THE STRUCTURAL DYNAMICS OF WIND TURBINES

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1. Introduction

The design of high technology wind turbines for generating power for the national grid is a relatively recent development in the U.K. The first medium sized machine (horizontal axis, 17m diameter, 30 kW) was built and commissioned by Sir Henry Lawson Tancred Sons and Co. Ltd. at Aldborough, North Yorkshire in June 1977 and as originally constructed it was also the first to be connected to feed the national grid (Nickols, 1979). Since then a number of smaller machines has been constructed to test the performance of a variety of different kinds of machine, though none has been connected to the grid. These smaller machines at Rutherford Laboratory, Swansea University and P.I. Specialist Engineers at Alresford, Hants., form the hardware core for a set of field measurements being made under the auspices of the Department of Energy by a joint team from CERL, Leatherhead and Reading University. All of the early work of the field measurement team concentrated on wind and performance measurements. Early in 1980 it was realised, as the result of structural failures both here and abroad (see for example Daniels, 1980) that the structural design of such machines was not a routine matter. Accordingly, a team at CERL and Reading embarked on a series of experimental studies designed to explore the structures and materials problems of wind turbines. Some theoretical work is also now in hand. This paper gives a brief summary of some of the structural dynamics problems which are being explored.

Two main types of machine are being seriously developed for power generation in the U.K., the more or less conventional horizontal-axis machine and the novel variable geometry vertical axis wind turbine (VGVAWT) conceived by Musgrove (Musgrove, 1976). The first U.K. megawatt size machine, to go on the Orkneys, has recently been announced by the Department of Energy and is a two-bladed horizontal axis configuration of diameter 60m mounted on a reinforced concrete shell tower. The first fully instrumented VGVAWT (two vertical blades 4m long on 6m diameter cross-arms) was commissioned at the Rutherford Laboratory in 1978 (Stacey and Musgrove, 1980). The design of a 25m VGVAWT is currently being undertaken by Sir Robert McAlpine and Sons, Ltd. for the Department of Energy. Another development is the projected scheme for clusters of machines both on land and offshore in the North Sea. Eventually, it is conceived that wind power could provide as much as 20% of the nations electricity needs and this will involve the use of about 1000 10MW size machines.

2. Structural Fatigue

The major consequence of structural vibration in wind turbines, apart from catastrophic resonance or flutter, will be fatigue failure. Rather like helicopters wind turbines may cynically but aptly be called fatigue machines. The level of dynamic stress, peak-to-peak, is often as high as 60% of the quasi-static stress due to mean wind or mean rotational speed. Unfortunately, this level of dynamic stress is not predictable with present information concerning (i) the nature of the natural wind, and (ii) the nature of the rotation rate harmonic content in rotor loading. One of the aims of the present field measurement programme is to gain empirical information concerning these two important factors. The information will be of great use in making coupon fatigue tests, using programmed loading, on the materials to be used for structural components. A considerable quantity of data has been collected on the Rutherford Laboratory VGVAWT, (Pretlove, 1981), and data will also shortly be collected from instrumentation already installed on the Lawson-Tancred machine in Yorkshire.

3. Structural Loading

The components of wind turbines are subjected to complex loading during operation which arises from gravity and inertia forces as well as from aerodynamic forces.

The dynamic element of gravity loading is important for horizontal axis machines and cycles at once per revolution. Confining consideration of this to large machines situated in windy locations so that rotation occurs for 50% of the time it is estimated that each blade will undergo about 10^9 stress reversals in a fifty year lifetime. The implication of this high number of cycles is that great care must be taken with fatigue conscious design. It has been shown recently, for example, that for welded joints in steel highway bridges subjected to such a high number of cycles, ignoring stress cycles below the so-called Fatigue Limit will lead to endurance predictions which are over-estimated by as much as six to one (Tilly and Nunn, 1980).

Inertia forces on wind turbine blades have only a small dynamic component due to speed fluctuations. However, if the rotor is not correctly balanced there are dynamic forces on the supporting tower structure even at steady speeds. The rotors of horizontal axis turbines have to yaw to face into wind and this can cause dynamic inertia forces on the blades and tower due to gyroscopic action. For two-bladed rotors this effect is aggravated because the principal moments of inertia of the rotor are different and a harmonic is generated at twice times the rotation rate (Prentis, 1979). These gyroscopic forces are also affected by whether the yaw is free, controlled rate or damped. A final complication is that in some two-bladed designs the rotor blade pair is freely-hinged to the rotor shaft over a limited arc of movement so as to minimise drive shaft bending moment. This mechanical complication, known as a teetered hub, also causes changes in the gyroscopic moment transmission to the tower.

The dynamic component of the aerodynamic loading arises partly from the natural wind, partly from its interaction with the aerofoil blades and partly from mean wind variation over the cycle. The natural wind is variable in both speed and direction. The speed variations consist of both gustiness and the effects of turbulence and to some extent are a function of terrain and location. The sum total of variability, the "quality" of the wind, is known to be different in different places and at the moment is not easily predetermined. A further complication is that some wind turbines will be operated in clusters so that one machine will be in the wake of another. This will introduce an artificial increase in the degree of turbulence experienced (as well as reducing the mean wind speed). A programme of work involving the CERL/Reading team and engineers from Denmark, Holland and the USA is in hand to investigate the structural effects of this using the two Danish MW size machines at Nibe in Jutland (described in Pedersen and Nielsen, 1980). There are two principal sources of dynamic loads which result from interaction of the wind with the aerofoil. The first is buffeting due to stalling which can occur when the ratio of tip-speed to windspeed is less than about four. The second is the interaction of blade and tower for horizontal-axis machines. This latter is particularly severe if the rotor is downwind of the tower. The effect of mean wind variation over the cycle is present only for horizontal axis machines and is due to the wind velocity gradient (wind shear) close to the ground. Most such machines have a tower height approximately equal to the blade diameter and the ratio of maximum to minimum mean wind speeds over the disc is then typically between 1.15 and 1.3 (Sachs, 1978).

4. Resonances and Instabilities

Many of the dynamic strains in wind turbine structures are caused by forcing off-resonance. However it is possible for resonance problems to arise, particularly in machines for which the operational rotor speed is not constant. Most of the main structural components may be carefully designed so as to avoid a coincidence of the fundamental frequency with the rotor running speed or blade passage frequency. However, there can be no guarantee that resonant vibrations will not be excited by harmonics associated with the running speed and, indeed, this is known to happen on the Rutherford Laboratory VGVAWT (Pretlove and Hess, 1981) and probably also occurs on other machines. Another aspect of the problem is resonance in minor components such as struts, stays and fittings.

A distinct problem is that of flutter or dynamical instability in wind turbine structures. This involves the coupling of two or more degrees of freedom of the structure and a suitable input of energy from the wind. Conventional techniques may be used to avoid binary torsion bending flutter in the blades. However, there are other degrees of freedom in the structure as a whole which may collaborate to produce disaster. One potential mechanism on horizontal axis machines is coupling between tower head yaw motion and tower "nodding", that is, tower bending. On vertical axis machines there is the possibility of coupling between cross-arm bending and torsion - and there is evidence of vibration of this type (Pretlove, 1981). On some horizontal axis machines power shedding is achieved at high wind speeds by stalling the rotor. It is possible, in this condition, for a vortex shedding instability to be induced: At the least, aerodynamic damping of blade bending motion is reduced.

5. Stiff and Compliant Design Philosophies

The "stiff" design philosophy derives from two design considerations either of which may predominate. The first is the use of low cost and therefore low strength materials and fabrication techniques. This results in both a high structural stiffness and mass. The second is the deliberate avoidance of resonance by making the natural frequency of the structure higher than the assumed or measured forcing frequencies. Two obvious objections to this philosophy for wind turbines are (i) that inertial and gravity loads predominate over aerodynamic loads in the rotor, particularly for large machines, so that low mass is at a premium, and (ii) that cyclic forcing functions may have non-trivial higher Fourier components. The "compliant" philosophy is to design the structure in high strength materials worked to their static strength limit thereby reducing both material costs and inertia loadings. The objections to this philosophy are that it leads to vibration problems, both resonances and instabilities, and to an increased danger of fatigue or brittle fracture. At the present time there is no clear evidence in favour of one philosophy or the other though in the U.S. the trend is towards compliant design, particularly for towers. Most of the rotor blades currently in use have a relatively high thickness-chord ratio (10-20%) and as a result constructions using materials of a high specific strength have a fundamental natural frequency well above rotation rate (see, for example, Hess and Pretlove, 1981). Where compliant design is used for towers high levels of structural damping are provided by means of bolted joints. Even so, it may prove necessary to add extra damping in the form of vibration absorbers and to pay special attention to the avoidance of vibrational instabilities.

6. Scaling Effects

In the U.K. extensive experience is being gained, at the present time, concerning the structural integrity of a wide range of small wind turbines through the current field measurement programme. This includes both horizontal and vertical axis machines with a variety of different features such as two- and three-bladed machines and machines with pitch control. There is a natural tendency to extrapolate such experience to the designs for the new generation of middle and large sized machines. For quasi-static structural loads and stresses this information will be a useful guide though careful analysis must go hand-in-hand with extrapolation (Gordon, 1978). For dynamic loads and especially for instability prediction such extrapolation will be a necessary procedure but may be not a sufficient one. Vibrational phenomena may arise for large machines which are not indicated at all on the smaller ones.

Conclusion

In this paper the range of structural dynamic problems to be solved for the satisfactory design of large wind turbines has been reviewed. A start has been made to tackle these problems both here and abroad but there are still many unknown quantities. If power generation from the wind is going to be undertaken seriously in the U.K., as now seems likely, then an increasing effort is going to be needed to solve these problems. They present an interesting and important new challenge to structural dynamicists.

A list of the references made in this paper is available from the author.