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Effects of the duct thrust on the performance of ducted wind turbines

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ABSTRACT

This work investigates the performance of ducted wind turbines (DWTs) through the axial momentum theory (AMT) as well as through a semi-analytical approach. Although the AMT points out that the duct thrust plays a key role in the enhancement of the power extraction, it does not allow for the evaluation of the flow field around the duct. For this reason, a semi-analytical model is also used to investigate the local and global features of the flow through a DWT. In comparison to the AMT, the proposed semi-analytical method can properly evaluate the performance of the device for each prescribed rotor load distribution and duct geometry. Moreover, in comparison to other linearised methods, this approach fully takes into account the wake rotation and divergence, and the mutual interaction between the turbine and the shroud. The analysis shows the opportunity to significantly increase the power output by enclosing the turbine in a duct and that the growth in the duct thrust has a beneficial effect onto the device performance. Finally, some insights on the changes occurring to the performance coefficients with the rotor thrust and the duct camber are obtained through a close inspection of the local features of the flow field.

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1. Introduction

Nowadays, the most important research lines dealing with wind technology concentrate on a more efficient exploitation of the available wind resources, an objective typically achieved both through the improvement of conventional systems as well as through the development of new and unconventional devices. In this context, ducting a wind turbine (see Fig. 1) can allow a gain in the power coefficient in comparison with an open one characterised by the same rotor diameter, thus improving the amount of energy extraction. Moreover, with the help of inflatable shrouds (see for instance Samson et al. [1] and Samson and Katebi [2]), ducted wind turbines (also termed diffuser augmented wind turbines or shrouded wind turbines) could also be employed at high altitude where the energy output can considerably be increased thanks to the high value of the wind speed there available. In fact, as well-known, a cubic-like power dependence exists between the power output of the turbine and the wind velocity. Furthermore, ducted buoyant wind turbines, which also offer the opportunity to be installed in logistically challenging sites or with poor ground winds, are characterised by a low cost (mainly due to the absence of the tower) and by a reduced impact on the landscape. A further advantage that can be gained by ducting the turbine is the reduction of the tip losses and of the related noises [3].

In the past years DWTs were only considered for large power and ground applications, so that, due to the high cost and weight of the duct and of the tower, this kind of turbines has never experienced a wide diffusion and/or a commercial success. The great weight of the duct has also prevented the building of sufficiently high towers, so that the energy output was small due to the low value of the available wind speed. Due to the high cost of the device it was also very difficult to propose an economically appealing product. Actually, most designers were trying to obtain the largest rise in the power coefficient by increasing the duct area ratio. However, ducts characterised by a large rotor to outlet area ratio frequently undergo boundary layer separation along the diffuser inner walls. Obviously, this separation also reduced the effective duct expansion rate thus preventing the desired gain in the power coefficient. Some solutions, mainly based on the blowing and swirling of the boundary layer [4,5], were also proposed with moderate success.

For small size turbines the weight and consequently the cost of the duct and of the tower have a relative minor impact on the overall cost, so that sufficiently high towers and ducts with a

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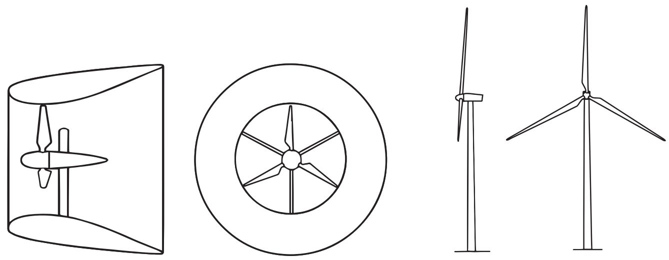

Fig. 1. Sketch of a ducted (left) and an open (right) wind turbine.

reasonable expansion rate can be employed. For this reason, DWTs have recently gained a new attention not only in the field of high altitude buoyant devices, but also for small size applications. Evidences of this are witnessed by the fact that more and more research programs are focused on DWTs and some companies have already developed commercial products.

In addition to the shortcomings associated with the high cost of the duct and of the tower, the spreading of the DWT technology has also been prevented by the lack of fast and accurate analysis models to be efficiently used for design purposes. Mainly, the study of the flow past a DWT has been carried out by experimental means, even if some analysis tools based on the classical AMT have been developed over the years. A first theoretical and experimental analysis of the ducted wind turbine operating principles can be found in the pioneering works of Sanuki [6] and Iwasaki [7]. Lilley and Rainbird [8] carried out a preliminary theoretical study based on the momentum and vortex theories. They found that the gain in the power extraction with a suitable design of the duct can be at least 65 percent, as compared to the open rotor configuration with the same diameter. In the seventies, several design experiences and wind tunnel investigations were carried out at the research department of the Grumman Aerospace Corporation (see for instance [4,9–12]). These works were mainly devoted to the development of boundary layer controlled diffusers, to the implementation of an axial momentum theory for DWT and to the analysis of the economic feasibility of the DWT concept. They concluded that this kind of machine could be economically attractive for small rated power output when a light fibreglass reinforced plastics construction of the diffuser is adopted. Further works based on the combined use of the axial momentum theory and of experimental means are those developed in Israel during the sixties and seventies [5,13–15]. With the help of the AMT, de Vries [3] presented an extensive analysis of DWTs which constituted the basis for many future works. Koras and Georgalas [16] and Georgalas et al. [17] calculated the performance of a horizontal axis 3–bladed ducted wind turbine using the lifting-line theory for the rotor modelling whilst the duct flow was represented as the superposition of ring vortices and sources. The main limitation of this work is that the aerodynamic interaction between the duct and the rotor is completely neglected, so that the model can be successfully applied only for device characterised by a huge value of the rotor tip gap. Successively, Politis and Koras [18] improved the aforementioned model by removing any assumptions regarding the tip clearance. However, their method can only be applied to lightly loaded rotors since the radial velocity induced by the duct and the rotor vorticity distribution is neglected. This means that the wake divergence is completely disregarded, an approximation that allows to simply represent the rotor vortex wake through a general helicoidal surface and the duct trailing vortex sheet by means of a cylindrical surface. Introducing an actuator disk model in a CFD based method and also with the help of an AMT approach, Hansen et al. [19] proved that the ratio between the power coefficients of a ducted and an open wind turbine with the same rotor thrust coefficient is equal to the ratio of the mass flows swallowed by the two machines. So that, if the duct induces a gain in the mass flow, then a proportional increase in the power output can be obtained by the DWT in comparison to the bare turbine. van Bussel [20] strived to develop an axial momentum theory for DWT having a close equivalence with momentum theory for bare turbines. He compared the result of his theory with those obtained by Hansen et al. [19] and also developed an extensive review and comparison of the available experimental data. The conclusions of the van Bussel [20] dissertation were that the specific energy extraction is identical for a ducted and an open wind turbine, that the DWT can achieve an overall performance increase proportional to the gain in the mass flow swallowed by the device and, finally, that a significant enhancement of the turbine power coefficient can be obtained only with a very strong reduction of the static pressure at the duct exit. Wang and Chen [21] studied the effects of the blade number on the ducted wind turbine performance with a CFD based method. Widnall [22] proposed a vortex method to solve the incompressible potential-flow past a DWT. With this approach a uniform change in static and stagnation pressure across the turbine disk is assumed and the slipstream divergence is also neglected. Aranake et al. [23] performed computational analysis of diffuser-augmented turbines using Reynolds Averaged Navier–Stokes equations supplemented with a transition model. McLaren-Gow et al. [24] developed a panel method capable to model the performance of a turbine ducted with a thin ring wing. The model was used to investigate the performance of three duct shapes with different camber. Jafari and Kosasih [25] analysed, through CFD techniques, the performance of an AMPAIR 300 wind turbine shrouded with diffusers of different shapes. The study focused on the effects of the diffuser length and area ratio on the performance enhancement. Tavares Dias do Rio Vaz et al. [26] adopted a Blade Element Method (BEM) approach to the analysis of DWTs. The model is characterised by a low computational cost and also shows a good agreement with the available experimental data. However, their approach cannot explicitly predict the velocity induced by the diffuser so that a data transfer from experiments or CFD is needed.

A special kind of ducted wind turbine, the so-called “flanged” wind turbine, also exists. In those machines the flange generates a large scale flow separation region behind it where a very low and unsteady pressure zone consequently appears. In this way a gain in the mass flow swallowed by the rotor and in the power output seems obtainable. In the last years several studies dealing with this topic have been proposed, see for example [27–35], but this list should be not considered as exhaustive.

Not disregarding experimental and CFD based methods, from the above literature review, it clearly appears that the axial momentum theory is still the most employed approach to analyse the performance of ducted wind turbines. Moreover, thanks to its low computational cost, the AMT has been also extensively adopted for design purposes. However, as described later on in Section §2 (where a review and some new formulations of the AMT for DWTs are reported), this method does not offer the opportunity to directly estimate the performance of the device for a prescribed rotor thrust coefficient and a given geometry of the duct. For this reason, the present paper also employs the nonlinear and semi-analytical actuator disk method proposed by Bontempo and Manna [36,37,50,51] and Bontempo et al. [38–41] for the analysis of the flow past DWT (see Section 3 for a brief description of the method). Compared to the AMT, the advanced nonlinear theory can directly evaluate the flow field around the duct and the performance of the device for each prescribed rotor thrust coefficient and duct geometry. Moreover, in comparison to other linearised

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