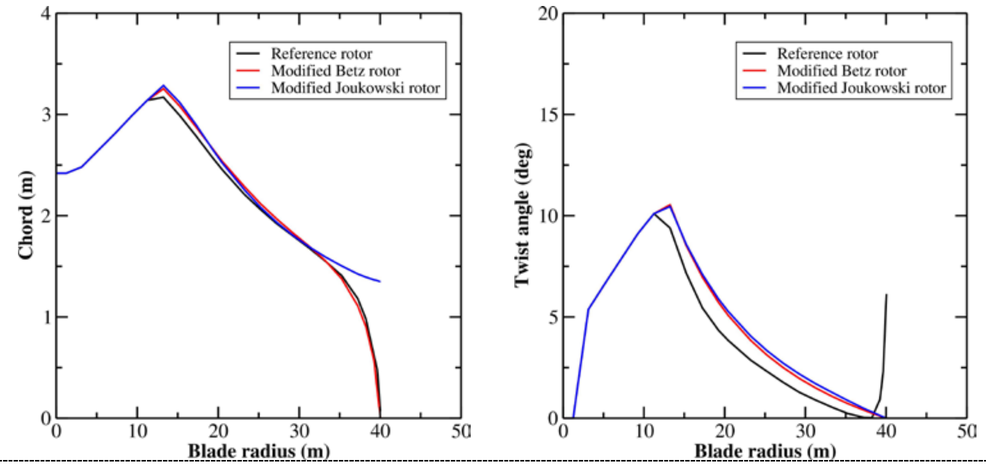

Figure 6. Chord (left) and twist (right) distributions of the reference, re-designed Betz and Joukowski rotors.

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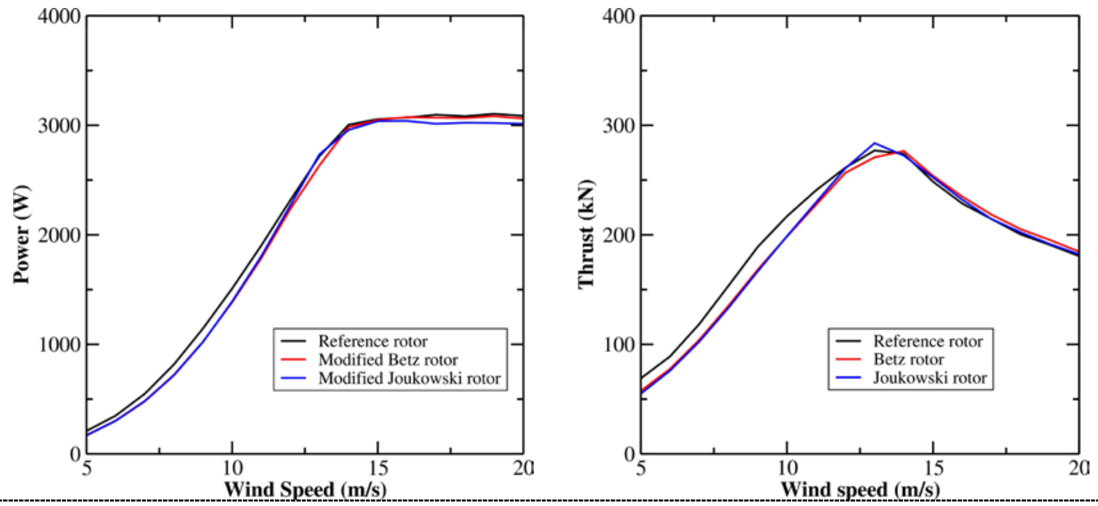

Figure 7. Power and thrust performance of the re-designed 2.75 MW Betz and Joukowski rotors.

5. Conclusions

Low noise wind turbine rotors have been designed using the concept of Betz and Joukowski. The designed rotors have a similar power performance as the reference rotor but noise emission of the new rotors is much smaller than the reference one for both low and high frequency noise and in both clean and rough cases. In the future, cost of energy will be considered in the design of low noise wind turbine rotors.

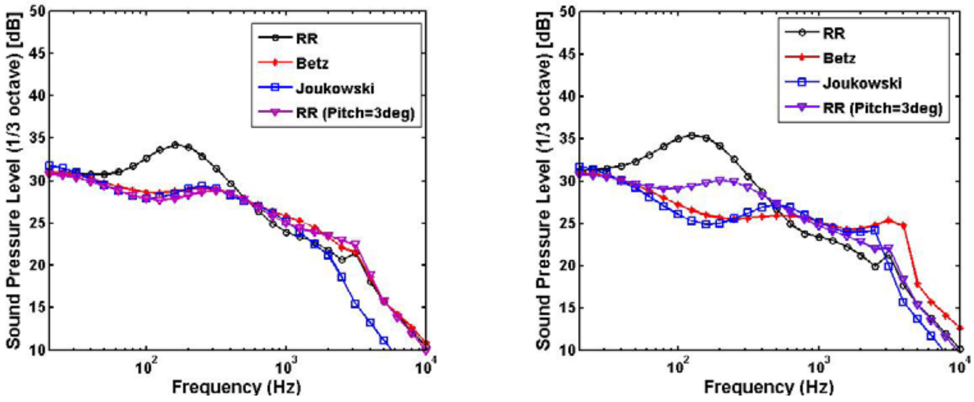

Figure 8. Noise emission of the redesigned 2.75 MW Betz and Joukowski rotors with a rotor speed of 12.3 RPM at a wind speed of 6.1 m/s, inflow turbulence intensity of 3%. Clean surface (left) and rough surface (right).

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Acknowledgments

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