

INCREASE IN THE SAVONIUS ROTORS EFFICIENCY VIA A PARAMETRIC INVESTIGATION

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Abstract :

The aerodynamic behaviour of slow running wind turbines of Savonius type has been largely studied, but the disparity of these studies makes it difficult to compare the results. Through an exhaustive bibliographical research, it is possible to identify the influent parameters, and to show that the aerodynamic efficiency of the Savonius rotor can be notably improved via a judicious choice of its geometrical parameters. This study suggests to use a double-stepped Savonius rotor with two paddles and two end-plates. The height of the rotor should be twice its diameter. The primary overlap ratio must be between 0.15 and 0.3 times the diameter of the paddle, whereas the secondary overlap ratio should be equal to 0.

This study is followed by a numerical simulation of the flow. The results of the simulation propose the optimal values for the geometrical parameters. This simulation leads us not only to precise the nature of the flow, but also to determine the aerodynamic behaviour of the rotor. The results are compared to experimental data. In particular, a prediction of the aerodynamic torques for few geometrical configurations is given. The influence of a central shaft is studied, such as the presence and the geometry of an external chassis. The influence of the Reynolds number is investigated. These considerations make it possible to define an optimal geometrical configuration.

keywords :

wind energy ; Savonius rotor ; aerodynamics ; numerical simulation ; parametric investigation ; efficiency ; power coefficient

1 Introduction.

When a wind site is chosen to install wind machines in order to produce electricity, it is expected to extract the maximum possible energy from the wind. The choice of an "aerogenerator" should be done via this sole criterion.

Wind turbine are generally designed for a nominal working point, i.e. for a given velocity of the wind which is obviously linked to an attended delivered power. Consequently, the notion of the produced energy, for example for a whole year, is often forgiven ; the notion of installed power, or that of installed power per square-meter of cross wind, are generally preferred. This idea incites the operators to prefer wind machines of higher efficiency for the equipment of wind sites.

The choice of a wind machine is obviously based on its energetic performances. To simplify our presentation, we have drawn the working curves of main conventional wind turbines (figure 1). These curves, extracted from the monograph of Wilson and Lissaman [1], give the power coefficient C_p , ratio of the aerodynamic power of the turbine to the power of the incident wind, as a function the speed ratio λ . λ is also called the velocity coefficient and is equal to the ration of the tip peripheral speed to the wind velocity. The power coefficient is directly linked to the global efficiency of a wind machine.

The curves of figure 1 show that the fast running horizontal axis wind machines (two- or three-bladed airscrew) have incontestably the best efficiencies. Consequently, these machines are systematically chosen for the equipment of wind sites. On an other hand, the Savonius rotor [2], which is a slow running vertical axis wind machine ($\lambda \approx 1.0$) has a rather poor efficiency : $C_p \approx 0.2$.

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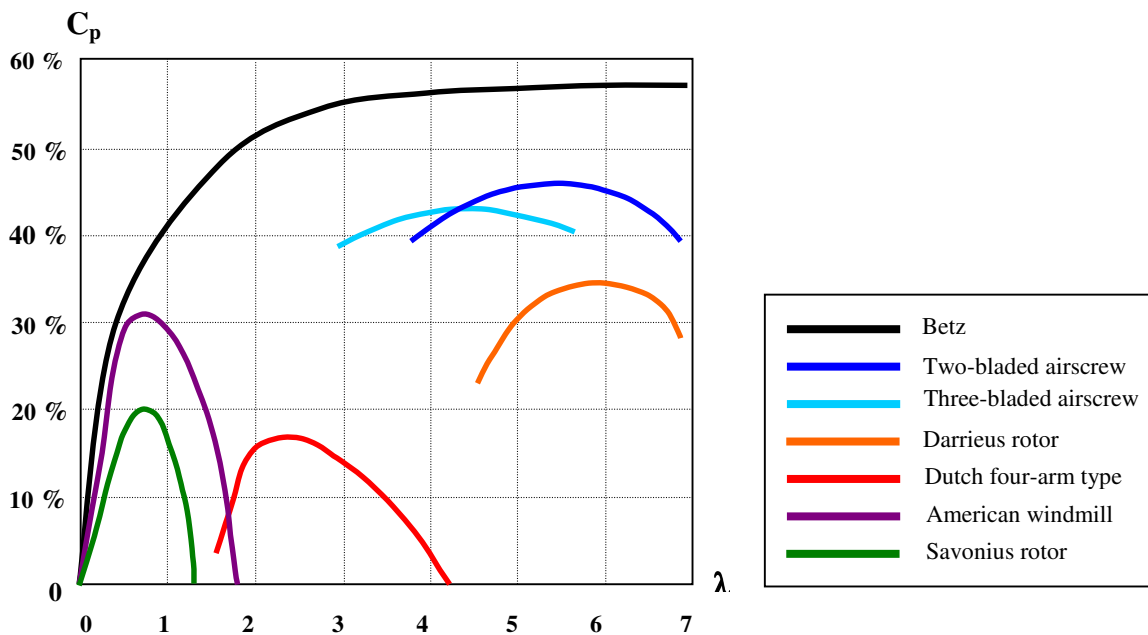


FIG. 1 – Performances of main conventional wind machines [1]

The studies dealing with the performances of Savonius rotors are numerous and various. The reader can refer to Le Gourrières handbook [9] for a clear and a complete description of the expected performances of such a rotor. Some of these studies present global experimental results issued from measurements in situ. For different values of the wind velocity, the power coefficient is given. Nevertheless, it is difficult to compare these results because of the differences in the geometry and dimensions of the rotors, in the experimental conditions or moreover in the Reynolds numbers.

Some studies have been carried out in wind tunnels [10, 11, 12, 13, ...]. Generally, the global performance of a rotor, derived from the conventional Savonius rotor, is presented but no parametric study was really realized. The flow, which is greatly non-stationary, is very complex: the aerodynamic studies are rare and old, and do not permit the prediction of the energetic behaviour of the rotor. Sometimes, some visualisations of the flow in and around the rotor are proposed, but with a poor description of the physical phenomena. However, Chauvin et al. [10] give a precise description of the aerodynamics of the conventional Savonius rotor, obtained by pressure measurements on the paddles.

Numerical simulations have also been carried out on this kind of rotors. These studies include static or dynamic modelling. Nevertheless, the results suffer from a lack of a global description of the rotor. Aldoss et al. [15] used the discrete vortex method to predict the flow around a pair of coupled Savonius rotors. They suggested the reason few numerical studies had been successful was due to the “complexity of the flow pattern about the rotor and to the separation of the flow from the blade surfaces”.

Fujisawa [11] carried out a study comparing experimental results with a numerical study also using the discrete vortex method. He concluded that the numerical calculations were adequate to “predict the basic features of the variation in flow fields with rotor angle”. However, the reproduction of the flow field around a stationary rotor was poor, and Fujisawa supposed that it was due to false assumptions used in the calculations [11]. He suggested that the assumption that the flow was strictly bidimensional was incorrect, and that the separation of flow at the blade tips was not well modelled.

Kawamura et al. [16] investigated numerically the running performance of the rotor, using a domain decomposition method. Two computational domains are used and connected to each other. One domain contains the rotating rotor and the other one contains the fixed walls; both domains have common overlapping regions. The running performance of the Savonius rotor, such as the torque coefficient, is obtained for various tip speed ratios. The effects of the walls on the running performance is also investigated. It is found that the power coefficient can be sensibly raised.

Using a specific comparison method, namely the L-sigma criterion, Menet et al. [3, 4] have shown that despite its poor efficiency, the Savonius rotors are in fact more resistant to mechanical stresses than all fast running wind turbines. Under these circumstances, the corresponding delivered power is largely superior to that of any fast running

wind machine, in the case of using the same intercepted front width of wind, and the same value of the maximal mechanical stress on the paddles or the blades. It is clear that, considering the L-sigma criterion, the Savonius rotor is a better wind machine than all the fast running horizontal axis wind turbines. In fact, the Savonius rotors can be considered to be high productivity and low technicality wind machines. It is probably the reason why they are often used for water pumping, especially in poor countries and in isolated sites [5, 6].

The design of a Savonius rotor is in fact very simple. The whole rotor turning around a vertical axis is composed of two vertical half-cylinders, as shown in figure 2. The movement is due of the difference between the drag on the advancing paddle and the drag on the other one.

Noticing the undisputable advantages, in terms of performances and mechanical behaviour, a prototype of Savonius rotor, designed for measurements in situ, has been built up [7, 8]. The study carried out on this prototype showed that the main problem for the production of "wind electricity" is the design of the generator. This previous consideration constitutes a good justification for additional studies about this kind of rotor.

Through an exhaustive investigation, the influence of geometrical parameters on the efficiency is presented in the second section. In the third section, a numerical approach is used to complete this investigation. Available experimental data are compared to numerical results in order to validate the simulation. The aim is to show the influence of the geometrical parameters on the flow structures in order to increase the efficiency of the Savonius rotors.

2 – Parametric Investigation of Savonius rotors.

Using notations of figure 2, the velocity coefficient is defined as:

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

For a Savonius rotor of height H , a wind of velocity U , the mechanical power P and the mechanical torque on the axis can respectively be written as follows:

$$P = C_p \rho R H U^3, \quad (2)$$

$$\text{and } M = C_m \rho R^2 H U^2, \quad (3)$$

where C_p and C_m are respectively the power coefficient and the torque coefficient.

In the following sections, a rotor is called a *conventional Savonius rotor* if the geometrical parameters a and e are respectively equal to 0 and $\frac{d}{6}$. This rotor has been largely studied [9]. The values of C_p and C_m are experimentally determined as a function of the velocity coefficient λ (figure 3).

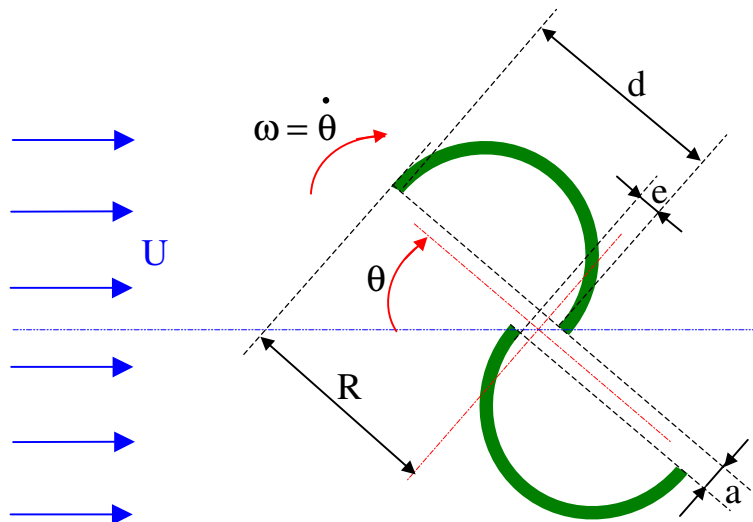


FIG. 2 – Scheme of a Savonius rotor.

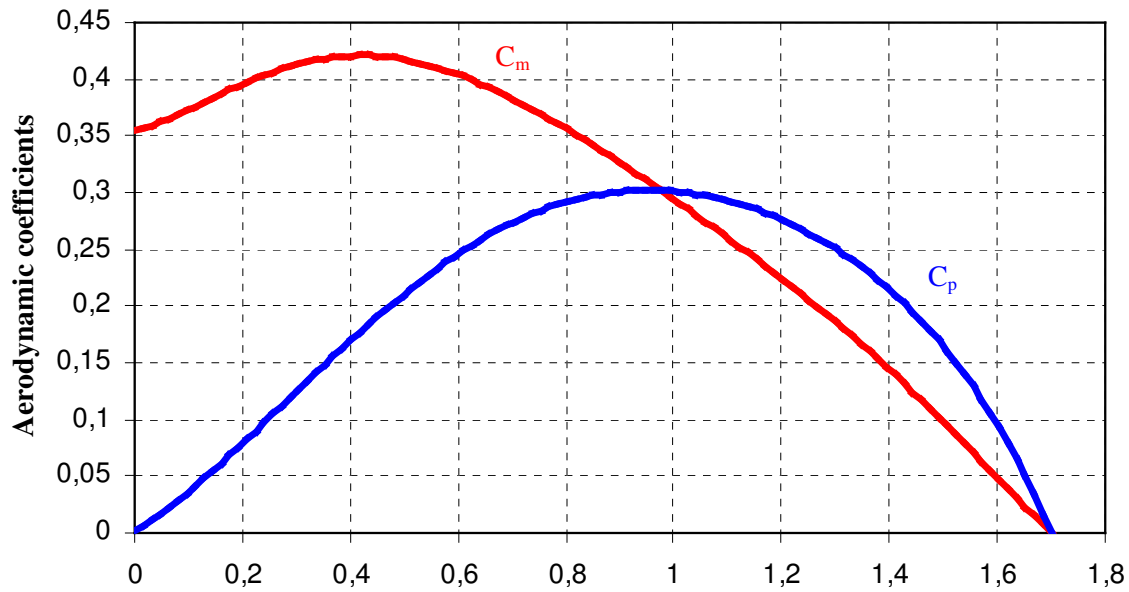


FIG. 3 – Expected performances of the *conventional Savonius rotor* [9].

It is possible to identify few geometrical parameters which should modify sensibly the expected performances represented in figure 3. Table 1 collects the main data which lead to a maximal power coefficient for a rotor of Savonius type. The combination of these results should allow to obtain an optimum Savonius rotor.

In order to verify these hypothesis, a prototype of such a rotor was realized [7, 8]. One can notice that if a double-stepped rotor (each step being staggered from the other with a 90° angle) ensures a sufficient stability of the mechanical torque (figure 4), a higher number of steps is not necessary and should uselessly loads the rotor and raise its inertia. In the same way, a higher number of paddles than 2 no longer raises the efficiency of the rotor, and decreases it in most cases [12].

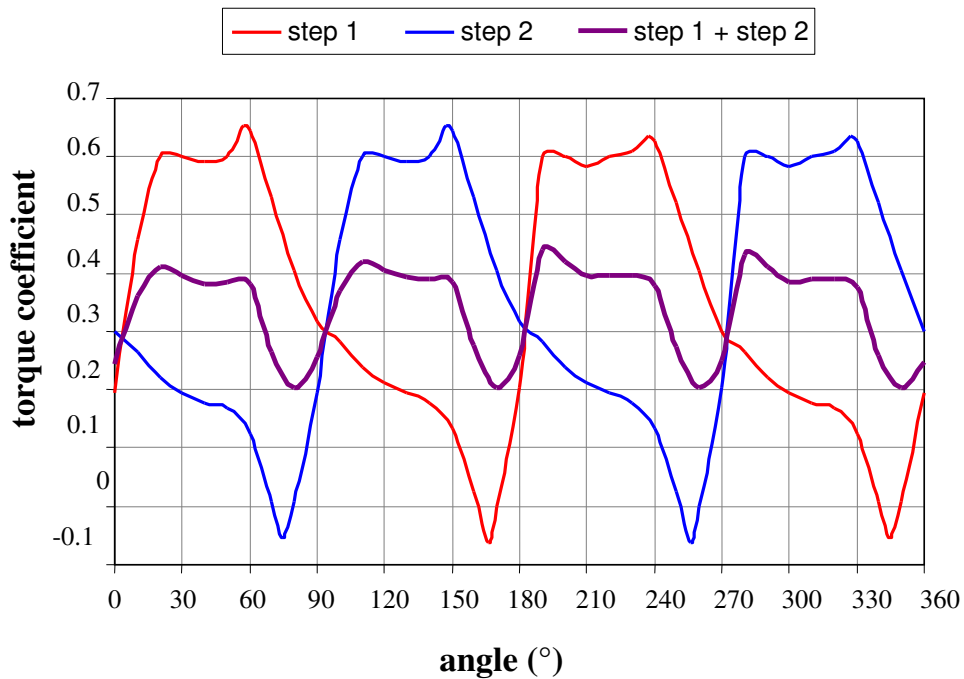


FIG. 4 – Influence of the number of steps on the expected starting torque [7].

In summary [14], an optimum rotor should be a double-stepped rotor, with two paddles equipped with two end-plates which "canalize" the flow inside the rotor. The total height of the rotor should be twice its diameter.

Number of steps	Number of paddles	End-plates radius R_f	Height of the rotor H	Primary overlap e	Secondary overlap a
$2 \rightarrow \infty$	≥ 2	1.1 R	4 R	$0.15 d \rightarrow 0.3 d$	0

TABLE 1 – Optimal values for main geometrical parameters (giving highest values for C_p)

Let us notice that all the geometrical characteristics leading to the *optimal* Savonius rotor are only the ones of an "ideal" rotor, i.e. realized independently from the manufacturing and the use necessities, mainly the ones which require the rotor to be rigidified. In particular, a central shaft seems to insure a better mechanical behaviour, such as an external chassis for the rotor [7]. The influence of these two supplementary geometrical parameters will be studied within a numerical simulation.

3 Numerical model description

The model used in this study is a mono-stepped rotor of infinite height. This hypothesis has allowed to carry out the calculations on the two-dimensional model represented in figure 2. Three geometric parameters are selected for the numerical study. These parameters are :

- the overlap ratio, namely e/d . This parameter influences the structure of the flow inside the rotor and consequently its aerodynamic performances;
- the diameter of the central shaft, namely e' . This diameter is often necessary for the mechanical design, but it could create a blockage effect inside the rotor;
- the geometry of the external chassis which permits to rigidify the rotor but generates in the same time a wake degrading the flow entering the rotor.

The influence of the dynamic parameter, namely the Reynolds number Re_D , based on the rotor diameter, has also been investigated.

A numerical model is then defined on the basis of the reference geometry (Figure 2). The finite volume mesh obtained is about 50 000 cells large and made of quadrilaterals. The mesh is finer near the paddles as can be seen in figure 5.

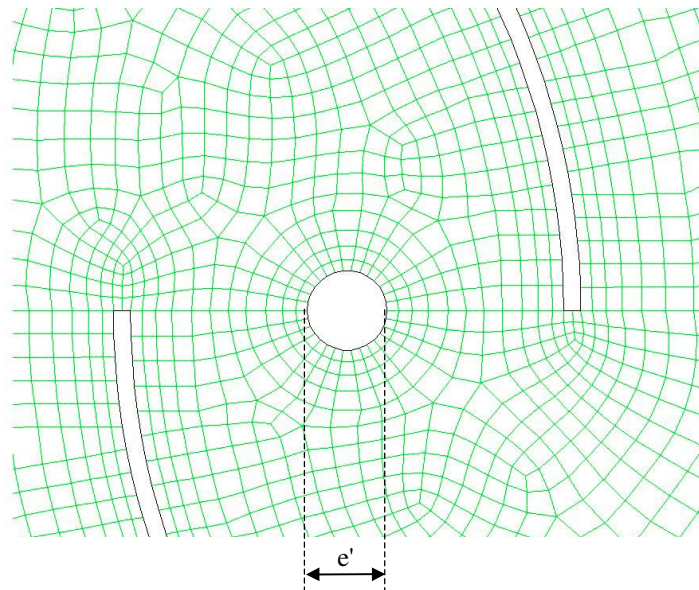


FIG. 5 - The mesh near the paddles.

The computations rely on the Navier-Stokes solver package Fluent 6.0. For more information about the meshing and the simulation, see the report of Cailleau et al., 2002 (Cailleau N., Cottier F., Laville A., Piget B.: "Optimisation d'une éolienne lente à axe vertical en vue de la production locale d'électricité", rapport ENSIAME 02PLPENS06, 2003, Valenciennes France).

In order to achieve accurate results without excessive time consuming computations, first-order discretisation schemes have been used for the pressure and the velocity computations of an incompressible flow, together with a high Reynolds number two equations turbulence model.

The calculations have been realized using a static calculation (rotor supposed to be fixed whatever the wind direction) and also a dynamic calculation; in this second case, the velocity coefficient was equal to 1.0 (nominal working point in accordance with figure 3). These calculations are continued until the residual values (variations in certain chosen parameters e.g. velocity in the wind direction), have all dropped below 1×10^{-3} ; then the simulation is assumed to have reached convergence.

A sensitivity study has been carried out to verify the model accuracy between a static simulation and a dynamic one. To do so, a static simulation of the flow around the *conventional* Savonius rotor ($e/d = 0.242$; $a = 0$; no central shaft) has allowed to determine the pressure distribution on the paddles. Then the static torque has been calculated as a function of the wind velocity angle θ (figure 6). These numerical results are compared to the experimental data [9]. The present simulation gives satisfactory results since the differences between the experimental data and the numerical simulation are always inferior to 10%, except for angles θ around 0° and 180° where a great instability of the torque is observed.

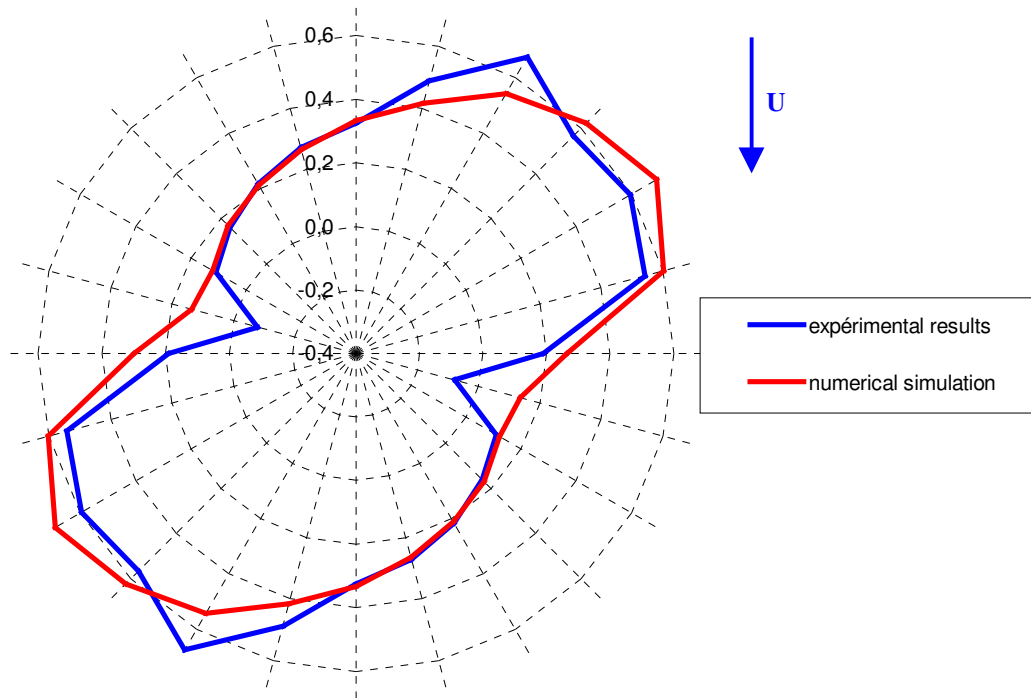


FIG. 6 – Torque coefficient (static calculation)
(Reynolds number : $Re_D=1.56 \times 10^5$)

In a second step, a dynamic calculation (rotating rotor) has been carried out for the same value of the Reynolds number: $Re_D=1.56 \times 10^5$. In this study, the velocity coefficient is set equal to 1.0. The torque coefficient C_m has been evaluated by calculating the average value of the torque on a whole revolution of the rotor. The results are compared to the ones given with the static calculation. The difference between the two curves generally not exceeds 2% whatever the angle θ . Consequently, only static simulations are used in the further calculations. A static study represents then less consuming time calculations with an equivalent precision for a parametric evaluation.

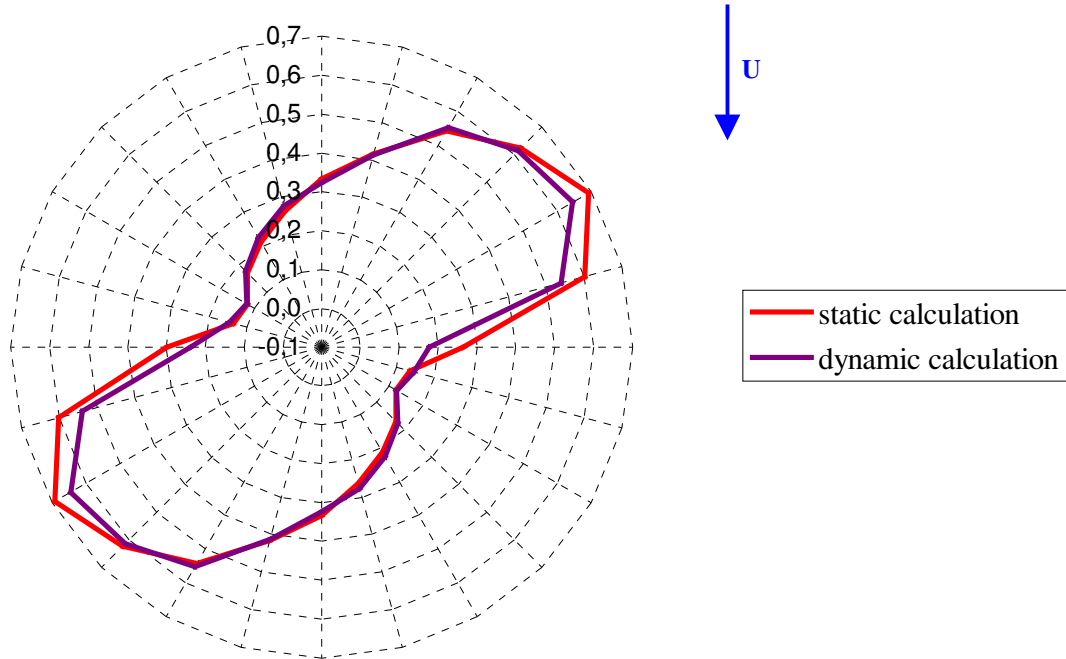


FIG. 7 – dynamic torque coefficient ($Re_D=1.56 \times 10^5$; $\lambda=1.0$)

4 Numerical study results

4.1 Influence of the overlap ratio : e/d .

In order to estimate the influence of the overlap e on the global efficiency of different rotors, a "static" simulation is used to calculate the torque coefficients. In fact, the overlap ratio e/d is preferred because it is a non-dimensional parameter. Different values of this ratio are used. The diameter D of the rotor is changed each time in order to maintain the Reynolds number Re_D equal to 1.56×10^5 , as in the previous calculation. Table 2 collects the global results obtained for a wind angle $\theta = 90^\circ$ (figure 2). The results confirm without any ambiguity that the conventional value $e/d=0,242$ is an optimal value.

Overlap ratio: e/d	0.100	0.129	0.160	0.220	0.242	0.280	0.320	0.500
Torque coefficient: C_m	0.24	0.29	0.27	0.28	0.33	0.27	0.24	0.18

TABLE 2 – Influence of the overlap ratio on the torque coefficient C_m

4.2 Influence of the shaft.

A static calculation of the flow around a conventional Savonius rotor with a central shaft should give inaccurate results. In fact, the rotation of this shaft induces obviously an aerodynamic behaviour very different from that of a single rotor without shaft. It is the reason why the present simulation has been carried out using a dynamic calculation. The velocity coefficient is here equal to 1.0.

Only two shafts (diameter e') have been tested. The aim was not to determine the exact influence of the shaft, but to estimate the new overlap ratio for a rotor with a shaft inside. The diameter of this shaft has been fixed to the value $e'=e/5$. The case 1 ($e/d=0,242$) corresponds to the previous optimal overlap ratio (cf. §. 3.4), whereas the case 2 fixes the ratio $(e-e')/d$ equal to 0.242 to take into account the blockage effect induced by the shaft. In the two cases, the Reynolds number is equal to $1,56 \cdot 10^5$. These two cases are compared with the case of a rotor without shaft, i.e. $e'=0$. The results of these simulations are reported on figure 8.

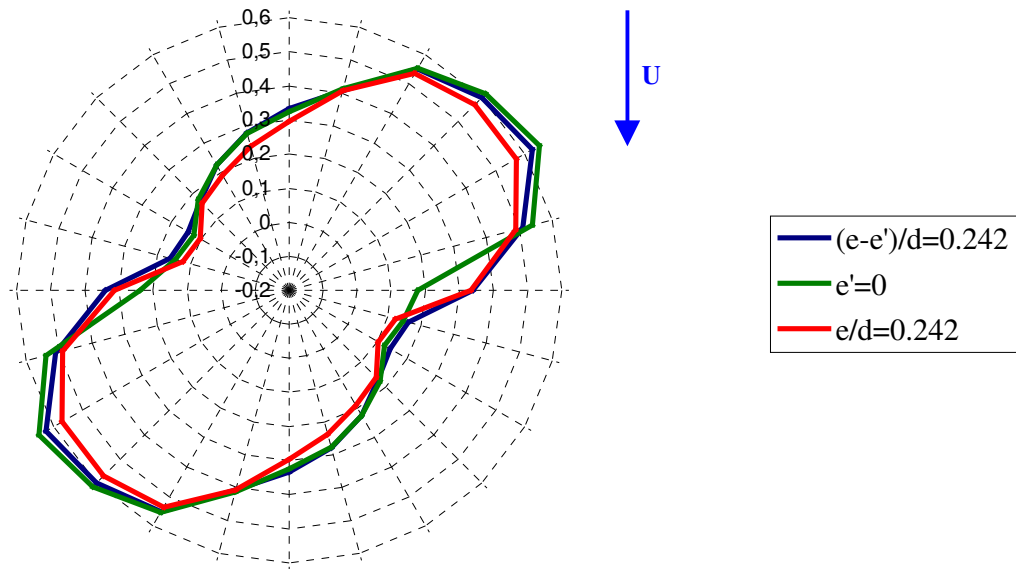


FIG. 8 – Influence of the shaft on the dynamic torque coefficient ($Re_D=1.56 \times 10^5$)

It is clear that a shaft does not perturb the internal flow if the paddles are disposed with an overlap which must be re-calculated as shown above. A positive effect must even be present for few angular positions (figure 8).

Figures 9 and 10 give a representation of the pressure distributions and of the flow field inside the Savonius rotor for the optimal configuration $(e-e')/d=0.242$.

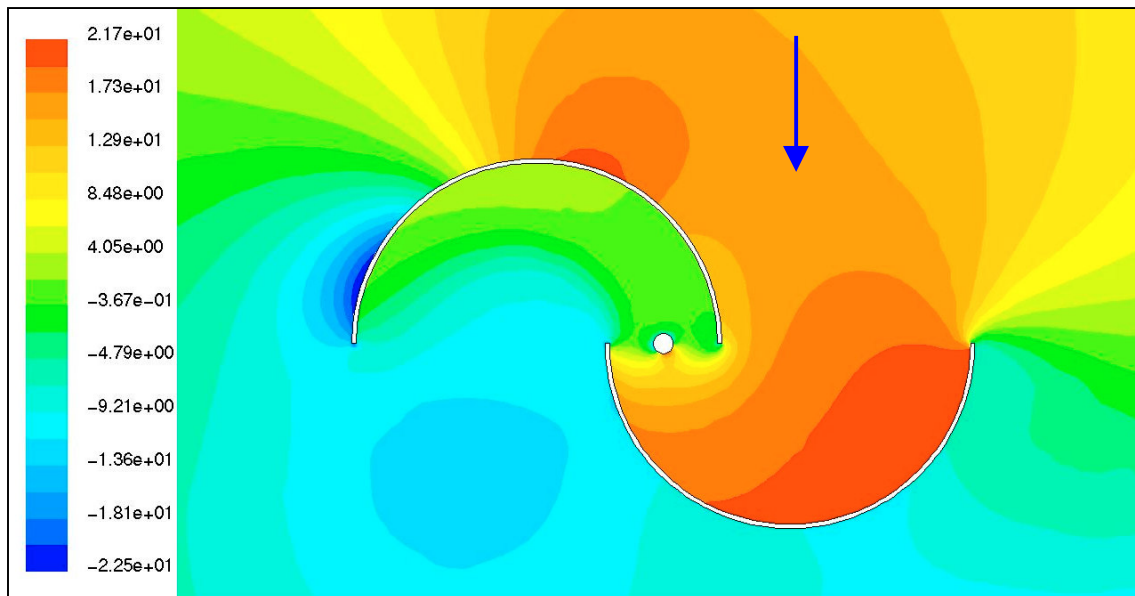


FIG. 9 – Pressures distribution for $(e-e')/d=0.242$ and $Re_D=1.56 \times 10^5$
(unit : Pascal)

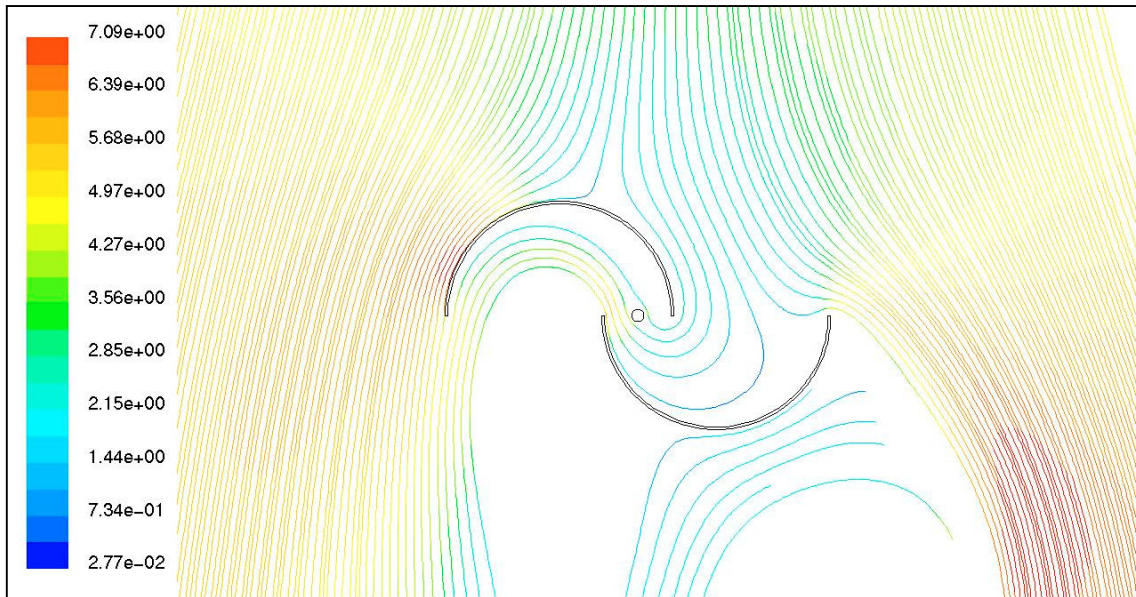


FIG. 10 – Example of velocity field for $(e-e')/d=0.242$ and $Re_D=1.56 \times 10^5$, i.e. $U=5\text{m/s}$ (unit : m/s)

4.3 Influence of a chassis.

A systematic study has been made with an external chassis around the rotor, in order to point out the possible decrease of the aerodynamic efficiency of the rotor (wake effect). Several chassis have been studied, as shown in the report of Cailleau et al., 2002 (Cailleau N., Cottier F., Laville A., Piget B.: "Optimisation d'une éolienne lente à axe vertical en vue de la production locale d'électricité", rapport ENSIAME 02PLPENS06, 2003, Valenciennes France).

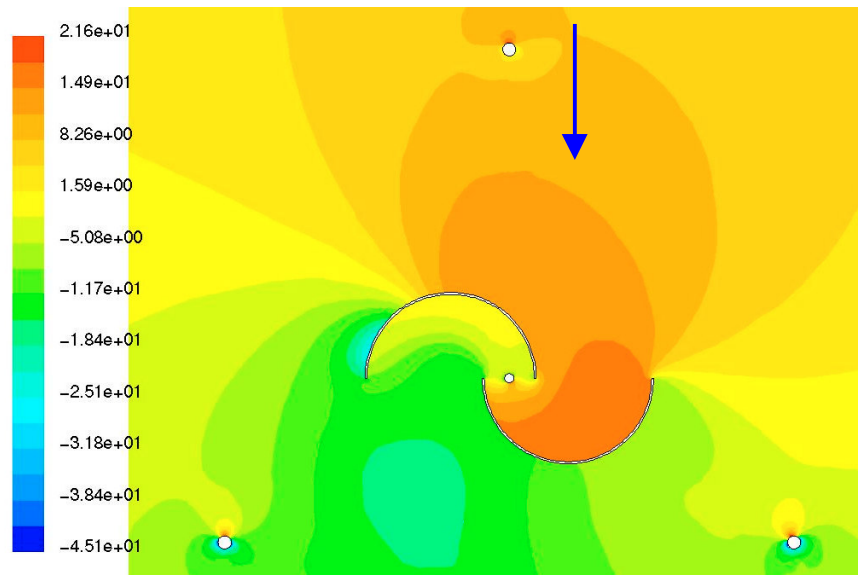


FIG. 11 – Pressure distribution for a rotor with a modelled chassis - $Re_D=1.56 \times 10^5$, i.e. $U=5\text{m/s}$ (unit : m/s)

A three-feet pyramidal chassis has been chosen for the rotor, but in the 2-D simulation, the distance between each foot of the chassis and the axis of the rotor is about 500 mm (mean distance for the whole chassis). Although it is shown that the flow is not greatly influenced by the presence of the chassis (see the report referenced above), a mechanical torque is induced because of the disymetrical pressure distribution (figure 11) , particularly for the angles where a foot is present. The calculation of the dynamical torque is reported on figure 12, and should be compared with the values reported on figure 7.

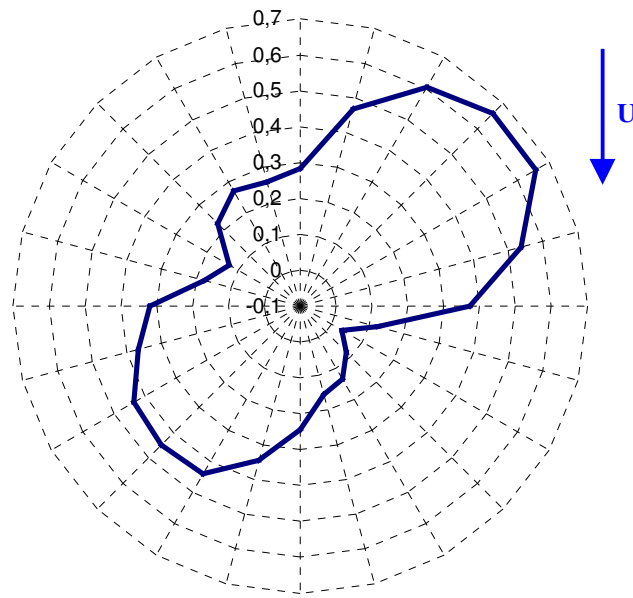


FIG. 12 – Dynamic torque coefficient for a rotor with a modelled chassis - $Re_D=1.56 \times 10^5$. (i.e. $U=5\text{m/s}$)

4.4 Influence of the Reynolds number.

A systematic calculation has been made to evaluate the influence of the Reynolds number for the optimal rotor (parts 2.3, 3.4, 3.5). The calculation has been made at the nominal working point $\lambda=1.0$ (figure 3) and for $\theta = 90^\circ$. This study shows that the influence of the Reynolds number on the torque coefficient and the power coefficient is always lower than 3% in the studied range of Reynolds numbers ($1 \times 10^5 < Re_D < 5 \times 10^5$). The results are compiled in figure 13.

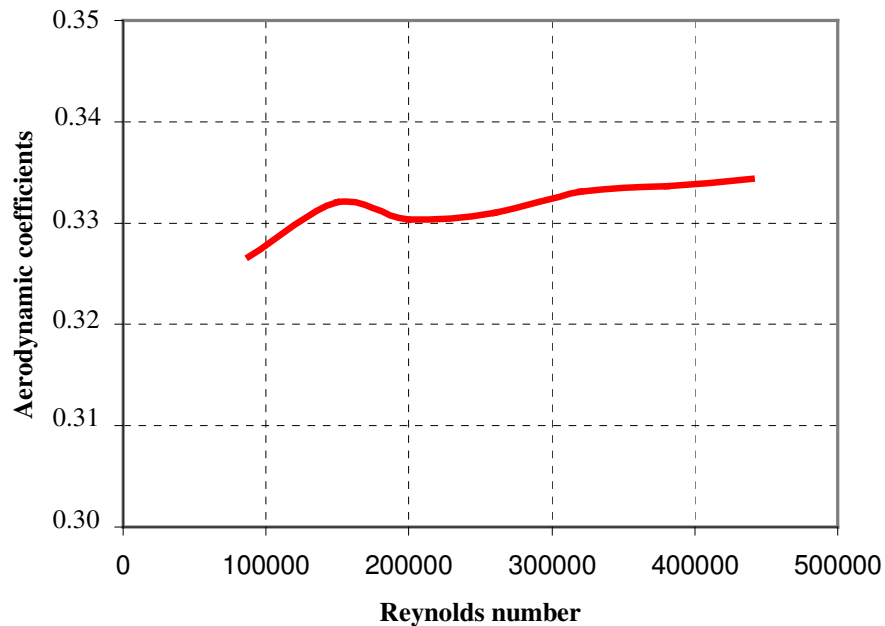


FIG. 13 – Influence of the Reynolds number on the aerodynamic coefficients.

5 Conclusions

The present study, destined to precise the aerodynamic behaviour of Savonius rotors, was realized in two parts. First a bibliographical study has identified the main influent geometrical parameters. Then a numerical simulation has estimated this influence and proposed optimal values for these geometrical parameters.

The results are incontestably higher values of the power coefficient i.e. the aerodynamic efficiency of the rotor.

In the following, it will be obviously necessary to develop a 3-D simulation and to propose other forms of paddles to increase the global efficiency of such a rotor.

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