AEROELASTIC MODELING OF WIND TURBINES

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1 Introduction

Over the last twenty years the technology of wind turbines underwent fast pacing development and progress. One should only take into account the increase in size by a factor of ~10 in order to get an idea of what happened. Today's machines have reached a diameter of more than 100m and produce energy at nominal power levels of several MW. Throughout this quick development phase, safety and reliability had always top priority which brings us to the content of these lectures.

The structure of all constructions is deformable. The level of deformation depends on the loading action on them as well as on the design specifications or constrains. Wind turbines are subjected mainly to aerodynamic loading as a result of their operation[1]. This means that we shall be dealing with a coupled system involving aerodynamics and structural dynamics. Most of the necessary background on aerodynamics has been already discussed in previous lectures, so here we will deal only with those aspects that are relevant to aeroelasticity. The basic idea is that as the flow passes over the wind turbine, the aerodynamic loads which will develop will result in the dynamic response of the system first by rotating the rotor but also by deforming the whole structure. The flow will be definitely unsteady and under certain conditions highly non-linear. Especially for stall regulated machines, but also for pitch regulated machines around rated operating conditions, the onset of stall is always a difficulty we have to deal with. Besides introducing significant vibration due to hysteresis, it can also degrade the aerodynamically induced damping and therefore leading to stability problems as well as high fatigue loads. But this is not all. Wind inflow in nature is turbulent which means that besides the unsteadiness which results in from the aeroelastic coupling, the excitation will vary in space and time both in magnitude and direction. The consequence of the turbulent character of the wind inflow is that the wind turbine will be subjected to fatigue loading which affects both its reliability (or else its time life) and safety. Furthermore in order to complete the picture, it is important to have in mind that wind turbines usually operate in clusters. So depending on the layout a wind turbine can be subjected to wake induced unsteady excitation originating from close by wind turbines. So in summary all the above should be convincing that the aerodynamic part is clearly challenging.

A lot of progress has been made in aerodynamic modelling so that in principle at least at a research level the wind energy community is capable of producing detailed aerodynamic computations using unsteady RANS models [1]. However when coming to aeroelasticity the computational cost involved is still too high. So in practical applications simplifications are necessary, some of which we will discuss in this lecture.

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[1] Besides aerodynamic loading, for off-shore applications, wave loading must be added. For on-shore constructions earthquake loading is in some cases necessary, while in icy climates, the effect of ice accretion must be taken into account as well.

In terms of structural modelling the situation seems more manageable. First the beam model is still a satisfactory approximation. Recently there have been developments concerning 2nd order non-linear beam theories while in many cases the classical beam theory has been upgraded to the Timochenko beam model which includes the shearing force. At present stability tools are at a high level of development and a lot of results have been added during the last few years helping to better clarify the relevant engineering issues. However there are some open issues which need further development, the most important of which concerns large deformations and rotations which could be anticipated in future designs if the structure of wind turbines becomes more flexible. Another important aspect is the prediction of structural damping which in some cases can play an important role [2]. Blades are made of composite materials which besides being degraded by aging, they behave differently depending on the ambient temperature.

So in conclusion aeroelastic analysis of modern wind turbine is a quite complicated problem with a lot of challenging multi-disciplinary issues still open (see [3] for recent review).

Aiming at a systems approach, in section 2 the concepts regarding the dynamic analysis of multi-component configurations are presented and the multi-body approach of dynamic analysis is explained. Based on this material, in section 3 we describe in detail the way one can derive the dynamic equations of a complete wind turbine. In particular for a typical turbine the kinematic and loading conditions that join a multi-component configuration into one single system are specified and the form of the final equations is given. Section 4 is devoted to aeroelasticity and more specifically to the coupling conditions between the flow and the structure. In this connection, an important part will concern the calculation of aerodynamic loads and in particular how this calculation introduces into the dynamic equations the dependence of the air loads on the structural response. Finally in section 5 we combine all of the previous developments and discuss the aeroelstic modelling of wind turbines through examples.

2 Multi-body Analysis

So far we considered the case of a single beam. However often in practice, and this is the case of a wind turbine, the configuration under consideration consists of several beams for each on of which a separate motion is defined. In principle it is possible to formulate the dynamics of such a system directly with respect to the global or inertial frame. But it turns to be easier to consider each component separately. Such an approach defines the so called multi-body analysis.

2.1 Bodies in motion

Let $[O;xyz]_G$ be the global (inertial) co-ordinate system and consider a body in motion for which all of the structural information we have, is defined with respect to a local system [Oxyz]. Let **R**, **A** define respectively the position and the orientation of [Oxyz] with respect to $[Oxyz]_G$ (Figure 2-1)