State of the Art in the Optimisation of Wind Turbine Performance Using CFD

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Abstract:	Wind energy has received increasing attention in recent years due to its sustainability and geographically wide availability. The efficiency of wind energy utilisation highly depends on the performance of wind turbines, which convert the kinetic energy in wind into electrical energy. In order to optimise wind turbine performance and reduce the cost of next-generation wind turbines, it is crucial to have a view of the state of the art in the key aspects on the performance optimisation of wind turbines using CFD (Computational Fluid Dynamics), which has attracted enormous interest in the development of next-generation wind turbines in recent years. This paper presents a comprehensive review of the state-of-the-art progress on optimisation of wind turbine performance using CFD, reviewing the objective functions to judge the performance of wind turbine, CFD approaches applied in the simulation of wind turbines and optimisation algorithms for wind turbine performance. This paper has been written for both researchers new to this research area by summarising underlying theory whilst presenting a comprehensive review on the up-to-date studies, and experts in the field of study by collecting a comprehensive list of related references where the details of computational methods that have been employed lately can be obtained.
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Author Comments:	This paper practically reviewed CFD (Computational Fluid Dynamics) modelling and its application on the performance optimisation of WTs (wind turbines) for the first time. This paper has been written for both researchers new to this research area by summarising underlying theory whilst presenting a comprehensive review on the up-to-date studies, and experts in the field of study by collecting a comprehensive list of related references where the details of computational methods that have been employed lately can be obtained which resulted in prospecting of high citations.

State of the art in the optimisation of wind turbine performance using CFD

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Abstract

Wind energy has received increasing attention in recent years due to its sustainability and geographically wide availability. The efficiency of wind energy utilisation highly depends on the performance of wind turbines, which convert the kinetic energy in wind into electrical energy. In order to optimise wind turbine performance and reduce the cost of next-generation wind turbines, it is crucial to have a view of the state of the art in the key aspects on the performance optimisation of wind turbines using CFD (Computational Fluid Dynamics), which has attracted enormous interest in the development of next-generation wind turbines in recent years. This paper presents a comprehensive review of the state-of-the-art progress on optimisation of wind turbine performance using CFD, reviewing the objective functions to judge the performance of wind turbine, CFD approaches applied in the simulation of wind turbines and optimisation algorithms for wind turbine performance. This paper has been written for both researchers new to this research area by summarising underlying theory whilst presenting a comprehensive review on the up-to-date studies, and experts in the field of study by collecting a comprehensive list of related references where the details of computational methods that have been employed lately can be obtained.

Keywords: Wind energy, Wind turbine, Optimisation, Computational Fluid Dynamics (CFD), Optimisation algorithm, Objective function

1. Introduction

The rapid consumption of energy over the past two decades, especially in developing countries, has rapidly increased the depletion of traditional fossil fuel resources and caused significant environmental pollutions. Therefore, in recent years, significant efforts have been devoted to replace traditional fossil fuels with clean renewable energies. Wind energy, a very important branch of clean energy, has gained remarkable attention due to its geographically wide availability and zero pollution [1, 2]. Unlike traditional fossil fuels, the reserve of wind energy is principally endless. A major utilisation of wind energy is by WT (Wind Turbine), a type of device that directly converts the kinetic energy of wind into controllable power such as electricity through the wind-turbine interactions [3]. To this end, the efficiency of wind energy utilisation is highly dependent on the performance of the WT, which should be optimised for maximum wind energy conversion.

The working principle of WTs can be generally described as follows. Driven by the pressure gradient and viscous boundary layer, WT blades are forced by the air to move continuously and part of wind kinetic energy is then converted into the mechanical energy of the turbine [4]. With such produced mechanical energy, WT can generate controllable energies. Thus, the performance of a WT is mainly related to the fluid-structure interactions, which are largely affected by the geometry and materials of the WT [5]. A WT with better geometry and lighter but strong enough materials can convert a greater percentage of wind kinetic into mechanical energy and therefore reduce the unit price of wind power.

The fluid-structure interactions between the wind and the turbine are rather complex, usually involving the complicated inertial movement of the turbine [6,7], turbulent air flow around the turbine [8] and sometimes even gas compressibility [9, 10], which poses great challenges to theoretical studies. Therefore, experimental testing and numerical simulation have been extensively applied to the investigation of the performance optimisation of WTs. In the early stage of performance optimisation of WTs, restricted by the computational resources and theoretical development, most scientific studies and practical exploration of performance optimisation for WTs were conducted by experiments through the trial-and-error approach [11-13]. However, such optimisation strategy is highly time-consuming and costly. With the growth in turbine size, the experimental approach becomes increasingly unaffordable. With the rapid development of computer hardware and numerical algorithms in recent years, numerical simulation has become dominant in the performance optimisation for WTs, which reduces the development cycle significantly [14].

Several numerical approaches have been applied to the performance optimisation of WTs, such as BEM (Blade Element Momentum) [12-14] and CFD (Computational Fluid Dynamics) [15]. BEM is fast in predicting aerodynamic performance and characteristics; however, its results highly depend on the accuracy of the 2D airfoil aerodynamic data, which are difficult to obtain in some cases. CFD is a numerical method that virtually obtains the flow field around the turbine, and it is capable of providing detailed information on air flow and forces on the turbine, making it a valuable tool to predict the aerodynamic performance of WT blades and visualise the flow fields around the blades. CFD has also been deemed as a promising tool to optimize turbine performance accurately due to its high fidelity [16]. A considerable amount of studies and applications have been dedicated to the performance optimisation of WTs using CFD [17]. Thus, it is highly necessary to review the state-of-the-art progress in this area and point out possible future directions.

Due to the complex aerodynamic shape of WT blades and the rotation of the blades, CFD modelling of WTs is quite challenging and needs special considerations. In general, there are two main approaches to model the rotation of WT blades in CFD, i.e. reference frame [18] and dynamic mesh [19]. In the reference frame scheme, WT blades and pre-generated mesh across the flow field do not move and the flow of the air is transferred to the turbine referenced coordinate [14, 20]. Due to its relatively simple numerical treatment and low computational requirement, the reference frame approach has been widely used in the CFD modelling of WTs [21-23]. However, such approach can only be applied to steady state, and the transient movement of the blades cannot be correctly modelled. The dynamic mesh approach, in which the change of movement of WT blades due to the simultaneous change of air condition can be accurately captured, is deemed more accurate for modelling the transient movement of the blades. The trade-off of the dynamic mesh is its highly computational expenses, as the computational mesh needs to be re-generated at every time step [24, 25]. In this paper, a detailed summary of these two CFD approaches for modelling WTs is presented, and the difference, advantages and disadvantages, experimental validation and other aspects are discussed.

So far few review papers regarding this exciting topic are published. Bai and Wang [14] investigated experimental methods and numerical approaches for estimating aerodynamic performance (such as BEM, Enhanced BEM and CFD) for HAWTs (Horizontal Axis Wind Turbines). Bhutta group [26] reviewed several configuration and design methods of VAWTs (Vertical Axis Wind Turbines). Akwa et al. [27] presented a review on the performance of Savonius WTs. However, the CFD-based performance optimisation of WTs is not covered by these papers. To advance the progress on the improvement of WT performance, it is crucial to have a view of recent development in this field. Therefore, in this paper, a comprehensive review on CFD-based performance optimisation of WTs is presented.

This paper is structured as follows. Section 2 reviews the CFD modelling of WTs, including the geometry, meshes, boundary conditions, turbulence model, discretization method and treatment of blade rotation used in the CFD modelling as well as the latest application of CFD on WTs. Sections 3 and 4 review the objective functions and algorithms used in the optimisation of WTs, respectively. Section 5 reviews the up-to-date activities on CFD-based performance optimisation of WTs. Section 6 presents a critical discussion of perspectives for future studies in performance optimisation of WTs using CFD, followed by conclusions in Section 7.

2. CFD (Computational Fluid Dynamics) modelling

Due to the advancement of computing resources, CFD has been receiving extensive attention in recent years. CFD is a promising and valuable tool for simulating the aerodynamic characteristics of WT blades and visualising flow fields as well as testing new designs. It provides the flow motion around the blades through solving both continuity and momentum (Navier-Stokes) equations [28-33].

Having identified the problem to solve, there are three main steps in the CFD modelling, i.e. pre-processing, solving and post-processing, as depicted in Fig.1.

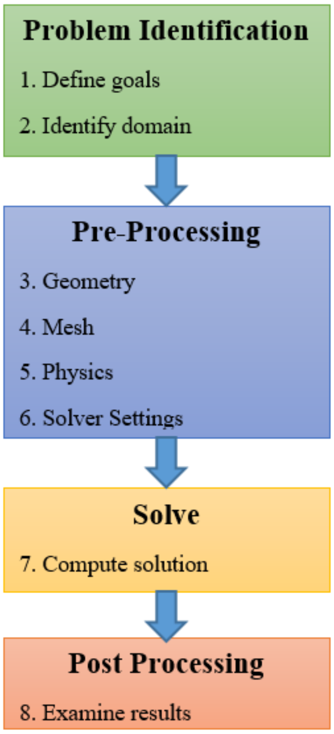

Figure 1. Main steps in CFD modelling

The pre-processing stage includes geometry creation, mesh generation, physics definition and solver settings. At the solving stage, Navier-Stokes equations are generally solved with some turbulence modelling to take into account the effects of turbulence. The post-processing stage is used for examining the results with various techniques, such as contour plots, streamlines and vector plots [34-40].

2.1. Geometry

To perform CFD modelling of WT blades, the blade geometry needs to be exactly described in a digitised format. WT blades generally have complex geometric shapes with varied spanwise cross-sectional information, i.e. airfoil shape, twist angle and chord distributions. WT blade geometry is generally constructed using CAD (Computer Aided Design) software, such as CATIA [41, 42] and SolidWorks [43, 44].

2.2. Mesh

Meshing is a critical part of the CFD modelling and has significant impact on the computational time. It is quite challenging to generate an appropriate mesh for the CFD modelling of WTs due to the complex aerodynamic shape of WT blades. The types of CFD meshes can be roughly categorized into three groups, i.e. structured, unstructured and hybrid meshes.

2.2.1. Structured mesh

In the structured mesh, connection of grids is regular and abutting elements are in particular order. The rectangular and hexahedral grids are typical 2D and 3D structured mesh, respectively, and an example of 2D structured mesh is depicted in Fig. 2 [45]. Structured mesh has advantages in high resolution, easy convergence and low memory usage; however, it is time-consuming and difficult to generate in cases of sophisticated geometries, e.g. highly twisted blades.

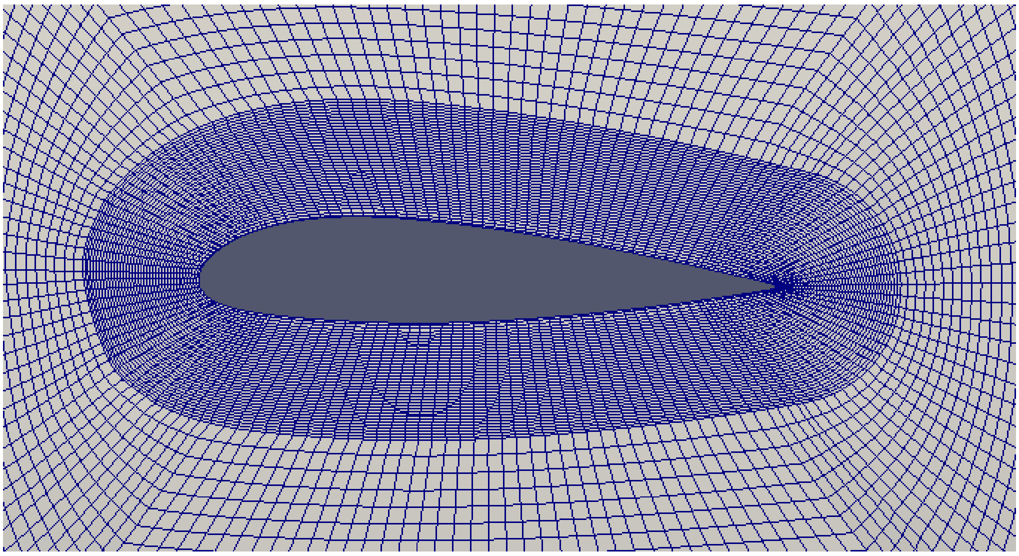

Figure 2. Structured mesh (Reproduced from Ref. [45])

2.2.2. Unstructured Meshes

Unstructured mesh refers to the mesh in which the connection of adjacent grids is irregular, and an example of unstructured mesh used in the CFD modelling of WTs is depicted in Fig. 3 [46]. The main advantage of unstructured mesh is its ease of mesh generation for sophisticated geometry; however, it consumes more computational time, as it generally results in higher cell count than structured mesh when filling the same volume.

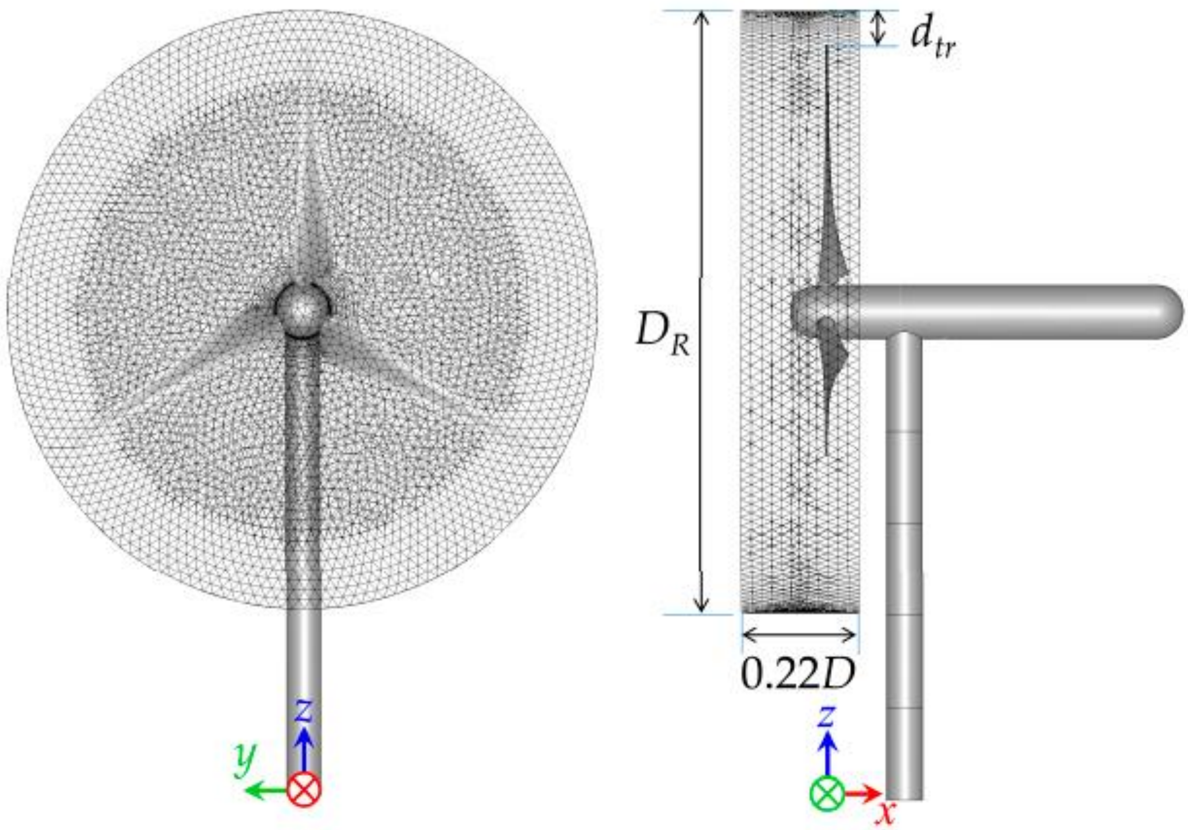

Figure 3. Unstructured mesh [46] (Reproduced from Ref. [46])

2.2.3. Hybrid Meshes

Hybrid mesh is a combination of structured and unstructured meshes, and an example of hybrid mesh is depicted in Fig. 4. In the hybrid mesh, the structured mesh is generally used for important regions (such as boundary layers around the blade), while the unstructured mesh is used elsewhere [47, 48]. The hybrid mesh is capable of combining the benefits of both structured and unstructured meshes, and therefore it has been widely used in the CFD modelling of WTs [49-51].

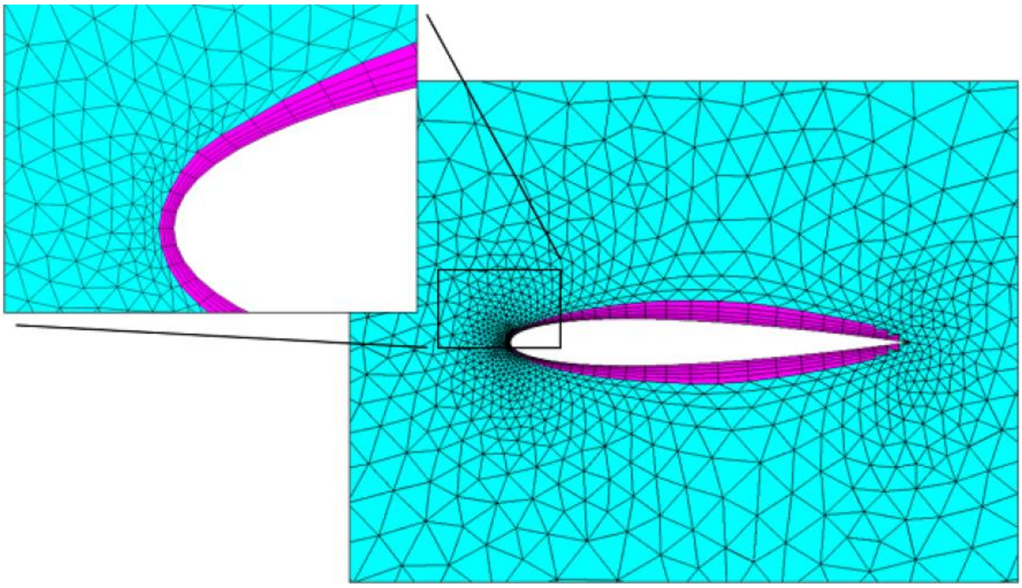

Figure 4. Hybrid meshes [51] (Reproduced from Ref. [51])

2.3. Boundary Conditions

The size of the computational domain used in the CFD modelling of WTs is generally proportional to the diameter of the rotor. The shape of the computational domain is various as required. The rectangular [46-48] and semi-circular [52-57] domains are generally used for 2D CFD modelling [46-57], while the cubic [58-61], conical [62] and cylindrical [52, 63] domains are typically used for 3D CFD modelling [59-64].

In the CFD modelling of WTs, the far-field wind velocity and atmospheric pressure are generally used as inlet and outlet boundary conditions, respectively. The surfaces of the WT are generally treated as non-slip wall. The top, bottom and side surfaces of the computational domain are generally treated as non-slip wall as well. The typical boundary conditions and computational domain used in CFD modelling of WTs are presented in Fig. 5 [52].

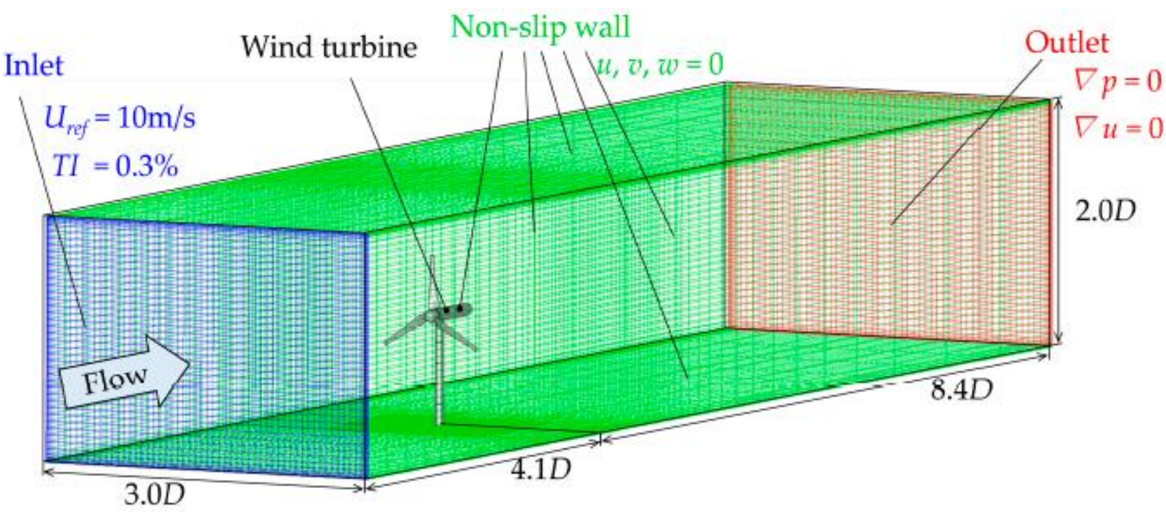

Figure 5. Boundary conditions of computation domain of WTs [52] (Reproduced from Ref. [52])

2.4. Turbulence model

Turbulence models are generally used to deal with turbulent flow in the CFD modelling, and choosing an appropriate turbulence model is vital for simulating the flow field around WTs [65, 66]. The turbulence models used in the CFD modelling of WTs can be roughly categorized into three groups, i.e. RANS (Reynolds Average Navier Stokes), LES (Large Eddy Simulation) and hybrid models.

2.4.1. RANS (Reynolds Average Navier Stokes) models

RANS models provide approximate time-averaged solutions to the Navier-Stokes equations, focusing on non-fluctuating and large-scale features of the flow. RANS-based turbulence models can be roughly categorized into two groups, i.e. one-equation and two-equation turbulence models. One-equation RANS turbulence models, such as SA (Spalrat-Allmaras) [67], Prandtl's [68, 69] and Baldwin-Barth [31], are based on the one time-averaged transport equation. It should be noticed that the Baldwin-Barth model and the Prandtl model are rarely used now. Among these models, the SA model, which is insensitive to the near wall treatment and appropriate for modelling wake and complex flow [70, 71], making it become the most commonly used one-equation RANS model.

For two-equation RANS turbulence models, the k-ε and k-ω models are widely used in the CFD modelling of WTs. The k-ε model calculates turbulence kinetic energy (k) and dissipation rate (ε) [72], and it can be further categorized into four different models, i.e. standard, realizable, RNG (Re-normalization group), and Low-Re k-ε models. k-ω turbulence model involves the solution of transport equations for the turbulence kinetic energy (k) and the specific rate of dissipation (ω). The most popular of subcategory of this model is k-ω SST turbulence model, of which results match well with experimental results [73, 74].

2.4.2. LES (Large Eddy Simulation)

Initially proposed in 1963 by Smagorinsky to simulate atmospheric air current, LES has been applied to CFD modelling of WTs in recent years. In LES, large eddies are solved explicitly while the small eddies are implicitly accounted by using a SGS (subgrid-scale) model. Large eddies in turbulent flow generally contain most of the turbulent energy and are responsible for most of the turbulent mixing as well as the momentum transfer. These eddies in full detail are directly captured in LES whereas they are modelled through time averaging in RANS, making LES inherently more accurate than RANS [75].

Solis-Gallego et al. [76] performed LES-based CFD modelling for a small wind turbine airfoil at different angles of attack to predict the trailing edge noise of the airfoil. The LES modelling results showed good agreement with experimental measurements. Wang et al. [77] studied the aerodynamic performance of blunt wind turbine airfoils using LES and compared the numerical results against experimental measurements. Good agreement was achieved between LES results and experimental measurements, and results also indicated that the trailing edge size can affect the separation bubbles and transition process in the boundary layers for the blunt wind turbine airfoils. More examples of applying LES to CFD modelling of wind turbines can be found in Refs. [78, 79].

2.4.3. Hybrid models

Hybrid RANS/LES techniques can be generally categorized into two groups: zonal and non-zonal. The first one takes RANS and LES as a separate model and employs them concurrently. The main concern in this method is about the regions between RANS and LES where some kind of interpolation must be used to provide smooth transition between them. It is likely to be error-prone for trial-and-error technique, particularly for sophisticated geometries. In the second approach, it is not necessary to choose RANS/LES regions [80, 81]. DES (Detached Eddy Simulation), which was first proposed in 1997 and first used in 1999 [82-85], is one of the prominent non-zonal hybrid RANS/LES models. DES treats near-wall regions in a RANS-like manner and the rest of the flow in an LES-like manner, which combines the best aspects of RANS and LES in a single solution strategy [85].

2.5. Discretization method

Analytical solutions generally do not exist for many non-linear models (such as CFD models based on NS equations), and therefore one of the way for solving these problems is to approximate the solutions using numerical methods [86, 87]. The numerical discretization techniques used in the CFD modelling can be roughly categorized into three groups, i.e. FEM (Finite Element Method), FVM (Finite Volume Method) and FDM (Finite Difference Method).

2.5.1. FEM (Finite Element Method)

FEM is mainly utilised in the structural analysis, but it is also applicable to fluid dynamics. For instance, ANSYS CFX [88], a widely used commercial CFD software package, is based on FEM. By using the Smooth Piecewise Continuous function, the PDEs (Partial Differential Equations) in the FEM are converted into algebraic equations to approximate unknown quantities. The governing equations are generally multiplied by a weight function and then integrated over the entire domain [89]. The basis of this method is to eliminate the PDEs or simplify the PDEs into ordinary differential equations, which can be then solved by numerical methods.

The solution domain in the FEM is generally divided into finite number of sub-domains, known as elements. A simple function is assumed for the variation of each variable inside each element, and then the summation of them is used to describe the whole field. The FEM is useful for solving PDEs over complicated domains or when the domain is variable [90, 91].

2.5.2. FVM (Finite Volume Method)

FVM is a special case of FEM when the weight function is equal to 1 everywhere in the domain. In the FVM, the integral forms of the governing equations are considered [92], and the solution domain is subdivided into a finite number of contiguous control volumes. The conservation equations are then applied to the centroid of each control volume, at which the computational nodes are located, to obtain the discrete equations for the element [93]. FVM is currently the most versatile discretization technique used in the CFD modelling, and it is suitable for complex geometries and applicable to any type of grids [94].

2.5.3. FDM (Finite Difference Method)

In FDM, difference between amounts of different points at various space and time leads to the approximation of the derivative of a variable by the Taylor series, transforming the governing differential equations into algebraic equations [95].

In order to extend to the entire points of domain, various forms of the derivatives of variables at each point that are related to its neighbourhood points are written, obtaining a set of numerical equations. When this process is exerted to all points of domain, infinite number of terms and very small difference in variables make the equations mathematically accurate [95]. It should be noted that FDM is not inherently appropriate for complexity, and therefore it should be applied to structured grids [96].

2.6. Treatment of blade rotation

The rotation of WT blades can significantly affect the aerodynamic performance of the turbine, and therefore it should be taken into account in the CFD modelling of WTs. The methods used for treating the blade rotation in the CFD modelling can be roughly categorized into three groups, i.e. reference frame, sliding mesh and dynamic mesh, as illustrated in Fig. 6.

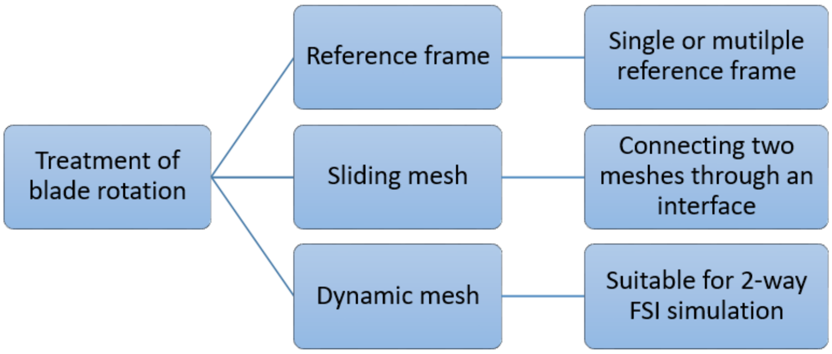

Figure 6. Methods used in the treatment of blade rotation

2.6.1. Reference frame

The reference frame is the most prevalent method used for treating the rotation of WT blades. According to the number of reference frames is used, this method can be categorized into two groups, i.e. SRF (Single Reference Frame) and MRF (Multiple Reference Frame). In the SRF, the entire computational domain is treated as a single moving reference frame. SRF is simple to implement but it is not capable of handling the problems that involve multiple rotating parts or stationary components (e.g. WT towers). In the MRF, a rotating reference frame is generally used for the region around the rotor blades, and a fixed reference frame is used for the rest of the computational domain. MRF is capable of handling the problems that involve both rotating and stationary parts. Due to its reasonable accuracy and computational efficient, MRF has been widely used in the CFD modelling of WTs [97-99].

2.6.2. Sliding mesh

The sliding mesh method allows adjacent grids to slide relative to one another. In this method, the rotational velocity is constant during each time step, and therefore this method is generally used in steady state flow. The main point of this model is that meshes do not deform by the rotation of reference frame. Cai et al. [100] used sliding mesh technique to investigate interface between static and moving parts in flow domain. Bedon et al. [101] adopted sliding mesh technique to optimize performance of Darrius WT airfoil. More examples of using sliding mesh in CFD modelling of WTs can be found in Refs. [102-104].

2.6.3. Dynamic mesh

CFD models can be coupled with structural models to perform FSI (Fluid Structure Interaction) modelling. FSI modelling of WTs can be performed using two types of coupling scheme, i.e. one-way coupling and two-way coupling. In the one-way coupling, the effects of deformed rotor on the fluid field are ignored, and both reference frame and sliding mesh techniques are applicable to take account of the blade rotation. For the two-way coupling, it is necessary to use dynamic mesh technique to take account of the blade rotation and the dynamic coupling of the fluid and structure. In this method, the mesh is generally updated at each time step, taking account of the deformation of the structure. Cheng et al. [105] investigated effects of blade vibration on aerodynamic load through a two-way FSI modelling using dynamic mesh.

2.7. CFD Applications on WTs

As one of pioneers, Sorensen and Hansen [106] simulated two different CFD models using incompressible RANS with k-ω SST turbulence model. The model was capable of predicting power curve accurately until 10 m/s wind speed. Beyond this speed, the accuracy significantly drops due to flow separation. Bazilevs et al [107] developed an FSI model based on residual-variation-multiscale formulation. The model coupled fluid flow with airfoil structure based on Kirchhof-Love theory [108, 109], in which the rotational and deflection motion are de-composited. The model was demonstrated to be capable of predicting torque coefficient precisely.

Mohamed et al [110] performed CFD modelling of 25 various airfoils using compressible URANS-based solver in order to identify the suitable airfoil shape. Balduzzi et al [111] analysed fundamental parameters of Darrieus turbine using unsteady URANS-based solver. Through comparing three types of turbulence models, i.e. Standard k-ε, RNG k-ε and k-ω SST, it indicated that the k-ω SST model has the highest precision among these turbulence models.

Balduzzi et al [112] applied the COSA RANS code to evaluate unsteady performance of the Darrieus rotor blade and compared the CFD results against the BEM results. The torque curve obtained from 3D CFD analysis and BEM analysis showed similar trend, whereas the downstream revolution torque profile was distinct. Grid refinement was then utilized to minimise uncertainty in simulating complex flow phenomena, such as tip vortex flow, dynamic stall and interaction of tip and wake. Wu and Porte-Agel [114] performed a large-eddy simulation of WTs to examine effects of wake flow and casualties. Estimations of power output and forces of WTs were made by the conventional actuator-disk model. The results from the model showed good agreement with the data from Horns Rev wind farm.

Make and Vaz [115] studied the flow over two floating WTs using RANS CFD calculations. In order to minimise the possible uncertainties, numerical sensitivity studies were performed regarding domain size, grid refinement, iterative convergence and turbulence model. Two types of turbulence models, i.e. k-ω SST and SA, were used and it demonstrated that the k-ω SST model predicted more accurately. In the study, both full-scale and model-scale model were compared against with experimental data, showing good agreement. A comparative RANS solver study between pressure-based (FLUENT) and density-based (COSA) was accomplished by Balduzzi et al [116]. For both cases, a good agreement with experimental data was achieved. Further, sensitivity analysis in grid refinement, domain size and boundary conditions were performed. A work regarding the influence of domain size was accomplished by Rezaeiha et al [117]. In the study, effects of domain size and azimuthal increment were minimised for 2D and 2.5D simulations for a low-solidity 2-bladed VAWT at TSR (tip speed ratio) of 4.5 by using URANS-based solver. Three refinements of grid were performed for grid dependence. It was observed that 10 times the diameter of turbine is the suitable size for locating both inlet and outlet boundaries.

Gebraad et al [118] developed a new numerical model to optimize the turbine yaw settings. The model is capable of well predicting power output for both conventional and optimised yaw settings. A LES model was simulated by Stevenes et al [119] to evaluate alignment angles, and the results from the model matched well with the data from Horns Rec wind farm. The preferable power coefficient was obtained at the alignment angle of 11^o where wake flow is significantly less effective. More examples of the CFD applications on WTs can be found in Refs. [29, 120-128].

3. Objective functions used in optimisation of WTs

The objective functions used in optimisation of WTs can be roughly categorized into four groups, i.e. minimization of the COE (cost of energy), maximization of the annual energy production, minimization of the blade mass and MO (Multidisciplinary Optimisation).

3.1. Minimization of the COE (cost of energy)

Currently, the mostly used objective function in the optimisation of WTs is the minimization of COE, which is defined as [130]:

$$COE = \frac{C_{TA}}{AEP} \qquad (1)$$

where C_{TA} and AEP are the total annual cost and the annual energy production, respectively.

COE of WTs depend on several factors, e.g. installation, electrical cable cost, maintenance, etc. Scale and orientation of the turbine can also affect the COE [131-133].

3.2. Maximization of the AEP (annual energy production)

An aerodynamically efficient blade is the incipient requirement to attain maximum power output of WTs [134-138]. WT blades are generally made of composite materials due to their high stiffness-to-weight ratio and good fatigue performance.

The maximum AEP for a given distribution has been taken as an objective function in many studies on the optimisation of WTs [139-144]. The AEP over the wind speed spectrum is given by [145, 146]:

$$AEP = h_{year} . K_{avl} \int_{V_{in}}^{V_{out}} P(V)F(V)dV \tag{2}$$

where h_{year} is the number of hours in a year, usually 8760 hours; K_{avl} represents the availability of the turbine; V_{in} and V_{out} are the cut-in and cut-out wind speeds, respectively; $P(V)$ represents the power curve of the WT; $F(V)$ is the wind speed distribution.

3.3. Minimization of the blade mass

WT blade structure is generally required to be designed as light as possible, in order to reduce the material cost of the blade and lower both centrifugal and gravity loads on the blade. The minimum blade mass can be taken as an objective function, expressed as:

$$F_{obj} = \min(m_B) \tag{3}$$

where F_{obj} and m_B are the objective function and blade mass, respectively.

3.4. MO (Multidisciplinary Optimisation)

MO is another important objective function which has been extensively used by many researchers [137, 148-154]. There are numerous inadequacies in single objective approaches, of which purpose is to discover the "best" solution corresponding to the maximum or minimum value of a single objective function. However, most of the actual industrial problems involve multiple objectives, e.g. maximizing reliability, maximizing performance, minimizing the COE, etc. [155, 156]. MO allows decision-makers to consider the trade-offs benefits of different objectives and then prioritise objectives within the short time [157]. The MO techniques have been demonstrated to be accurate and capable of resolving the vast majority of sophisticated industrial optimisation problems [129].

In the MO, it is crucial to identify solutions in the Pareto optimal set. Pinpointing the total Pareto optimal set is practically impossible due to its size. Therefore, a practical method is crucial to investigate the best-known Pareto set that clarifies the Pareto optimal set. Generally, most of the MO methods ought to reach the following three conflicting constraints [159-161], i.e. 1) the best-known Pareto front ought to be as close as feasible to the true Pareto front. 2) the best-known Pareto front must capture the entire spectrum of the Pareto front. This needs deep studying solutions at the extreme ends of the objective function space; and 3) solutions ought to be consistently distributed and diverse over the Pareto front to provide the decision-maker an accurate image of trade-offs.

4. Optimisations algorithms

The algorithms used in the optimisation of WT performance can be roughly categorised into three groups, i.e. calculus-based, heuristic and meta-heuristic algorithms.

4.1. Calculus-Based optimisation

The basis of calculus-based optimisation is a first/second order objective function, which is differentiable and continuous by converging search space to convex or concave. This method has been categorised into different algorithms such as Generalized Benders Decomposition, backtracking, branch-bound/cut, Extended Cutting Plane, the gradient and Newton based [162,163].

There are two basic optimisation techniques to obtain the optimal solution. The first method is to explore all possible solutions. This calculus-based algorithm, for instance Gradient and Newton-based methods, requires objective function to be simple, differentiable and continuous to bind the search space. Additionally, it is time-consuming in computing and cannot overcome the local extreme point in local search. Therefore, several approaches [164, 165] have been introduced based on global and multi-start process, in which a local search is performed to obtain optimal solution. The second technique is implicit solution such as branch-bound method [166], whereas it has showed poor results in comparing to explicit appraisal in non-convex solution. The relaxation method [167-169] was proposed to solve the initial problem and decrease its complexity. The optimal solution procedure can be then employed to overcome non-convex search space by developing relaxation method.

Various denominations have been given for different types of problems to optimisation model which is referred as MINLP (Mixed-Integer Nonlinear Programming Problem) [170, 171]. Archer et al [176] proposed an approach to solve wake effect. In regard to extend further MINLP technique, the performance criteria and effective factors were wiped out to decrease complexity of the problem.

4.2.1. GBA (Gradient Based Approach)

GBA is the most popular and important calculus-based algorithm applied to the performance optimisation. GBA resolves optimisation problems in the design space based on the gradient of objective and constraint functions [177]. It can be used for both constrained and unconstrained problems with multiple variables. This method begins with an initial design and attempts to search for a local minimum that is closest to the initial design in an iterative way [178, 179].

Amaral et al. [180, 181] presented the aerothermal optimisation of a high-pressure WT using the GBA, maximising the lifetime of a WT blade operating at a very high pressure. Nowak and Wróblewski [182] and Mazaheri et al. [183] investigated the optimum shape of a C3X turbine blade using GBA. Lately, hybrid GBA and GA techniques have been investigated by [184-188]. Bizzarrini et al. [189] compared the results of a hybrid scheme and a GA and concluded that the hybrid technique is more effective due to its higher precision as well as higher sensitivity to local minima. Similar conclusions were also drawn by Varga [186] and Refs. [187-189].

4.2. Heuristic optimisation

Heuristic method was first proposed in 1982 by Daniel Kahneman and Amos Tversky [190]. It employs a deterministic or non-deterministic solution process to seek near-optimum solutions for sophisticated problems based on previous experiences. Heuristic methods are useful where attaining the exact optimum solution is impossible. Additionally, they are fast enough and have better performance than Calculus-based optimisation methods [71, 191].

Heuristic methods can be further categorized into two groups, i.e. constructive and iterative methods. The constructive heuristics attempt to create multiple sequential deterministic (or non-deterministic) assemblies of variable, taking account of all defined constraints. Iterative heuristics enhance a complete solution by performing a controlled estimation of local search space of each involved variable. Constructive heuristics are generally faster than iterative heuristics [192-194]; however, they might fail to find a feasible solution in cases of highly constrained problems.

4.3. Meta-heuristic algorithms

Meta-heuristics (also known as hyper-heuristics) are higher-level heuristic methods, which achieve a near optimal solution more precisely than common heuristics [195, 196]. Metaheuristic algorithms are generally based on optimisation process observed in the nature, such as PSO (Particle Swarm Optimisation), GA (Genetic Algorithm) and SA (Simulated Annealing).

4.3.1. PSO (Particle Swarm Optimisation)

PSO was firstly proposed by Kennedy and Eberhart in 1995, and it was inspired by the social behaviour of bird flocking as well as fish schooling [197, 198]. PSO has been recently applied to the optimisation of WTs [199-201].

Ferrari et al. [130] developed an aerodynamic optimisation model for Savonius VAWT rotors through combining CFD with PSO. Meneses et al. [200] proposed hybrid MILP (Mixed Integer Linear Programming) and PSO method to search for the best location of both ESS (Energy Storage System) and wind power, minimising the power generation costs. Ata [201] proposed the function of PSO in artificial neural network to calculate ESS, obtaining the best set of weights [202-205]. Reddy [206] proposed two different models and the objective functions are considered to be the COE and cost of reserves. The first model includes reserve offers from the conventional thermal generators and the second model includes reserve offers from both thermal generators and demand/consumers.

Liao et al. [208] employed Prelayers, a program that links FAST and the improved PSO algorithm, to optimise blade structural layout Kahla et al. [209] extracted a maximum of power below the fluctuating wind speed with the aid of PSO and proved that the PSO has improved the WT performance.

4.3.2. GA (Genetics Algorithm)

Genetic algorithm is an optimisation technique which imitates Darwin's opinion of the population (the survival of the fittest) over a set of individuals (candidate solutions) that progresses from one generation to another [211]. At the beginning of GA, some chromosomes are erratically opted via the initial population, employing a special search technique. Values are then assigned to the selected chromosomes with respect to the fitness function, and two chromosomes that have the highest fitness value are selected as initial parents. Subsequently, these parents are reproduced to develop a new generation using mutation and crossover operators in a repetitive process [212]. Crossover and mutation operators contribute to perturb the characteristics of parents to create distinct offspring with better characteristics than their parents [213]. The produced generations then substitute their parents in the next reproduction process if they have more promising values than their parents based on the fitness function. The evolution is an iterative process and generally terminates when either a maximum number of generations has been produced or the population has reached a satisfactory fitness level. The typical flowchart of GA is depicted in Fig.7 [214]. GA has the advantage in discovering non-derivable, non-continuous and non-linear domains [215, 15].

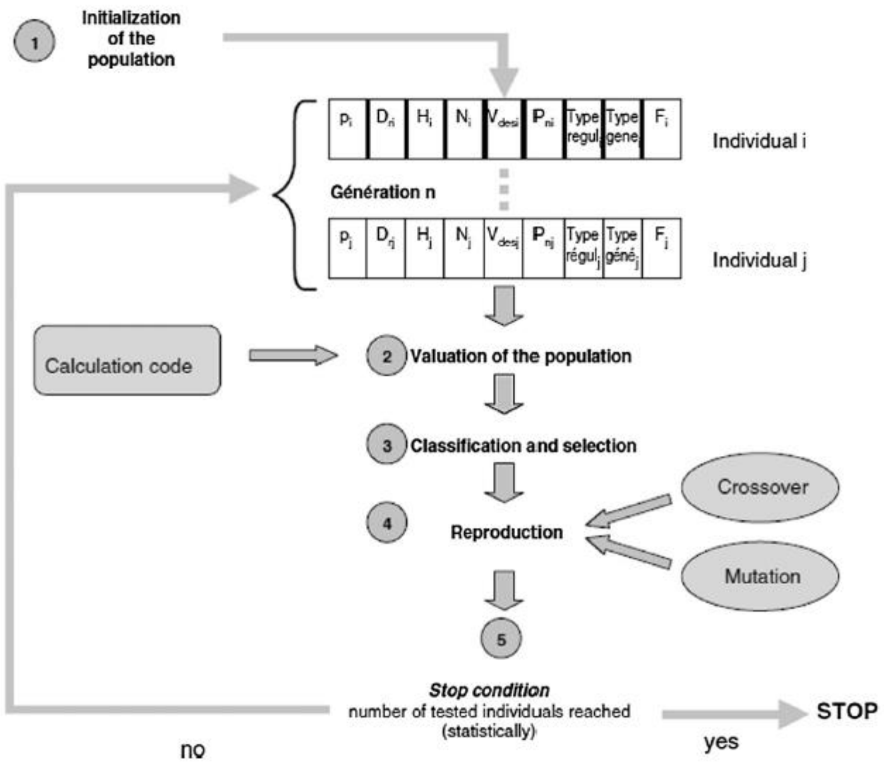

Figure 7. Optimisation outline of GA [214]**. (**Reproduced from [214])

Alpman [216] investigated the effects of choosing the chord length and twist angle distribution for a two-bladed stall-regulated HAWT, with GA employed as an optimizer to achieve the highest AEP. Tabatabaeikia et al. [217] accomplished an innovative sequence of optimised numerical simulations through CFD code to recover the exhaust energy of VAWT generators to enhance the performance of the turbine (see Fig. 8), minimising the cost as well as diminishing the noise. Rodrigues et al. [218] designed an offshore WT (as depicted in Fig. 9) consisting of moveable and floating turbines. They employed GA algorithms based on inner loops to optimise the location within the mooring lines. Wang et al. [219] demonstrated that the GA requires lower computational time when comparing to both PSO and DP (Dynamic Programming) in finding the optimum number of thermal generators. Jafaryar et al. [220] proposed an optimised design for the asymmetric blade geometry of VAWT with five blades (see Fig. 10) based on GA. 15 types of NACA airfoils were compared, and the results indicated that NACA 7715 and NACA 4520 performed worst and best respectively among these airfoils.

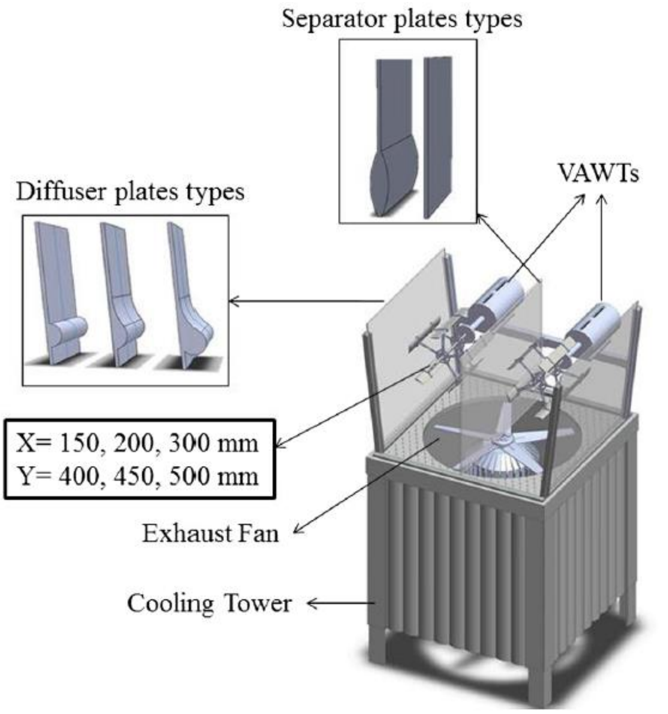

Figure 8. Optimisation issues of VAWT [217] (Reproduced from [217])

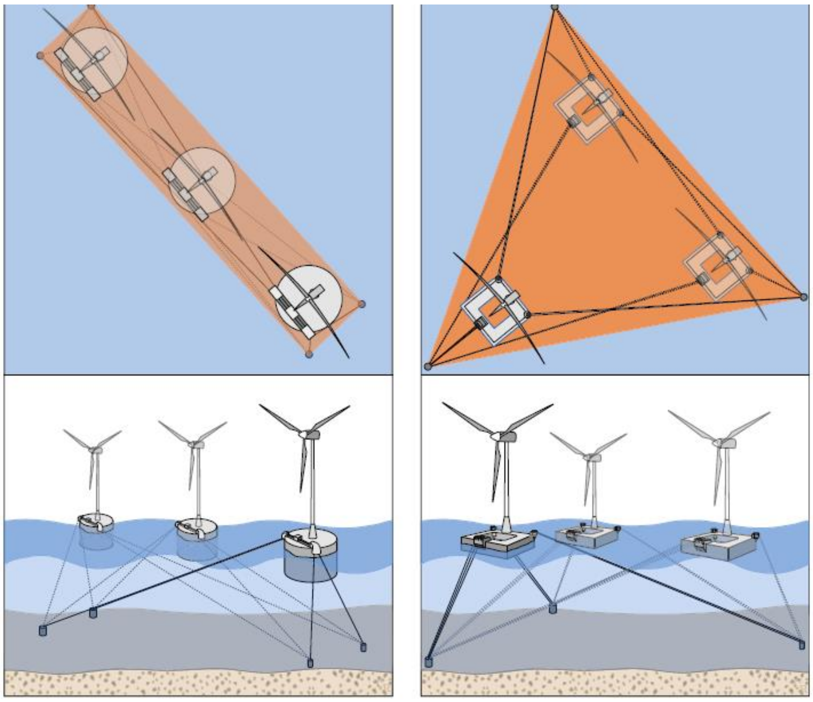

Figure. 9. Three different positioning of moveable WT [218] (Reproduce from [218])

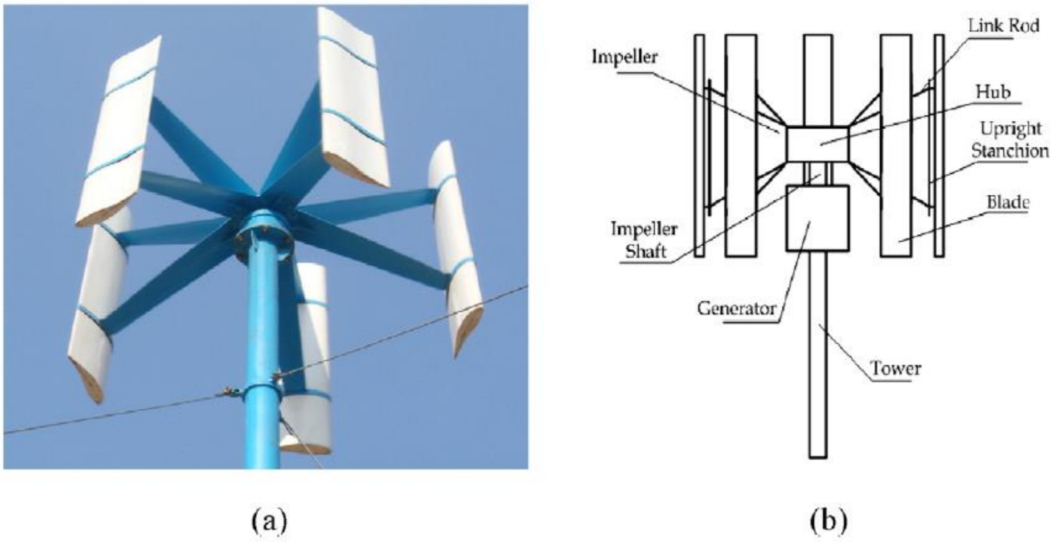

Figure. 10. Detailed schematic of VAWT with five blades [220] (Reproduce from Fig.1 of [220])

Rangi et al. [221] obtained an optimal airfoil through a GA which enhanced the performance of a 26% thick airfoil in steady conditions with both free and forced boundary layer transition. Refs. [222-225] discussed the research studies using hybrid system and claimed that GA is a suitable algorithm for optimizing airfoils. More details about GA in airfoil design can be found in Ref. [226, 227].

4.3.3. SA (Simulated Annealing)

SA is a probabilistic single-solution-based search technique inspired by performing the cooling of material in a heat bath (annealing in metallurgy), which was first proposed by Metropolis et al. [228]. The similarity between optimisation process and SA is that potential solution of the considered problems are analogous to the states of a physical system which is undergoing a process of annealing [229]. Local search will normally accept transitions between neighbours of solution when the quality is better than the current state, and the transition is generally modelled as a probabilistic procedure [230]. Elimination of states with lower quality increases until the process reaches the cooling stage [229]. SA has advantages in its ease of implementation and ability to escape local extreme points, making it suitable for solving various sophisticated problems [232-235].

5. CFD-based optimisation of WTs

CFD has been applied to optimise WTs, particularly WT blades, which play a vital role in WT performance. CFD-based optimisation of WTs are mainly focused on three aspects, i.e. 1) comprehending behavior of airfoils under fluid flow; 2) investigating effects of shapes and materials of airfoils on airfoil performance; and 3) finding the best shape of airfoil with optimisation algorithms. An illustration on the CFD based optimisation of WTs is depicted in Fig. 11.

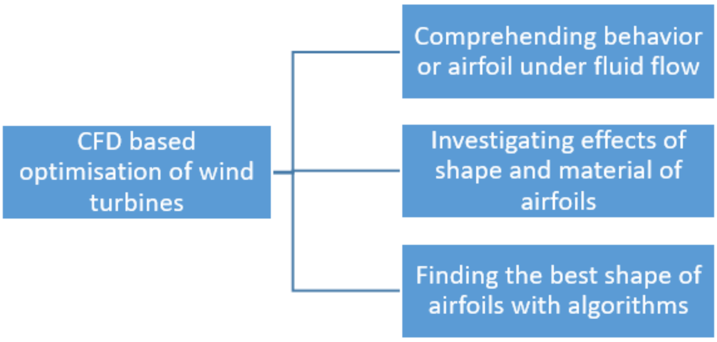

Figure 11. An illustration for CFD based optimisation of WTs

The most basic and necessary part of optimisation is to have a deep understanding on the behavior of airfoils under fluid flow. Cai et al [100] simulated a full-machine HAWT under unsteady flow, considering wind shear, tower shadow, etc. The results indicated that the maximum and minimum of aerodynamics loads occur simultaneously during the revolution of blades.

The effects of shapes and materials of airfoils on their aerodynamic performance have been investigated in several studies. Saeed et al. [236] evaluated an airborne WT with NREL Phase IV rotor under various conditions, considering or ignoring shell mounted configuration. The results proved that an airborne WT airfoil with shell mounted configuration performed better when comparing to the one without shell mounted configuration. Zamani et al. [237] conducted a 3D simulation for J-shaped NACA 0015 airfoil to optimise a Darrieus VAWT. Less noise and turbulence was achieved by trapping vorticities at the rear part of blades. Jafaryar et al. [220] combined response surface method and CFD to achieve maximum torque. The optimum asymmetrical airfoil shape showed the same trend as the symmetrical airfoil.

An important aspect of optimising WT airfoils is to use appropriate optimisation algorithm to find the best shape. Ribeiro et al. [238] proposed an airfoil optimisation technique for wind turbines by coupling CFD and optimisation algorithms. In the study, CFD simulations were performed with incompressible RANS equations in steady state using SA turbulence model. The CFD model was coupled with both single and multi-objective GAs to optimise the aerodynamic shape of airfoils. Results indicated that the airfoils obtained with single and multi-objective GAs were similar in shape and aerodynamic coefficients. Bedon et al. [239] proposed an optimisation model for WT airfoils by combining a genetic optimiser, a 2D URANS CFD model, a fitness calculator and an airfoil generator. The optimisation model was applied to develop a new airfoil shape for Darrieus VAWT blades, and the results indicated that the developed new airfoil shape can improve the aerodynamic performance of the blade. More studies on CFD-based airfoil optimisation can be found in Refs. [112, 240, 241].

6. Future development

6.1. Hybrid CFD/BEM

The CFD model is valuable to simulate flow filed thoroughly; however, it needs considerable computational time and resources [18]. The BEM technique is efficient to predict the aerodynamic performance of WT blades; however, its accuracy is highly dependent on the airfoil aerodynamic characteristics data, of which experimental data are sometime difficult to obtain [242, 243]. The hybrid CFD/BEM method provides a promising solution to combine the benefits of both CFD and BEM. In this method, the aerodynamic coefficients of 2D airfoils are obtained using CFD, while the aerodynamic loads calculation is performed using BEM. The hybrid CFD/BEM method is capable of predicting aerodynamics performance of WT accurately with reasonable computational time. The flow state especially laminar-turbulent transition around WTs can affect this method considerably. Hence, the further development could consider the laminar-turbulent transition [244, 245].

6.2. Innovative numerical technique to reduce computational time of CFD

Innovative numerical techniques have been recently proposed to reduce the computational time of CFD modelling of WT blades. Choosing an appropriate algorithm makes it possible to reduce computational time required by the CFD modelling. These algorithms consider different parameters to maximise the computational efficient. Some novel algorithms such as bat algorithm, shuffled frog leaping algorithm, cuckoo search, scatter search and ant colony optimisation [246, 247] showed satisfactory performance in terms of computational efficient, and the possibility of applying these algorithms to WTs could be further investigated.

6.3. Apply CFD to multi-objective optimisation

There are numerous inadequacies in single objective approaches whose purpose is to discover the "best" solution which corresponds to the maximum or minimum value of a single objective function. However, most of the actual industrial problems involve multiple objectives, e.g. maximising reliability, maximising performance, minimising cost, etc. Multi-objective optimisation involves more than one objective functions, making it more suitable to deal with practical engineering optimisation problems. Therefore, multi-objective optimisation is promising in the performance optimisation of WTs.

6.4. Apply CFD to optimise floating WT blades

FOWTs (Floating offshore wind turbines), which were firstly proposed in 1972, have been installed on floating platforms (such as tension-leg, spar and semi-submersible platforms) to generate electricity in deep water [248, 249]. Blue H technologies was the first FOWT installed in Italy, and it has not only achieved the high efficiency but also provided better place for fishing and shipping lanes since 2007 [250-252]. Make et al [115] analyzed effects of scale on FOWTs using RANS CFD simulations. The main purpose of the study was to reduce uncertainties in floating platform.

FOWTs are vulnerable to huge oscillations such as wave- and current-induced hydrodynamic loads as well as wind-induced aerodynamic loads. Accurately predicting the aerodynamic and hydrodynamic loads is important in the design of FOWTs. Therefore, further development of FOWTs would require the development of more reliable aerodynamic and hydrodynamic models for FOWTs. Another work that is worthy investigating is to study the coupled and uncoupled motions comprehensively, particularly the optimisation of the whole system. Further development could also consider numerical studies of unsteady dynamic effects induced by platform motions, e.g. heave, sway, rolling motions, etc.

7. Conclusions

This paper critically reviewed CFD (Computational Fluid Dynamics) modelling and its application on the performance optimisation of WTs (wind turbines). The following conclusions can be drawn from the present review.

■ With the development of computing resources, CFD has received significant attention in the recent years**.** CFD is significant in visualising the structure of flow and predicting aerodynamic loads. However, CFD modelling of 3D (three-dimensional) WT blades is still too time-consuming, which is the main barrier for its industrial application. BEM is more efficient in modelling the flow field and computing aerodynamic loads on WT blades. However, the results of BEM highly depend on the accuracy of the airfoil aerodynamic data, of which experimental data are sometime difficult to obtain. The hybrid BEM/CFD method, which combines the benefits of BEM and CFD, is promising in reducing the computational time while preserving prediction precision.

■ MO (Multidisciplinary Optimisation) has been the interesting topic of many investigators in recent studies, as the vast majority of the practical problems involves multiple objectives. MO allows decision-makers consider the trade-offs between benefits of different objectives and then achieve the optimal design considering multiple objectives.

■ The most important algorithm optimisation, such as PSO (Particle Swarm Optimisation), GA (Genetics Algorithm), SA (Simulated Annealing) and GBA (Gradient-Based Approach), were introduced. These topics are addressed by identifying the most important targets and issues in many aspects, including the optimisation formulas, schemes and models. Subsequently, a critical review with the aim of using these algorithms in the performance optimisation of WT with the combination of CFD was investigated. Among the numerous Meta-heuristic algorithm, GA is found to be the most widely applied in the optimisation of WTs.

Conflicts of Interest:

The authors declare that they have no conflict of interest.

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