Ocean Engineering 87 (2014) 151–161

Contents lists available at ScienceDirect

Ocean Engineering

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

Vibration mitigation of structures subjected to random wave forces by liquid column dampers

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ARTICLE INFO

Article history:
Received 5 July 2013
Accepted 16 May 2014
Available online 21 June 2014

Keywords:
Wave load
Offshore structures
Liquid column dampers
Vibration
Control

ABSTRACT

The effective performance of two passive vibration mitigating devices namely tuned liquid column damper (TLCD) and tuned liquid column ball damper (TLCBD) are studied for control of wave induced vibration. The stochastic dynamic analysis of structure with and without damper is first presented in frequency domain for parametric study on the performance of both the dampers to control wave induced vibration response. The optimum performance of TLCD and TLCBD systems is further investigated to study the effectiveness of a particular damper system over the other. In order to obtain optimal damper parameters to yield the best possible TLCD and TLCBD performance under a given condition, optimization is performed by minimizing the root mean square displacement of the structure. Numerical study is taken up to explore the effectiveness of both the TLCD and TLCBD. Though there is a wide gap between structural frequency and frequency of wave load, the performances of both the dampers are found to be potential for wave vibration mitigation. The optimum performance study in general shows that TLCBD perform better than TLCD. The performances of both the damper system are further verified in time domain under random wave load.

1. Introduction

Various offshore structures are widely applied for exploration and production of oil and gas, offshore exploitation such as operation station, cross-strait bridges, floating breakwater and complex of entertainment facilities. Such structures placed in the ocean for exploration and productions of resources beneath the ocean floor are subjected to various environmental conditions like ocean waves, wind and current, earthquakes and tsunami waves. These structures are in general heavily engineered and expensive. For offshore platform being employed as a public complex, the stability and comfort will be the major concern besides the safety requirement. Moreover, an accident of any kind can have devastating effects on the ocean environment. Therefore, controlling wave induced vibrations for efficient design of such structures is becoming an important issue. The present study focuses on the wave vibration control using tuned liquid column dampers (TLCDs).

Since its inception (Saoka et al., 1988), TLCD has attracted considerable attention in the field of vibration control of structures under wind and earthquake load due to the requirement of lower mass ratio and consistent behaviour over a broader range of exciting frequencies. Xu et al. (1992a, 1992b) investigated the possible application of TLCD in mitigating the cross-wind and along wind response of wind sensitive structures. Won et al. (1996) investigated the performance of TLCD for seismic vibration control considering non-stationary stochastic earthquake model. Gao et al. (1997) presented procedures for optimization of parameters of TLCD by minimizing the peak structural response to harmonic excitations in a wide frequency range of flexible structures. Balendra et al. (1995) conducted a parametric study to obtain the optimum parameters of TLCD for suppression of wind induced responses of towers with different fundamental frequencies and further investigated the performance of TLCD under random wind loads (Balendra et al., 1999). An important guideline for design of TLCD under white noise type of wind excitation was presented by Wu et al. (2005). A robust reliability-based design of TLCD is studied by Taflanidis et al. (2007) under earthquake excitation considering model parameter uncertainty. Chakraborty et al. (2012) studied the performance of TLCD considering maximum liquid motion constrained in seismic vibration control. The existing studies on TLCD as discussed above are primarily for wind and seismic vibration control. However, the applications of wave vibration control are comparatively limited. Alves and Batista (1999) suggested the use of tuned mass dampers (TMDs) in the

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http://dx.doi.org/10.1016/j.oceaneng.2014.05.004

columns of a tension leg platform (TLP) hull to attenuate the heave response of TLP for reduction of stress level in riser tendons and minimizing fatigue problems. Patil and Jangid (2005) studied passive vibration control of offshore jacket platforms using various energy dissipation devices such as viscoelastic, viscous and friction dampers under wave loading. The viscoelastic dampers found to perform better due to the fact that the added viscoelastic dampers led to increased viscous damping and lateral stiffness. This helps to reduce the response of offshore jacket platforms significantly. A typical system of a tension-leg type floating platform incorporated with TLCD was investigated by Lee et al. (2006). From both the analytical and experimental results, it was found that properly tuned liquid damper system could effectively reduce the dynamic response of the platform. Spillane et al. (2007) introduced the idea of a tuned oscillator consisting of vertical caissons which are open at the bottom to the sea and closed on the top by a dual chamber operating as an air spring. It was experimentally verified that the water column inside the caisson acted equivalently as a TMD and led to considerable reduction of vibrations of deep-water TLPs. A robust design of mass dampers was proposed by Taflanidis et al. (2009) for coupled heave and pitch response mitigation of TLPs under random wave excitation. The traditional TLCD system was further modified by Lee and Juang (2012) with an innovative concept of underwater TLCD system and found that the accurately tuned such system could effectively reduce both the vibration amplitude and tensile forces measured in the mooring tethers of offshore platform.

The studies of existing literature revealed that the application of liquid dampers in seismic and wind vibration effect is noteworthy. But, the same is not the case for wave loading; except the study by Lee et al. (2006) and Lee and Juang (2012). Keeping this in view, an attempt has been made in the present study to explore the effectiveness of liquid column dampers for control of wave induced vibration of structure. To be specific, the work deals with comparative study on the performance of TLCD and tuned liquid column ball damper (TLCBD) to mitigate the vibration of structures subjected to random wave forces. In doing so, the theoretical formulations for structure with and without dampers (both TLCD and TLCBD) system in frequency domain are first presented. Subsequently, the parametric study on the performance of TLCD and TLCBD in reducing wave induced vibration effect is performed to understand the importance of various parameters in controlling the dynamic response of structure. The random wave force is modelled by well-known Morison equation (Malhotra and Penzien, 1970). The statistical properties of the wave force are obtained by using the Pierson–Moskowitz (PM) wave height spectrum (Pierson and Moskowitz, 1964). The optimum performance of TLCD and TLCBD systems is further investigated to study the effectiveness of a particular damper system over the other. The stochastic structural optimization (SSO) is performed by minimizing the root mean square displacement (rmsd) of the structure in order to obtain the optimal damper parameters to yield the best possible TLCD and TLCBD performance under a given condition. The performances of both the dampers are further verified in time domain under random wave load time history. A comparative study is made to explore the effectiveness of both the damper systems in mitigating wave induced vibration of structures.

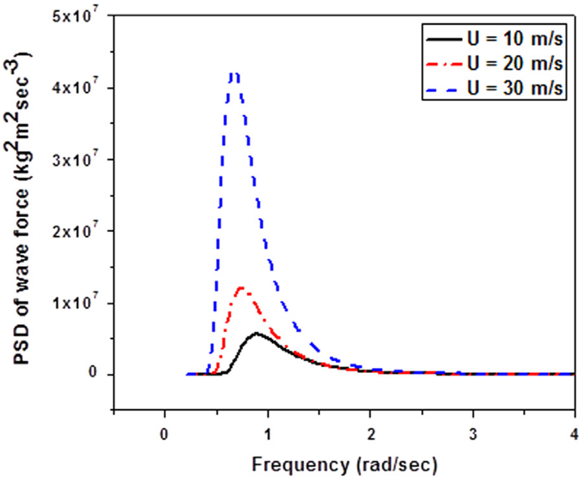

Fig. 1. PSD of wave load.

2. Stochastic dynamic analysis under wave load

The random wave forces acting on an offshore fixed-tower structure can be computed by considering corresponding projected area and volume of the structure using Morison equation. The resulting dynamic equation of motion of a structure fixed at base can be written as (Chakrabarti, 1987)

$$m_0\ddot{x}+c_0\dot{x}+k_0x=K_M(\ddot{u}-\ddot{x})+K_D|\dot{u}-\dot{x}|(\dot{u}-\dot{x}) \tag{1}$$

where m_0, c_0 and k_0 are the mass, damping and stiffness of the single degree of freedom (SDOF) system; x, $\dot{x}$, $\ddot{x}$ are the displacement, velocity and acceleration of the structure. $\dot{u}$, $\ddot{u}$ are the wave velocity and acceleration, respectively. The coefficients, $K_M=\rho C_m v$ and $K_D=0.5\,\rho C_d a$ in which C_m and C_d are the inertial and drag coefficients, respectively, ρ is the density of water, v is the projected volume and a is the projected area per unit length. The structural components of jacket type platform providing the buoyancy is considered to be small as compared to the wave-length, therefore, neglecting the wave–structure interaction, Eq. (1) can be simplified to

$$m_0\ddot{x}+c_0\dot{x}+k_0x=K_M\ddot{u}+K_D|\dot{u}|\dot{u}=f(t) \tag{2}$$

The random wave force acting on offshore fixed-tower structure is obtained by using the Morison equation. The primary loading is in the form of wind produced surface waves, modelled as a zero mean ergodic Gaussian process consistent with the usual random model for ocean waves. The force can be expressed by $f(t)=f(\omega)e^{i\omega t}$, where $f(\omega)$ is the random amplitude of wave force. The statistical properties of the covariance function of $f(t)$ using ensemble averaging with Gaussian random wave model under the assumption that $\dot{u}(t)$ and $\ddot{u}(t)$ are a stationary bivariate Gaussian stochastic process have been derived by Borgman (1967). For the present study, the PM wave height spectrum defined by Eq. (A.4) in Appendix A is used to describe the power spectral density (PSD) of wave velocity and acceleration. Subsequently, the force spectrum i.e. the PSD function of the wave force $f(t)$ is obtained from Eq. (A.8). The details of obtaining the PSD with useful references are briefly discussed in Appendix A. Typical variation of PSD of wave force is presented in Fig. 1 for various wind velocities. The Philip's constant α is taken as 8.1×10^{-3} and $B=0.74g/U$, where U is the characteristic wind speed over water and g is the gravitational constant.

Assuming a linear structural behaviour, the structural response can be considered to be harmonic (Lee et al., 2006) as $x(t)=x(\omega)\exp(i\omega t)$. Substituting this and the associated time derivative in Eq. (2), one can readily obtain the following:

$$x(\omega)=\frac{f(\omega)}{(-m_0\omega^2+i\omega c_0+k_0)}=H_x(\omega)f(\omega) \tag{3}$$

Here, $H_x(\omega)$ is termed as the complex frequency response function (FRF) corresponding to the surge motion of the structure expressed as

$$H_x(\omega)=\frac{1}{(-m_0\omega^2+i\omega c_0+k_0)} \tag{4}$$