Static and dynamic study of a conventional Savonius rotor using a numerical simulation

Étude statique et dynamique d’un rotor Savonius conventionnel par simulation numérique

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Résumé : (Times 14 gras, espace AP 5 pt)

Le présent papier est une contribution à l’étude de l’écoulement autour d’un rotor de type Savonius afin d’en déterminer les performances aérodynamiques. L’étude est effectuée sur la base de simulations numériques sur un code de calcul CFD du marché (Fluent 6.3) utilisant la méthode des volumes finis.

Dans les simulations numériques, l’équation de continuité et les équations de Navier-Stokes avec des moyennes de Reynolds sont résolues en même temps que les équations du modèle de turbulente k-ω SST. La validation numérique se fait relativement aux célèbres résultats expérimentaux de Blackwell et al.

Les calculs sont d’abord effectués en statique pour un rotor conventionnel. De tels résultats, abondants d’un point de vie expérimental, sont en fait très rares en simulation numérique. Dans un second temps, l’étude dynamique du rotor Savonius est effectuée. Les grandeurs aérodynamiques telles que les pressions, les vitesses, et les efforts aérodynamiques, sont calculées et permettent de déduire les courbes de fonctionnement de l’éolienne.

Dans tous les cas, la méthode numérique est explicitée, de même que le type et le nombre de mailles, les lois de parois, la méthode permettant de simuler un « rotor tournant ».

On montre que les calculs statiques et dynamiques sont en bon accord avec la littérature.

Abstract :

The present paper is a contribution to the study of the flow in and around a Savonius rotor for the determination of its aerodynamic performances. The study is done by the use of numerical simulations with a CFD software (Fluent 6.3).

The RANS model is used, additionally with the k-ω SST turbulence model. The numerical validation is made with the famous results of Blackwell et al.

First a static calculation is made. Such results are numerous from experiments but are rare from a numerical point of view. Then a dynamic study is made. Aerodynamic quantities, such as pressures, velocities and aerodynamic forces, are calculated to obtain the operating curves of the rotor. In all cases, the numerical method is explained, such as the type and number of cells, wall laws, the method which simulates a “rotating rotor”.

It is shown that the static and dynamic calculations are in good agreement with the literature in the field.

Mots clefs: Rotor Savonius, simulation numérique, CFD

Keywords: Savonius rotor, numerical calculation, CFD
1 Introduction.

Wind turbines are dimensioned for a nominal running point, i.e. for a given wind velocity. Currently, because of their higher efficiency, fast running horizontal axis machines are preferred to slow-running Vertical Axis Wind Turbine (VAWT) [1]. However, it has been shown that a slow-running Vertical Axis Wind Turbine, such as the Savonius rotor [2], can extract more energy than fast running wind machines [3].

This idea seems to be in contradiction to the general literature in the field because the Savonius rotors have an aerodynamic behaviour where the characteristics of a drag device dominate, which clearly induces a low efficiency. But the delivered energy is more important than the installed power. Because of its high starting torque, a Savonius rotor can theoretically produce energy at low wind velocities, and because of its low angular velocity, it can deliver electricity under high wind velocities, when fast running wind turbines must generally be stopped [1,4].

The advantages of the Savonius rotor are numerous [4], but its efficiency is rather poor. For a few years, many studies have led to raise performances of these machines [5,6,7,8] or to develop better wind turbines coming from the Savonius concept [9,10,11,12,13].

Despite these different results, most of the studies are made without a clear strategy of improvement, which is due to the complexity of the non-stationary flow in and around the rotor.

But the real question is to know if the Savonius rotor is a machine just coming from the past or useful for the future. Because of new needs of wind energy, especially with the appearance of “micro-turbines” adapted to isolated sites or urban area, the second hypothesis seems to be the most appropriate [14,15].

Recent developments of computational Fluid Dynamics (CFD) on complex structures help to understand of the Savonius rotor aerodynamic behaviour. It allows the pertinent values of the flow characteristics, such as the aerodynamic efficiency, without using complex and numerous experiments. The idea is to improve these aerodynamics characteristics.

Ten years ago, we have initiated a numerical calculation on a Savonius rotor [16]. The idea was to lead a parametric investigation aiming to choose for example an optimal value for the overlap ratio; then an “optimal” rotor has been chosen which optimized the aerodynamics characteristics, namely the static torque. Many other numerical studies have been made since then. Let us describe only the more recent ones. Afungchui et al. propose an interesting method, well known in the field of fluid mechanics, giving the pressure field on a Savonius rotor [17]. But the calculation is based on a potential flow modeling: the comparison with the experiments reported by Blackwell et al [10] give unsatisfactory results, probably because of the viscous behavior of the flow. D’Allexandro et al. [18] propose a bi-dimensional RANS resolution of the flow equations using a k-ε turbulence model coupled with a transport equation for the quantity $\nu$. The results are not only compared but also “initiated” by experimental results using an original methodology. No static calculation is made but the dynamic behavior is in good agreement with the experiment results. Akwa et al. use a k-ω SST turbulence model to predict the aerodynamic performance of Savonius rotors as a function of the overlap ratio [19]. The results are compared to reference [10] with a good agreement, except at high rotational speeds. No static calculation is reported. Zhou and Rempfer give a precise description of the aerodynamic performance, notably the pressure distribution on each blade, but they don’t report about the power coefficient against the speed ratio, and just compare the conventional Savonius rotor with a Bach type turbine [20].

Although they deal with Savonius rotors, the main objective of these different papers is generally to produce acceptable results (i.e. validated by experiments) by the use of specific numerical methods or adapted turbulence models for the calculation. The numerical results generally refer to different experimental results for the validation, so that it is difficult to compare them. Only few of them give full results for the dynamic torque or the aerodynamic power. Besides, to our knowledge, no one gives an acceptable result concerning the static torque, which is however very important for the aerodynamic behavior because the main characteristic of the Savonius rotor is to start at low wind velocities whatever the wind direction.

The present paper aims to fill this lack, giving numerical results for the static torque on a Savonius rotor, and presenting the dynamic behavior in reference to the results of the more exhaustive experimental results coming from Blackwell et al. experiments [10]. The studies are realised using the Fluent CFD code.
2 Description and Performance of the conventional Savonius rotor.

The Savonius rotor is made from two vertical half-cylinders running around a vertical axis (Figures 1, 2). The speed ratio of a rotor which radius is $R$ is defined as:

$$\lambda = \frac{\omega R}{U}. \quad (1)$$

If the height of the rotor is $H$, the mechanical power $P$ and the aerodynamic torque $M$ for an incident velocity $U$ of the wind can respectively be written as follows:

$$M = C_m \rho R^2 H U^2, \quad (2)$$

$$P = C_p \rho R H U^3. \quad (3)$$

In the case of a 2D-calculation (rotor of infinite height), $P$ and $M$ will be given for each meter of height.

The characteristic curves of the Savonius rotor (power coefficient $C_p$ and torque coefficient $C_m$, towards the speed ratio $\lambda$), coming from experiments are known [21] as reported in figure 2.

In the following, the data coming from experiments of Blackwell et al. [10] are used for the comparison. The authors have run several configurations. The only one using two buckets and both static and dynamic test conditions, refers to configuration n°11, which will be used for the present calculation: $R=0.4512$ m, $r=0.25$ m, $e/d=0.1$. The thickness of the blades is not specified in the study: a thickness of 2mm has been chosen, which corresponds to the thickness of standard aluminum planes. The flow velocity is equal to 7 m/s, which corresponds to a Reynolds number $Re=4.32 \cdot 10^5$.

3 Numerical model.

The numerical model used in this study is a rotor of infinite height. This hypothesis has allowed carrying out the calculations using a bi-dimensional simulation.

The calculation and the post-treatment are defined on the basis of the referenced geometry (Figure 1). A Reynolds Averaged Navier Stokes (RANS) scheme is used, with a finite volume discretisation. The mesh is refined near the walls as shown on figure 3: after a converged solution, a maximum wall value $y^+=\nu y/\nu<15$ is obtained (figure 4), where $\nu$ is the “shear velocity”, $\nu$ is the “kinematic viscosity” of the fluid, and $y$ is the distance between the first and second grid points of the wall; this result is said to be appropriate [22].

For the simulation, a sliding mesh has been used. Two domains have been designed: the first one, including the rotor, is able to move inside the other one, as shown on figure 5. The two domains are separated by an interface where the elements must have roughly the same size (figure 6). The type of cells in the first domain is triangular, whereas classical quadrilateral cells are used in the second domain (exterior domain). Two exterior domains have been tested: a circular one and a rectangular area. In the two cases, about 600000 cells have been generated. Second-order discretisation schemes have been used for the pressure and the velocity computations of the flow (supposed to be incompressible), together with a high Reynolds number two equations turbulence model, namely a $k-\omega$ SST model.
The pressures far away from the rotor are controlled to validate the size of the domain, which is chosen so that values of the pressures far from the rotor are not influenced by the rotor. For example, in the case of a circular domain this size is equal 80.D. Figure 7 illustrates the size of the rectangular domain compared with the size of the rotor. Figure 6 represents the static pressure field, which confirms the appropriate choice of this size in the case of a circular domain because the pressure is constant far from the rotor.

In the following, the pressures on the blades are calculated, which lead to the torque coefficients values and consequently to the power coefficient value for the dynamic cases, according to relations (2) and (3).

4 Results and discussion.

4.1 Static calculation.
Figure 9 presents an example of the flow field in and around a Savonius rotor for a given direction of the wind velocity. It is clearly shown that not only the “advancing” blade produces a logical positive work, but
the “returning” blade, because of the overlap, participates to the flow inside the rotor and then to the running. This phenomenon can be seen for different values of the velocity direction $\theta$. These simulations allow the calculation of the torque coefficient $C_m$ against $\theta$. (figure 10), which is to our knowledge a new result for the literature in the field.

![Flow field around the rotor for $\theta = 45^\circ$](image)

**FIG. 9 – flow field around the rotor for $\theta = 45^\circ$**

![Static torque coefficient vs wind incidence](image)

**FIG. 10 – static torque coefficient vs wind incidence**

We can see that the torque coefficient is always positive, which means that the rotor is able to start whatever the angular position. The results are very close to the experimental results coming from Blackwell et al [10]. The uncertainty of the experiments is not presented in the referred paper but the formula is given, so that it has been possible to represent experimental error bars on fig. 10. Besides, the thickness of the blades, which has probably a great influence on the flow field, is not given by Blackwell et al. Consequently, it is not obvious that the low difference must be attributed to our modelling:

Let us finally notice that the circular domain seems to give better results in comparison with data reported by Blackwell et al [10], which is probably due to the better interface between the two domains where the cells are orthogonal. Then such a domain will be used in the following.

### 4.2. Dynamic calculation.

For the dynamic simulation, a value of the velocity coefficient $\lambda$ is chosen, and consequently $\omega$ is known because $R$ and $U$ are given. The rotor is moved with this rotational velocity $\omega$, and the torque is calculated for different values of the $\theta$ every $1^\circ$, which correspond to a given time step $T$ because of relation (1) where $\omega$ is supposed to be equal to $\Delta \theta / T$. For additional values of the time step, the torque coefficient $C_m$ can be calculated and it is possible to draw a curve giving $C_m$ against the time for the given value of $\lambda$. (figure 11).

![Evolution of the torque coefficient vs time](image)

**FIG. 11 – Evolution of the torque coefficient vs time**

![Power coefficient vs speed ratio](image)

**FIG. 12 – Power coefficient vs speed ratio**

After few revolutions of the rotor, it is shown that $C_m$, depending on time, reaches a constant mean value. This value is collected and corresponds to the given value of $\lambda$. Another calculation is made for another value of $\lambda$ and so on. Results are reported on figure 12. We can see that the numerical results are in good agreement with the data reported by Blackwell et al [10], and seem to be inferior to the uncertainty of these experimental results. The maximum value of the torque coefficient is obtained for a velocity coefficient of about 0.45. The power coefficient $C_p$ is not reported here but is easy to calculate according to relation (3). It
is shown that the maximum value of $C_p$ is obtained for a value $\lambda$ of about 1.0, which corresponds to the nominal point also pointed out by Le Gourrières [22] and many other authors.

5 Conclusion.
A 2-D numerical simulation has been conducted to predict the aerodynamic behavior of a conventional Savonius rotor, either for the static or the dynamic case. The numerical method has been explained, such as the turbulence model. The validity of the wall laws have been discussed. Two domains have been tested: a circular one and a classical rectangular one. The results have been compared to different experiments, particularly those coming from Blackwell et al [10], and appear to be in good agreement with the experimental data; the gap between the results is inferior to the uncertainty of the measurements. In the future, a 3-D calculation should be made and the results will be compared to experiments. The sensitivity to the Reynolds number should be done. Then, it will be possible to improve the performance of the rotor by an appropriate choice of its geometrical parameters.

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References