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A simplified dynamic model for mast design of H-Darrieus vertical axis wind turbines (VAWTs)

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ABSTRACT

The use of small scale vertical axis turbines (VAWTs) in the urban environment is becoming increasingly popular. VAWTs are usually supported on steel masts to increase their efficiency. The resonance between the supporting masts and the VAWTs can disturb the power generation and trigger potential fatigue issues in the mast structure. As the turbine itself influences greatly the free vibration modes of the mast, VAWTs should not be modelled as a single lumped mass during a dynamic analysis. A simplified analytical model of an H-Darrieus VAWT is developed to allow the dynamic analysis of the supporting masts taking into account the coupling of the mast and turbine. The VAWT has a height of 5 m, a diameter of 3 m and a power output of 6 kW whereas the height of the masts ranges between 3 and 15 m. The coupled structure is analysed both analytically, through a multi-degree of freedom system, as well as numerically through the finite element (FE) method. The correlation of the estimated natural frequencies of the system through the FE method with site measurements was found to be within 10% and can allow designing adequately the mast. Harmonic forces representative of the turbine out of balance and cyclic aerodynamic forces are proposed and used to predict peak acceleration at resonance.

1. Introduction

There has been an increased interest in vertical axis wind turbines (VAWTs) in the last decade or so. The use of VAWTs is better suited to the urban environment because their design allows a more turbulent wind profile. Most of the VAWTs installed recently are of small size. For example, since 2007, there have been more than 500 small VAWTs, having power output ranging between 1.5 and 50 kW, installed across the UK [1]. The largest vertical axis wind turbine, located in Cap Chat, Quebec, Canada, is 110 m tall and has a 4 MW capacity. Tall buildings are suitable to locate wind turbines which have a low visual impact and reduced acoustic emission. The electricity can be used directly by the building users without any loss arising from its transportation. Wind turbines can be used successfully to reduce the CO_2 emission rate of buildings in the same manner as other sources of sustainable energy such as solar panels or heat pumps. The energy efficiency is required by Building Control for new build projects and large extensions. Wind turbines are an effective answer to buildings with low energy design.

VAWTs are usually supported on steel masts to increase their efficiency. Previous research efforts have concentrated either on the behaviour of the supporting steel masts alone or on the aerodynamics of the wind turbines. There is hardly any research or standards to provide guidance on how to assess the vibrations induced by VAWTs on their supporting masts. This paper presents a study of the vibrations induced by VAWTs onto their supporting mast or towers where both analytical and numerical models and tools which can be used by VAWTs manufacturers are developed. Resonance between the mast and the turbine must be avoided so that the power generation is optimum and not disturbed. The important dynamic aspects during the design of masts are the fatigue of welded elements and potential excessive displacements at the top of the mast. These are not associated with higher modes, which can be technically challenging to predict and require accounting for the rotation of the rotor and potential centrifugal forces. The model presented in this paper accounts for the lower modes and aims at being used by mast fabricators to quickly assess potential fatigue issues and vertical turbine fabricators to assess serviceability issues if the mast stiffness is not adequate. The potential of tower vibrations and resonance due to the dynamic behaviour of the turbine is mentioned in [2] without, however,

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any detailed quantitative prescriptions and this paper partly addresses this gap.

2. Background studies

The majority of the research available on vertical and horizontal axis wind turbines is focused on the wind turbine itself; even if the issue of the vibration induced by the out of balance forces is identified, it is customarily assumed that very stiff supporting structure and cables are used [3]. However, a VAWT is usually required to be supported on a mast or a grillage so that it can reach undisturbed high wind levels and ensure safety for the public.

Wind turbines are flexible structures with aerodynamic forces acting on the blades at harmonics of the turbine rotational frequency. The prediction and measurement of wind turbine modal frequencies is very important in the design of wind turbines to avoid resonance and fatigue and for their successful operation [4,5]. Usually, the vibration modes of the turbines are analysed independently of the mast structure. The main criterion to avoid excitation issues is to have the natural frequencies of the mast not too close from the natural frequency of the rotor [6].

Typical finite element (FE) analyses for horizontal axis wind turbine (HAWT) towers have been carried out in [7], as shown in Fig. 1. The simplified mass model (d) is sufficient to calculate the forces and natural frequencies as long as the natural frequencies of the tower and blades are far apart [8]. In this case, the tower has been modelled as a lumped mass multi degree of freedom (MDOF) flexible entity which includes one lumped mass at the top of the tower which allows for the mass of the blades and nacelles. Model (c) takes into account the soil–structure interaction but the soil effects were calculated to be less than 2%. Refined plate elements model (b) is used to calculate stress concentrations. The loading was simplified as being a set of forces and moments associated with a number of occurrences applied at the top of the mast. Because of high wind load at the top of the tower, vortex shedding is usually not the critical factor for this tower type.

The majority of the research carried out recently on the dynamic modelling of wind turbine systems focuses on the blades and nacelle components. The tower is usually less complex and, in most of the cases, it was seen as sufficient to ensure, by modifying the stiffness of the tower, that the tower natural frequency did not match a multiple of the rotational frequency of the blades. However, with the increasing size of HAWTs, it is becoming necessary to allow for the dynamic coupling of the tower and the rotating blades. An analytical Lagrangian model taking into account the kinetic energy and centrifugal stiffening can be developed to establish a representative time history of the tower tip displacement [9].

In the 1980s, the Natural Excitation Technique (NexT) was used for acquiring the modal parameters using output only model testing [10]. The method allows structures to be tested in their ambient environments and the resulting modal frequencies and damping ratios are then extracted from measured response data through a time-domain modal identification scheme employing cross-correlations functions. In the 1990s, Operational Modal Analysis (OMA) was developed to overcome the challenge of testing large structures excited with natural environmental inputs [11]. OMA can employ either time history-based and/or frequency domain-based techniques. Most of the research associated with OMA focused on the VAWTs of Cap Chat in Canada [5]. One potential complication for the wind turbines is the fact that their modal frequencies depend on the rotation speed of the turbine. The modal frequencies vary with the turbine rotation speed because of the effects of tension stiffening and centrifugal and Coriolis speed. However, these effects are more severe at very high speed, above 400 rpm for VAWT. In the example of the 2 m Sandia VAWT described [5], the modal frequencies of the turbine alone vary up to approximately 15% at 200 rpm and then dramatically at 800 rpm.

An OMA has been used for a rotating VAWT and the different frequencies and associated modes were successfully extracted [5]. The analytical solution of the structural dynamic characteristics of VAWTs has been developed to accurately predict the starting torque characteristics and blade vibratory stresses [12].

Recently, an article describing the aerodynamic load measurements on the airfoils of VAWTs has been published [13]. High amplitude vibration of the turbine was observed, primarily due to the resonance of the whirling mode of the turbine. The goal of the study was to validate a VAWT numerical aerodynamic model. However, because the level of turbine vibration was in some cases dominating completely the underlying aerodynamic loading, a way to minimise or eliminate the vibration response was developed by restraining the top of the turbine. Vibration should be minimised to reduce the potential noise impact and potential fatigue failure. Adding a guy wire system at the top of the turbine increases the primary structural mode because of the increased energy required to excite the primary mode of the fixed-pinned shaft [13].

The computational fluid dynamics (CFD) model developed in [13] can be used to determine the thrust and radial loading characteristics for one blade depending on the angle of rotation and for different blade speeds. It was shown that the resultant force is harmonic in both the stream-wise and cross-stream direction. The primary vibration response of the turbine was found to be coincident with the blade pass frequency.

A number of recent studies have concentrated on the investigation of the performance of VAWTs under low blade speeds and have shown that it can be feasible to efficiently use them under such operating conditions [14–16]. On the other hand, other studies have focussed on the analysis of the aerodynamics and performance of VAWTs through (CFD) simulations [17–19], FE structural analysis [20] as well as experimental testing [19,21] and on the optimisation of the design of the turbine itself [22,23].

3. The Quiet Revolution qr5 vertical axis wind turbine

Quiet Revolution has recently successfully developed a 5 m tall VAWT [24]. The profile of the three helical blades has been optimised for performance and quite operation. The low tip speed further reduces noise levels. The rotor size is 5 m tall and of 3.1 m in diameter having a total mass of approximately 450 kg. The blades are made of carbon and glass fibre. The 6 kW turbine can generate up to 7500 kW h per year depending on the average site wind speed. The turbines are mounted on tilt down masts. The mast standard heights are 3 m, 6 m, 9 m and 15 m. A standard arrangement on a 6 m mast is shown in Fig. 2. The masts are made of several conical sections rammed into each other.

The turbine applies some maximum forces to the mast which have been determined by wind tunnel testing. Under a maximum wind speed of 55 m/s = 200 km/h, the lateral wind force (in the x-direction, see Fig. 2) generated in the middle of the rotor is 5 kN and the vertical load (in the z-direction, see Fig. 2) is 4.4 kN. The lateral force produces an overturning moment on the mast which is the critical loading driving its static design. The helically swept blades of the Quiet Revolution wind turbine reduce the variation in lateral loading which was a typical issue with the Darrieus Turbine as discussed in [13].

4. Analytical modelling of the mast and turbine system

The derivation of the stiffness of the mast and the coupled mast and turbine system is required for analytical calculation of the