Engineering Structures 111 (2016) 131–151

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Structural control of wind turbines with soil structure interaction included

Breiffni Fitzgerald [a,*], Biswajit Basu [b]

[a] School of Civil & Structural Engineering, Dublin Institute of Technology, Ireland
[b] Dept. of Civil, Structural & Environmental Engineering, Trinity College Dublin, Ireland

ARTICLE INFO

Article history:
Received 8 September 2014
Revised 23 October 2015
Accepted 16 December 2015
Available online 6 January 2016

Keywords:
Wind turbine
Soil–structure interaction
TMD
ATMD
Structural control

ABSTRACT

The importance of considering soil structure interaction in structural control of wind turbines is investigated in this paper. An Euler–Lagrangian wind turbine mathematical model based on an energy formulation was developed for this purpose which considers the structural dynamics of the system and the interaction between in-plane and out-of-plane blade vibrations. Also, the interaction between the blades and the tower including a tuned mass damper (TMD) is considered. The turbine is subject to turbulent aerodynamic loading simulated using a modification to the classic Blade Element Momentum (BEM) theory with turbulence generated from rotationally sampled spectra. The turbine is also subject to gravity loading. The effect of centrifugal stiffening of the rotating blades has also been considered. The developed wind turbine model has been benchmarked against the NREL's aeroelastic model FAST. Three-dimensional models of the wind turbine foundation are designed and analysed in the finite element geotechnical code Plaxis. Bi-axial rotations of the foundation obtained from dynamic finite element analyses are used to calculate rotational spring constants. These spring constants are used in the wind turbine model to describe the soil–structure interaction (SSI) between the wind turbine foundation and the underlying soil medium. This paper shows that where there are uncertainties regarding the stiffness of the soil, passive vibration control schemes may be rendered ineffective. Furthermore, it is demonstrated that vibration control of wind turbines using the proposed active control scheme has a promising prospect in situations where soil parameter values are uncertain.

1. Introduction

1.1. Soil–structure interaction

When a structural element is in contact with the ground the structural displacements and the ground displacements are not independent of each other. The process by which the response of the structure affects the response of the underlying soil and by which the response of the soil affects the response of the structure is known as soil–structure interaction (SSI).

It is well known that the dynamic response of a structure on a flexible soil may be different from the response of a similarly excited structure supported on firm soil. Veletsos and Verbic [1] showed that the presence of flexible soil underneath the foundation of a structure increases the damping capacity of the foundation and reduces the structure's natural frequency. Luco [2], in a study on seismic response of tall chimneys, showed that soil–structure-interaction (SSI) had an effect only for softer soils and could lead to reductions or increases in response, depending on the characteristics of the chimney and the seismic excitation. Luco's work was verified by Moghaddasi et al. [3] who carried out a Monte Carlo simulation for a range of single degree of freedom (SDOF) structures and soil conditions excited by a series of seismic excitations. Novak and Hifnawy [4,5] showed that the response of a structure when subject to dynamic wind loading can be affected by SSI.

A full review of the development of SSI can be found in Kausel [6].

1.2. SSI for wind turbines

Traditionally, the use of SSI in design and analysis was restricted to structures in seismic zones [7,8]. In traditional design and in past studies, wind turbine foundations were often modelled as fully fixed. In this simple model the soil-foundation system is not considered. Recent studies have attempted to improve on this simplification and there has been significant work on SSI related to wind turbines in recent years.

* Corresponding author.
E-mail address: breiffni.fitzgerald@dit.ie (B. Fitzgerald).

http://dx.doi.org/10.1016/j.engstruct.2015.12.019
0141-0296/

Zaaijer [9] modelled the dynamic behaviour of foundations of offshore wind turbines. The author investigated the sensitivity of the support structure's natural frequency to variation in foundation types. This work was extended by Camp et al. [10]. Particular attention was paid to the uncertainty of several key geotechnical design parameters. The report found that the sensitivity of gravity base foundations to soil parameters is higher than for piled foundations, lending to the presumption that gravity base foundations cannot be uniform within a wind farm, but rather designed for local soil conditions at the location of the foundations. Following this, Zaaijer [11] investigated the sensitivity of the support structure's natural frequency to variation in models for pile foundations. Murtagh et al. [12] showed that accounting for a flexible soil-foundation system can have the effect of reducing a wind turbine's fundamental natural frequency and introduces a considerable amount of damping to the system. Bush and Manuel [13] compared fixed-base and flexible-based foundation models and showed that inclusion of the soil-foundation system can affect the dynamic response of the turbine.

Adhikari and Bhattacharya [14] characterised the dynamic behaviour of wind turbines on flexible foundations subjected to wind and wave loading. Their model was based on an Euler–Bernoulli beam–column with elastic end supports. The elastic end-supports are considered to model the flexible nature of the interaction of these systems with the foundation.

Harte et al. [15] studied the dynamic interaction between the wind turbine structure and the foundation system. Impedance functions were used to couple the foundation to the structure. Although SSI is generally considered to have a positive effect on structural vibrations (by adding damping to the system), this study revealed that the relative displacement of the nacelle showed only a slight reduction in response when SSI was considered. In fact, SSI was found to have a detrimental effect on the total displacement of the nacelle, especially for softer soils.

1.3. Control of wind turbine vibrations

Traditionally in vibration control studies wind turbine foundations have been modelled as fully fixed. In this simple model the soil-foundation system is not considered. This idealized model may lead to underestimation of the damping and could potentially lead to overestimation of stiffness and thus the system's natural frequency. Many studies have investigated wind turbine dynamics and control without including SSI in their models (e.g. [16,17]).

In recent years the effects of SSI on vibration control of wind turbines has been examined by more researchers. Stewart and Lackner [18] investigated offshore wind turbine load reduction by employing optimal passive TMDs. Both fixed-bottom and floating substructures were considered in this study. In another recent study Fitzgerald and Basu [19] studied the effect of damage to turbine foundations on the structural dynamics of a wind turbine.

1.4. Focus of this study

The aim of this study is to investigate the effects of SSI on the response of a wind turbine, specifically on the response of the nacelle and the impact it has on the design of a tuned mass damper (TMD) in controlling nacelle vibration.

A multi degree of freedom (MDOF) model of a wind turbine has been developed in this paper. The model has been developed using an Euler–Lagrangian approach which leads to a time varying system with the possibility of negative damping. This model has been benchmarked against the NREL's aeroelastic code FAST. Time domain simulations are performed on the model using turbulent aerodynamic loading and gravity loading.

Three-dimensional models of the wind turbine's foundation are designed and analysed in the finite element geotechnical code Plaxis. The bi-axial rotations of the foundation are used to calculate rotational spring constants for use in wind turbine models to describe the SSI between the wind turbine foundation and the underlying flexible soil medium. The response of a wind turbine model with a fully fixed foundation (i.e. no SSI considered) is compared to a wind turbine with a foundation (including the effects of SSI).

Soil stiffness is often initially estimated from a ground investigation. Soil stiffness for design is based on empirical formulae or the experience/judgement of the engineer. This can sometimes lead to inaccuracies and uncertainties regarding the true soil stiffness. This paper shows that when there are uncertainties regarding the stiffness of the soil, passive vibration control schemes may be rendered ineffective. This paper also proposes an active vibration control scheme that is effective in reducing the wind turbine vibrations even when there is uncertainty or inaccuracy with regard to the stiffness of the soil.

2. Wind turbine models

Dynamic models of wind turbines are created using the Euler–Lagrange formulation. The wind turbine models consist of rotating pre-twisted blades modelled as continuous beams of variable mass and stiffness. The blades are coupled in the in-plane and out-of-plane directions. The blades are attached at the root to a mass representing the tower/nacelle of the turbine which can also have in-plane (side-to-side) and out-of-plane (fore-aft) vibrations. The model therefore accounts for coupling in the two directions of blade vibration and accounts for blade–tower interaction. A schematic of the wind turbine vibration model is shown Fig. 1.

Two cases are studied. The first case studied considers a wind turbine model with a fully fixed foundation (i.e. no SSI, shown in Fig. 1). The second case considers a wind turbine with a foundation (including the effects of SSI, shown illustratively in Fig. 2).

Three models are considered to investigate these two cases. The first model is an uncontrolled model. This model has 8 degrees of freedom (DOF) without a foundation. This accounts for three blades and the nacelle/tower vibrating in two different directions. Including a foundation modelled as a mass with bi-directional rotational stiffnesses, gives an uncontrolled model with SSI included and has 10 DOF. The next model developed is a passively controlled model. A TMD is attached to the nacelle/tower to control the out-of-plane nacelle vibration since the vibration in this direction is significantly larger than the side-to-side vibration. This gives rise to a 9 DOF model without a foundation and a 11 DOF model with foundation. The last model is an actively controlled 9/11 DOF model with actuators controlling the TMDs in the previous model. The models are derived using an Euler–Lagrange energy formulation approach after Fitzgerald et al. [20].

2.1. Uncontrolled model with no foundation

The in-plane and out-of-plane vibrations of the ith blade are modelled by two generalized DOFs, $q_{i,in}(t)$ and $q_{i,out}(t)$. The coupled in-plane and out-of-plane mode shapes, $\phi_{in}(x)$ and $\phi_{out}(x)$, have been normalized at the tip so that $q_{i,in}(t)$ represents the in-plane tip displacement and $q_{i,out}(t)$ represents the out-of-plane tip displacement. The structural twist of the blade is accounted for in the calculation of the in-plane and out-of-plane mode shapes. Therefore, these mode shapes each have both edgewise and flapwise components. In the following formulation, it has been assumed that the in-plane and out-of-plane displacements at any point x along the ith blade, represented by $u_{i,in}(x,t)$ and $u_{i,out}(x,t)$