Engineering Structures 31 (2009) 358–368

Contents lists available at ScienceDirect

Engineering Structures

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

Tuned liquid column dampers in offshore wind turbines for structural control

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ARTICLE INFO

Article history:
Received 19 June 2007
Received in revised form
20 July 2008
Accepted 1 September 2008
Available online 1 October 2008

Keywords:
TLCD
Offshore wind turbine
Vibration control
Wind loading
Wave loading
Correlation

ABSTRACT

With offshore wind turbines becoming larger, being moved out further at sea and subjected to ever greater wind and wave forces, it is necessary to analyse the dynamics and minimise the responses of these structures. In this paper, the structural responses of offshore wind turbines are simulated with an attached damper (Tuned Liquid Column Damper (TLCD)) for controlling the vibrations induced within the structure. This requires a realistic simulation of the forces that these tall, flexible and slender structures are subjected to, and consequently the implementation of a damper to control the resulting undesirable vibrations that are induced within the structure. Since sea waves are caused by wind blowing for a sufficiently long time, the state of the sea is related to wind parameters and there exists the possibility of correlating wind and wave loading conditions on structures. The Kaimal spectrum for wind loading is combined with the JONSWAP wave spectrum to formulate correlated wind and wave loadings. The offshore turbine tower is modelled as a Multi-Degree-of-Freedom (MDOF) structure. Cases for flat sea conditions, with which parallels to onshore wind turbines may be drawn, are first simulated. Simulations are presented for the MDOF structure subjected to both 'moderate' and 'strong' wind and wave loadings. Cases of the blades lumped at the nacelle along with rotating blades are investigated. The reduction in bending moments and structural displacement response with TLCDs for each case are examined. A fatigue analysis is carried out and the implementation of TLCDs is seen to enhance the fatigue life of the structure. An analysis, taking into account the extended fatigue life and reduced bending moments on the structure-TLCD system, is presented.

1. Introduction

With the present day energy crisis becoming more pronounced, due to depletion of fossil fuel stocks, offshore wind turbines are becoming a viable and attractive means of producing electricity. An offshore wind turbine harnesses the wind energy out at sea to produce electrical energy. To dynamically examine these slender structures in an offshore environment, it is necessary to correlate wind and wave loadings, and to investigate the force-structure interaction arising from such a correlation. Due to the slenderness of offshore wind turbines, the combination of wind and wave forces may produce excessive vibrations that will inhibit the mechanical system in the nacelle from converting wind energy to electrical energy. Reductions in fatigue life, and higher foundation and tower construction costs will also arise from uncontrolled vibrations in the offshore wind turbine structural system.

Turbulence from offshore wind produces small capillary waves at the sea surface, with similarly small wavelengths in the range of centimetres. The wind acts on the tiny walls that these ripples create, causing them to become larger. Wind blowing over the wave produces pressure differences along the wave profile, causing the wave to grow. The process is unstable because, as the wave gets bigger, the pressure differences get bigger, and the wave grows exponentially. Finally, the waves begin to interact among themselves to produce longer waves [1]. The interaction transfers wave energy from short waves generated by the Miles mechanism, to waves with frequencies slightly lower than the frequency of waves at the peak of the spectrum. Eventually, this leads to waves going faster than the wind, as noted by [2].

Davenport [3] proposed an expression for the velocity spectrum for the distribution of energy within turbulent wind flow, at a height related to the size of gusts at that height. However, this spectrum was independent of height, and was also seen to overestimate the energy in the higher frequency range. Harris [4] proposed a velocity spectrum which was independent of height, and that guaranteed a non-zero integral length scale of turbulence. Harris [5] subsequently provided a wind spectrum based on a modified version of the Von-Kàrmàn spectrum, which included the variation of spectral energy with height. Kaimal et al. [6] developed the first expression for the variation of spectral energy with height, which includes eddy currents of varying size acting between the structural nodes.

Despite the irregular random nature of wind inducing seemingly random wave heights and wave periods in a typical offshore

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doi:10.1016/j.engstruct.2008.09.001

setting, any associated changes that occur with the state of the sea are slow enough to allow the characterization of a sea state. A sea state is defined [7] as a wave situation that is approximately constant during some time interval of appropriate duration characterized by the significant wave height H_s and the characteristic zero crossing point T_z. The wave height H_s is the average height (trough to crest) of the one-third highest waves valid for the indicated 12 h period. The sea surface, which is made up of a superposition of sinusoidal waves with random heights and periods, will oscillate vertically in an aperiodic manner around a zero level reference point. The time intervals between each meeting of the sea surface and the zero level vary around an average value, T_z. Hence, the process is narrow-banded, and can be related to the mean wind speed.

Pierson and Moskowitz [2] assumed that if the wind blew for a long time over a large area, the waves would come into equilibrium with the wind, and low frequency waves are developed in a fully developed sea. A large area being defined as 5000 wave lengths on a side, and a long time being defined as 10,000 wave periods [8]. This is the concept of a fully developed sea. To obtain a spectrum of a fully developed sea, they used accelerometers to measure wave data on ships in the North Atlantic. Hasselmann et al. [9] measured wave data in the North sea and discovered that a sea never actually becomes fully developed. They developed their own spectrum (JONSWAP), which takes into account a higher peak than the Pierson–Moskowitz spectrum.

The expression for the in-line force per unit length along a cylinder was first investigated over 50 years ago [10]. The mitigation of vibrations of an offshore structural system with an additional damper, when subjected to in-line random wave forces, was investigated [11]. In the stochastic analysis performed, a random type of wave force derived from the Morison equation for small bodies was applied. It was observed that, in terms of the power spectral density, the effect of the vibration mitigation and the dynamic performance of the offshore structural system were greatly improved when the new damping devices were applied to the offshore structural system. By considering the environmental loading on a structure with TMD to be a long-term nonstationary stochastic process, characterized by a probabilistic power spectral density function (PSDF) [12], it was found that the use of a TMD could significantly reduce the fatigue damage of an offshore structure. A method of determining the 'generalized' wave force was based on an analytical approximation of the mode shape function, together with the physical wave loading being calculated from linearized Morison equation [13]. The effectiveness of H_2 active control is numerically demonstrated, with a reduction in the standard deviation of the deck motion of passive TMD case of 50% for the active TMD case with H_2 active control. A jacket-type offshore platform modelled as a SDOF structure with attached active mass damper (AMD) was recently simulated by using the linearized Morison equation is used to estimate the wave load [14]. An active control strategy [15] was used to determine the control force magnitude for serviceability and survival of tension leg platforms (TLPs), subjected to wind and wave loadings. Significant reduction in low-frequency hull motion of the TLP was observed. Thus, although several investigations have been carried out for the control of offshore structures, little attention has been focused on the vibration control of flexible offshore structures subjected to joint wind and wave loading with an additional damping system.

Structural engineers are increasingly turning to additional damping systems to protect structures from the damaging effects of the environment. Tuned liquid dampers (TLD), of which Sakai et al. [16] proposed the first tuned liquid column damper (TLCD) as a means of suppressing vibrations within structures, are dampers whose damping effects depend on a liquid residing in the damper and which are specifically tuned to the natural frequency of a structure. TLCDs, which are U-shaped liquid dampers, are a variation on the TLD which aim to utilize the gravitational restoring force of the displaced liquid more efficiently. The frequency of oscillation of the liquid in a TLCD for vibration control is specifically tuned to the natural frequency of a structure. The tuning ratio, which is the ratio of the natural frequency of the TLCD to that of the structure, is optimised in order to ensure an efficient transfer of shear force from the TLCD to the structure. Vibrations are suppressed within a structure with an attached TLCD, due to the gravitational restoring force acting on the displaced liquid. It is possible that a non-optimal design of the TLCD would result in dead mass in the TLCD, which does not present a problem in a TLD. However, in a TLCD energy is also dissipated through orifice(s) which reside within the cross section of the damper. The utilization of TLCDs as a means of suppressing vibration energy within structures is being accelerated due to factors such as: they can dissipate very low amplitude excitations (unlike Tuned Mass Dampers (TMDs)), they are consistent over a wide range of excitation levels, and they are self-contained passive damping devices, with little auxiliary equipment, personnel or power required to operate and maintain it, and are easy to install. TLCDs typically comprise of 1%–2% of the total mass of the structure, compared with 4%–5% of that with a pendulum type damper. Compared with other liquid dampers (e.g., Tuned Liquid Dampers), TLCDs prove more efficient with respect to volumetric efficiency (when adequate horizontal space is available), TLCDs introduce extra damping effects and variable damping due to the orifice, and the damping effect of TLCDs is easier to quantify. Changing soil properties over time may alter the natural frequencies of the structure, and although the TLCD is usually tuned to the natural frequency of the structure, the orifice damping present in the TLCD will also dampen the shifted frequencies to a certain extent.

TLCDs have been implemented in Hotel Cosima, Hyatt Hotel and Ichida Building in Osaka [17] and also in One Wall Centre in Vancouver. An investigation into the effects of liquid storage tanks containing glycol on the dynamic response of offshore structures concluded that prudent selection of the geometry of the storage tanks would dampen the response of the platform of the offshore structure [18]. Samali et al. [19] investigated the application of TLCDs to tall buildings, and concluded that they may be successfully used to damp vibrations in such buildings. Xu et al. [20] studied the application of TLCDs compared to TMDs and concluded that TLCDs are as effective as TMDs in damping structures, but also possess practical advantages. Hochrainer [21] established a geometric analogy between the sealed TLCD (linearized) with the gas-spring effect (in parallel action with the gravitational restoring force) to the linear TMD (pendulum type). Balendra et al. [22] demonstrated the effectiveness of TLCDs in suppressing wind-induced accelerations for towers with varying natural frequencies. Balendra et al. [23] studied the performance of the TLCD on vibration control of structures with a varying degree of taper. They concluded that flexural buildings experienced greater acceleration and displacement reductions than shear buildings. They also observed that the height at which the maximum reduction in structural acceleration is achieved, decreases with the degree of taper. Gao et al. [24] investigated the optimisation of the TLCD through a parametric study. It was seen that it is possible to install a TLCD in a flexible structure by increasing the area ratio when the required length of liquid column is too long. Hochrainer and Ziegler [25] presented optimal solutions for benchmark MDOF structures with multiple TLCD. Ziegler [26] showed that the TLCD is a practical and cost effective alternative to the TMD in civil engineering structures. Ghosh and Basu [27] proposed and studied the use of a complaint spring connected TLCD for nonlinear structures. Other studies into TLCDs have been conducted by [28–36].