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Using pipe-in-pipe systems for subsea pipeline vibration control

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ABSTRACT

Pipe-in-pipe (PIP) systems are increasingly used in subsea pipeline applications due to their favourable thermal insulation capacity. Pipe-in-pipe systems consist of concentric inner and outer pipes, the inner pipe carries hydrocarbons and the outer pipe provides mechanical protection to withstand the external hydrostatic pressure. The annulus between the inner and outer pipes is either empty or filled with non-structural insulation material. Due to the special structural layout, optimized springs and dashpots can be installed in the annulus and the system can be made as a structure-tuned mass damper (TMD) system, which therefore has the potential to mitigate the pipeline vibrations induced by various sources. This paper proposes using pipe-in-pipe systems for the subsea pipeline vibration control. The simplification of the pipe-in-pipe system as a non-conventional structure-TMD system is firstly presented. The effectiveness of using pipe-in-pipe system to mitigate seismic induced vibration of a subsea pipeline with a free span is investigated through numerical simulations by examining the seismic responses of both the traditional and proposed pipe-in-pipe systems based on the detailed three dimensional (3D) numerical analyses. Two possible design options and the robustness of the proposed system for the pipeline vibration control are discussed. Numerical results show that the proposed pipe-in-pipe system can effectively suppress seismic induced vibrations of subsea pipelines without changing too much of the traditional design. Therefore it could be a cost-effective solution to mitigate pipe vibrations subjected to external dynamic loadings.

1. Introduction

Pipe-in-pipe (PIP) systems are increasingly used in subsea pipeline applications due to the exceptional level of thermal insulation they provide. Pipe-in-pipe systems consist of an inner pipe, conveying the hydrocarbons, and an outer pipe, withstanding the external hydrostatic pressure. The annulus between the inner and outer pipes is either empty or filled with non-structural insulation material like mineral wool, polyurethane foam or aerogel [1]. Thanks to their exceptional thermal insulation capacity, pipe-in-pipe systems are well suited for the transportation of hydrocarbons at high pressure and high temperature (HP/HT), preventing hydrate formation and ensuring high discharge temperature at the arrival facility. Today, pipe-in-pipe systems are widely used in the North Sea, the Pacific, Gulf of Mexico and Africa.

Previous studies on subsea pipe-in-pipe systems mainly focused on the structural instabilities. For example, extensive experimental and numerical investigations have been carried out on the propagation buckling (e.g. [2–5]) and upheaval buckling [6] phenomena of subsea pipe-in-pipe systems. Besides these buckling issues, another factor that may severely threaten the integrity of subsea pipelines is the vibrations of free spans induced by various sources such as vortex shedding or earthquake. It is known that free spans can be formed due to the seabed irregularities during installation or the subsequent scouring and pipeline horizontal movements during operation [1]. Pipeline free spans can have a critical influence on the safety and integrity of the pipeline operation since they are susceptible to vortex-induced vibrations (VIV) and hence fatigue damage. Moreover, subsea pipelines may traverse through seismic active zones, different seismic hazards may impose severe damages to the pipeline systems. A review of many previous earthquake events reveals that for the buried pipelines, the permanent ground deformation due to soil failure may have severe influence on the pipeline integrity [7]. While for the unburied pipelines, both seismic ground waves and permanent ground deformation can cause severe damage to the pipelines [1].

Vortex shedding induced vibrations on the subsea pipelines have been systematically studied by many researchers and various vibration control methods and devices have been developed (e.g. [8,9]). Kumar et al. [10] provides an excellent review on these

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methods. For the seismic responses of subsea pipelines, literature review reveals that previous studies are rare. Nath and Soh [11] investigated the harmonic and seismic responses of offshore oil pipelines in proximity to the seabed using finite element method. Datta and Mashaly analyzed the transverse seismic responses of buried [12] and free-spanning [13] submarine pipelines under random seismic excitation in the frequency domain based on the spectral approach. Zeinoddini et al. [14] investigated the pipe/water interactions in free-spanning submarine pipelines under severe ground excitations. These studies show that severe earthquakes can result in catastrophic damages to subsea pipelines. How to mitigate these adverse vibrations is deemed important. To the best knowledge of the authors, no open literature reports the vibration control method for subsea pipelines when they are subjected to earthquake loadings.

As will be presented in Section 2, a pipe-in-pipe system can be properly designed as a non-conventional structure-tuned mass damper (TMD) system by adding optimized springs and dashpots in the annulus, which therefore has the potential to mitigate subsea pipeline vibrations induced by various sources without substantially increasing the manufacturing costs and weight of the pipe. A TMD is a device consisting of a mass, a spring and a dashpot that is attached to a vibrating primary structure to attenuate the undesirable vibrations induced by winds or earthquake loadings. The natural frequency of the TMD is tuned to the fundamental vibration frequency of the primary structure so that the damper will resonant out of phase with the original structure and a large amount of the structural vibrating energy is transferred to the TMD and then dissipated by the damper. Due to its simplicity and effectiveness, TMD systems have been widely applied since 1970s in many engineering structures such as tall buildings, towers and bridges [15]. In the conventional TMD design the auxiliary mass is very small, typically in the order of one to a few percent of the primary structure. Due to the small mass of the TMD system, a general agreement on the effectiveness of the conventional TMD system is not formed when it is used to mitigate seismic induced vibrations. Researchers indicate three inherent limitations to the seismic effectiveness of the TMD as summarized by De Angelis et al. [16]: (i) the lack of robustness against deviations in design parameters; (ii) a high dependency on earthquake frequency content; and (iii) the impulsive character of the earthquake excitation. To enhance the effectiveness of the TMD system, a larger mass ratio (up to 100% and even more in terms of modal quantities) was introduced by some researchers and this system was normally described as a non-conventional TMD [16].

By adding large mass to the primary building and bridge structure is not technically practical and may raise safety issues sometimes. To avoid these problems, the masses already present on the structure to be protected are converted into tuned masses in the non-conventional TMD design, while the structural or architectural function of the structure is retained [16]. In other words, no additional mass is needed for the non-conventional TMD system. This non-conventional TMD system has been studied by some researchers recently and was applied in some building (e.g. [17–23]) and bridge [24] structures. Previous studies show that it is feasible and effective to use non-conventional TMD systems to reduce the vibrations of primary structures.

This paper proposes using pipe-in-pipe systems for the vibration control of subsea pipelines. It will be demonstrated that this system can be designed as a non-conventional structure-TMD system as mentioned above to mitigate pipeline vibrations. The optimum values for the springs and dashpots installed in the annulus are derived in Section 2. To demonstrate the effectiveness of the proposed system, a subsea pipe-in-pipe system with a free span subjected to transverse earthquake is adopted as an example and numerical analyses are carried out by using the finite element code ANSYS. The detailed numerical modelling is presented in Sections 3 and 4 define the earthquake loadings that will be used in the analysis. In Section 5, the seismic responses of the traditional and proposed pipe-in-pipe systems are calculated and discussed. Finally in Section 6, two possible design options and the robustness of the proposed system are commented.

2. Pipe-in-pipe as a non-conventional TMD system

2.1. Traditional pipe-in-pipe system

There are two types of pipe-in-pipe systems commonly used in the offshore industry [25]: (i) fully bounded or compliant PIP, in which the entire annulus is filled with insulation material, and (ii) unbounded or non-compliant PIP, in which the insulation is achieved by wrapping standard size insulation pads onto the inner pipe. In the compliant PIP system, load transfer is continuous and the inner and outer pipes deform uniformly. In the non-compliant PIP system the inner and outer pipes can move relative to each other, it is therefore has the potential to be designed as a structure-TMD system and suitable for the vibration control when it is subjected to different sources of vibrations.

Fig. 1 shows a typical non-compliant pipe-in-pipe system. A non-compliant PIP normally comprises an inner pipe, an outer pipe, insulation layer(s), bulkheads and centralizers. Bulkheads are forged fittings attached to the pipe-in-pipe pipeline to maintain structural integrity during installation and operation and to serve as installation aids in variety of ways [1]. They are normally welded to both the inner and outer pipes at several locations especially at both ends, to fully constrain relative axial motions between the inner and outer pipes. The centralizers are generally polymeric rings that are clamped on the inner pipe at regular intervals. The spacing between two adjacent centralizers may be 2 m for reeled pipelines and can up to 12 m for the S-lay and J-lay installation methods [1]. The purpose of the centralizers is to effectively centralize the inner pipe to prevent possible damage (like abrasion or crushing) to the thermal insulation layer during installation and to minimize loads on the insulation layer during installation and operation. To facilitate the installation of inner pipe and centralizers, a gap of 1–10 mm is usually reserved between the centralizers and the outer pipe [6].

2.2. Proposed pipe-in-pipe system and equivalent TMD simplification

By examining the structural layout of the non-compliant pipe-in-pipe system as shown in Fig. 1 and also by comparing it with the structure-TMD concept mentioned in Section 1, it can be seen that the pipe-in-pipe system has the potential to be designed as a non-conventional structure-TMD system by replacing the hard polymeric centralizers by optimized springs and dashpots to connect the inner and outer pipes. By optimizing the spring stiffness and damping coefficient, the inner pipe can vibrate out of phase with the outer pipe and the vibration of the systems therefore can be suppressed. Fig. 2 shows the proposed pipe-in-pipe system.

Fig. 3 shows the structural model of a typical structure-TMD system. This model consists of a main system and a TMD system. The main system is characterized by the mass m_S, stiffness k_S and damping coefficient c_S. The corresponding parameters for the TMD system are m_T, k_T and c_T respectively. For the proposed pipe-in-pipe system shown in Fig. 2, the outer pipe can act as the main system and the inner pipe can be considered as the TMD mass. The stiffness and damping of the main system are determined by the surrounding environment (e.g. they are provided by the rock dumping for the unburied pipelines or surrounding soil for the buried pipelines). The optimized springs and dashpots