Numerical investigation of the effectiveness of using pipe-in-pipe system to mitigate seismic induced vibrations of subsea pipelines

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ABSTRACT: Pipe-in-pipe (PIP) systems are increasingly used in subsea pipeline applications where thermal insulation of the pipe is necessary. Pipe-in-pipe systems consist of an inner pipe, conveying the hydrocarbons, and an outer pipe, withstanding the external pressure. The annulus between the inner and outer pipes is either empty or contains non-structural insulation material. Vibration of subsea pipeline under ambient wave forces could substantially reduce its fatigue life. In extreme loading conditions such as earthquake ground excitations, excessive vibration could damage the pipe structure. Therefore control the vibration level is important in pipe structure design. This study investigates the effectiveness of installing the optimized springs and dashpots in the annulus of the pipe-in-pipe system to control its vibration. The system with such designs can be regarded as a tuned mass damper (TMD). This paper carries out numerical simulations on the effectiveness of using pipe-in-pipe system to mitigate seismic induced vibrations of subsea pipelines. The simplification of the pipe-in-pipe system as a TMD system is firstly presented, the seismic responses of the traditional and proposed pipe-in-pipe systems are calculated and the effectiveness of using pipe-in-pipe systems for the subsea pipeline vibration control is discussed. Numerical results show that the proposed pipe-in-pipe system can effectively suppress the seismic induced vibrations of subsea pipelines without adding any additional mass.

1 INTRODUCTION

Pipe-in-pipe (PIP) system is a technology widely used today to transport oil and gas in the subsea due to its exceptional level of thermal insulation (Bai and Bai 2014). Figure 1 shows a typical pipe-in-pipe system. It can be seen that this system consists of an inner pipe, conveying the hydrocarbons, and an outer pipe, withstanding the external pressure. The annulus between inner and outer pipes is filled with dry insulation material such as material wool, polyurethane foam, aerogel, granular or microporous materials. With such a design, pipe-in-pipe system can achieve excellent insulation capacity. To effectively centralise 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 during installation and operation, centralizers are clamped on the inner pipe at regular intervals (normally 2 to 12 meters according to different installation methods). Moreover, to facilitate installation of inner pipe and centralisers, a gap of 1 to 10 mm is normally reserved between the centralizers and the outer pipe. To maintain structural integrity during installation and operation and to serve as installation aids, bulkheads are normally welded to both the inner and outer pipes at several locations especially at both ends.

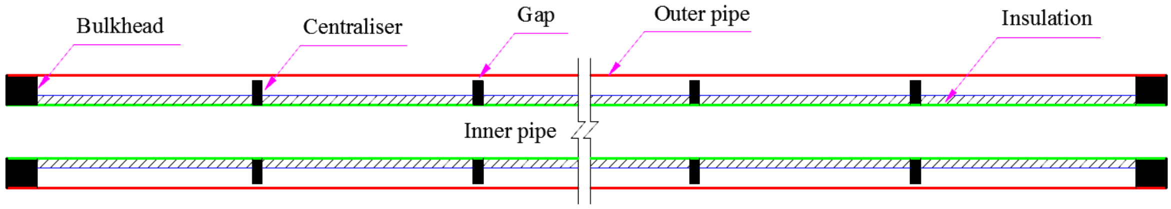

Figure 1. A typical pipe-in-pipe system (not to scale)

Due to unevenness and scouring of the seabed, a free span might be formed for the buried subsea pipeline system. This free-spanning pipeline is vulnerable to the vibrations induced by various sources such as vortex or earthquake. Catastrophic damages to free spans of subsea pipelines have been repeatedly observed in the past and proper vibration control is deemed necessary for subsea pipelines. Vortex induced vibrations on the subsea pipelines with free spans have been systematically studied by many researchers and various vibration control methods and devices have been developed (Kumar et al. 2008). However, to the best knowledge of the authors, no open literature reports the vibration control method for subsea pipelines subjected to earthquake loadings.

This paper proposes using pipe-in-pipe system for the subsea pipeline vibration control. In the proposed system, the hard polymeric centralizers are replaced by softer springs and dashpots to connect inner and outer pipes. Figure 2 shows the proposed system. This system can be simplified as a structure-tuned mass damper (TMD) system. 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 structural model of a structure-TMD system is shown in Figure 3. 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. 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 1970's in many engineering structures such as tall buildings, towers and bridges (Soong and Spencer 2002). For the proposed pipe-in-pipe system, 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 system can thus be supressed.

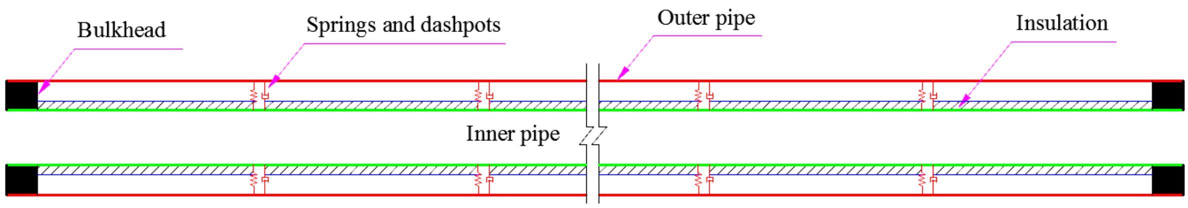

Figure 2. Proposed pipe-in-pipe system for the vibration control of subsea pipelines (not to scale)

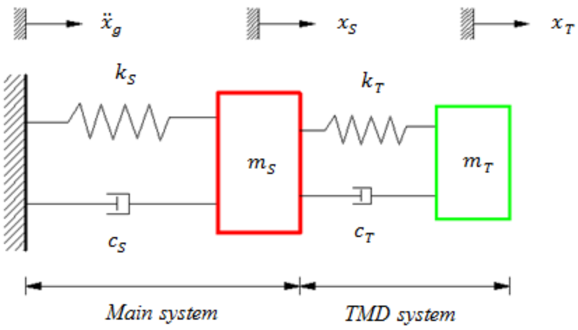

Figure 3. Structural model of a structure-TMD system subjected to earthquake loading

In the conventional TMD design the auxiliary mass is normally very small, typically in the order of one to a few percent of the primary structure. For the proposed pipe-in-pipe system shown in Figure 2, the outer pipe will 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. provided by the rock dumping for the unburied pipelines or surrounding soil for the buried pipelines). The optimized springs and dashpots provide stiffness and damping to the TMD system. According to this simplification, the mass ratio between the TMD system and main system is much larger (up to 100% and even more in terms of modal quantities) than the conventional TMD configuration. The proposed pipe-in-pipe system thus should be framed into the non-conventional TMD class (De Angelis et al. 2012). Following numerical simulations reveal that the large mass ratio makes the pipe-in-pipe system very suitable to be designed as a structure-TMD system.

This paper carries out numerical simulations on the effectiveness of using proposed pipe-in-pipe system to mitigate seismic induced vibrations of a subsea pipeline system with a free span. The simplification of the proposed pipe-in-pipe system to be a structure-TMD system is presented in detail and its effectiveness on the vibration control is discussed.

2 NUMERICAL MODELLING

2.1 Subsea pipeline systems

Figure 4 shows a buried subsea pipeline system, a free span is formed due to the unevenness and scouring of the seabed. To mitigate the possible vibrations of the free span induced by vortex or earthquake, the proposed pipe-in-pipe system shown in Figure 2 is used. The outer diameters of the outer and inner pipes are 0.324 and 0.219 m respectively and the thicknesses are 0.012 and 0.016 m. The length of the free span is L=24 m. To minimize the influence of the boundary conditions, the shoulder lengths are taken as three times of the free span (Vedeld et al. 2013), i.e. $\mathrm{L_{shoulder}} = 3\mathrm{L} = 72$ m. The total length of the analysed pipe-in-pipe system is therefore 168 m. The two ends of the inner and outer pipes are rigidly connected by bulkheads.

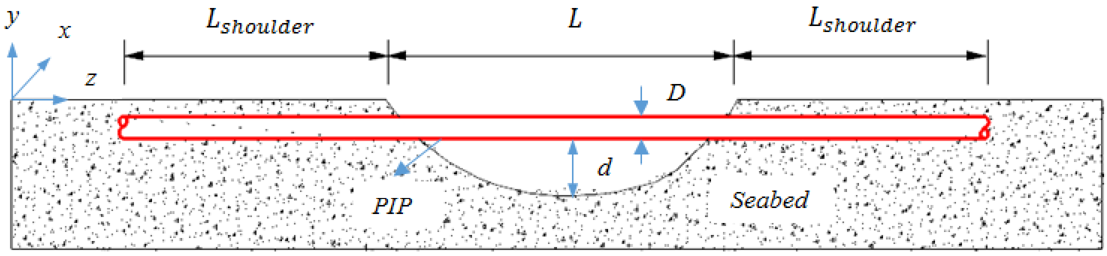

Figure 4. A subsea pipe-in-pipe system with a free span (not to scale)

2.2 Numerical model of the proposed pipe-in-pipe system

Three-dimensional (3D) finite element (FE) model of the proposed pipe-in-pipe system is developed by using finite element code ANSYS. Both the inner and outer pipes are modelled by SHELL63 element, an elastic shell with six degrees of freedom at each node. The density, Young's modulus and Poisson's ratio for the inner and outer steel pipes are 7800 kg/m^3, 210 GPa and 0.3 respectively. The cross sections of the inner and outer pipes are divided into 24 elements as suggested by Saberi et al. (2013). In the axial direction of the pipeline, the element size should be in the order of the outer diameter of the pipeline according to the recommendation given by DNV-RP-F105 (2006). Therefore an element size of 0.3 m is used in the axial direction.

For the free span of the pipeline, the interaction between the free span and the surrounding water is taken into account. The effectiveness mass of the free span can be calculated by considering the structural physical mass, the buoyant mass, which is the mass of the water displaced by the pipe and the added mass, which arises from the fact that the submerged body can induce acceleration to some of the surrounding fluid. For the pipelines in the shoulder and the inner pipe, only the physical masses are considered since they are either buried in the soil or protected from the water by the outer pipe. With these simplifications, the total mass of the outer and inner pipes shown in Figure 4 can be calculated as $\mathrm{M_S} = 15678$ kg and $\mathrm{M_T} = 13371$ kg respectively. The mass ratio defined as $\mu = m_T/m_S$ reaches 85.3%, which is much larger than the conventional TMD mass ratio.

The interaction between the soil and the pipeline shoulders are considered by the linear elastic soil springs as suggested by DNV-RP-F105 (2006). The spring stiffness in the lateral (x), vertical (y) and axial (z) directions is 10944, 14550 and 10944 kN/m^2 respectively. These parameters correspond to a soil condition of loose sand (Sollund et al. 2014). These soil springs are modelled by COMBIN14 elements along the pipe shoulder with an interval of pipeline element size in the axil direction (0.3 m). At the cross section, these soil springs are extending in three perpendicular directions with respect to the pipe. One end of the soil spring is rigidly connected with a pipe node and the other end is fixed. It is noted that in the numerical model, the contribution of each transverse/vertical spring to the total lateral/vertical stiffness is proportional to its share of the perimeter when projected onto the diameter (Saberi et al. 2013). It results in that the lateral/vertical springs located at the centre of the cross section are the stiffest. In the axial direction, the contribution of each spring is assumed to be the same.

The vibration frequencies and modes of the outer pipe can be calculated by carrying out an eigenvalue analysis after soil spring stiffness is determined. It is found that the first vibration mode is in the transverse direction with a frequency of 2.6505 Hz, the circular vibration frequency is thus $\omega_S = 16.654$ rad/s. The damping of the outer pipe is normally considered to comprise of hydrodynamic damping, soil damping and structural damping, which account for the contributions of the surrounding water, supporting soil and structure itself to the overall damping ratio. In the present study, a total damping ratio of $\xi_S = 5\%$ is assumed and modelled by COMBIN14 elements in ANSYS.

Various formulas have been proposed by different researchers to estimate the optimal stiffness ($k_{T,opt}$) and damping coefficient ($c_{T,opt}$) as shown in Figure 3. In the present study, the formulas proposed by Sadek et al. (1997) were adopted. With all the parameters defined above, it is calculated that $k_{T,opt} = 1.0081 \times 10^6$ N/m and $c_{T,opt} = 1.6381 \times 10^5$ Ns/m.

To demonstrate the effectiveness of the proposed pipe-in-pipe system to mitigate seismic induced vibrations, only the transverse earthquake loading (x direction as shown in Fig. 4) is considered in the present study. The springs and dashpots are installed both in the +x and –x directions with a spacing of 3 m along the pipe axis. The total number of springs and dashpots is 110 for the analysed pipe-in-pipe system. For each spring and dashpot, the stiffness and damping coefficient are therefore $k_1 = k_{T,opt}/110 = 9164$ N/m and $c_1 = c_{T,opt}/110 = 1489$ Ns/m.

These connecting springs are modelled by COMBIN39 elements in ANSYS, in which user-defined force-displacement relationship can be used. Figure 5(a) shows the force-displacement relationship of the springs, where δ is the size of the annulus, and it is 0.0405 m according to the dimension of the pipe-in-pipe system (Section 2.1). When the relative displacement between the inner and outer pipelines is smaller than δ, the stiffness is the optimum value k_1. When the relative displacement is larger than δ, the inner pipe will be in contact with the outer pipe. To avoid the possible penetration in the numerical simulation, a large stiffness k_2 needs be defined. In theory k_2 should be infinity because the tuned mass (inner pipe) will never penetrate the outer pipe. However, it is found that a very large k_2 can result in the simulation difficult to converge. A $k_2 = 4 \times 10^6$ N/m is found to have a good balance between the effectiveness and efficiency, which is used in the simulations. COMBIN14 elements are used again to simulate the dashpots and the damping coefficient is set as c_1.

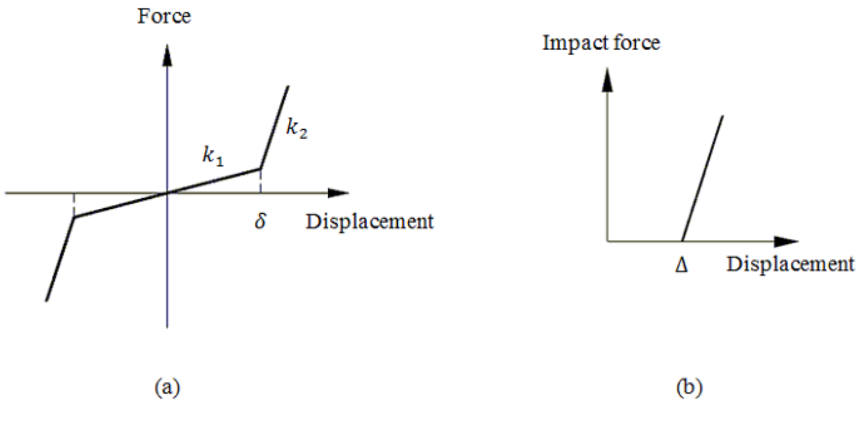

Figure 5. Force-displacement relation for (a) connecting spring and (b) impact element

2.3 Numerical model of traditional pipe-in-pipe system

For comparison, the seismic responses of the traditional pipe-in-pipe system shown in Figure 1 are also calculated. The inner and outer pipes are similarly modelled as described above. In this traditional system, a gap of 5 mm is assumed between the centralizer and the outer pipe. Colliding between the centralizers and the outer pipe may take place during an earthquake due to the existence of the gap. To realistically consider the possible pounding phenomenon, an impact element, which includes a gap element, a spring and a dashpot and commonly used to simulate the pounding between different components of bridges or between buildings, is adopted in the present study and modelled by COMBIN40 element in ANSYS. Figure 6 shows a typical impact element. The spring and dashpot will be activated when the gap is closed. Figure 5(b) shows the force-displacement relation of the impact element, where Δ is the gap size. In the present study, the stiffness and damping coefficient for each impact element are selected as $k_p = 3.62 \times 10^5$ N/m and $c_p = 2956$ Ns/m.

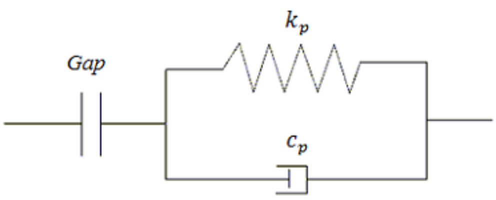

Figure 6. A typical impact element

3 EARTHQUAKE LOADING

Only the transverse (x direction in Fig. 4) seismic excitation is considered in the present study. The earthquake ground motion time history is generated to be compatible with the design spectrum for soft soil site (class De) specified in the Australian seismic design code AS1170.4 (2007). In the simulation, the peak ground acceleration (PGA) is set as 0.2g and time duration is 20 sec, the sampling frequency and upper cut off frequency are 100 and 25 Hz, respectively. Figure 7 shows the simulated acceleration time history and Figure 8 compares the response spectra of the generated time history and the given model, good match is observed.

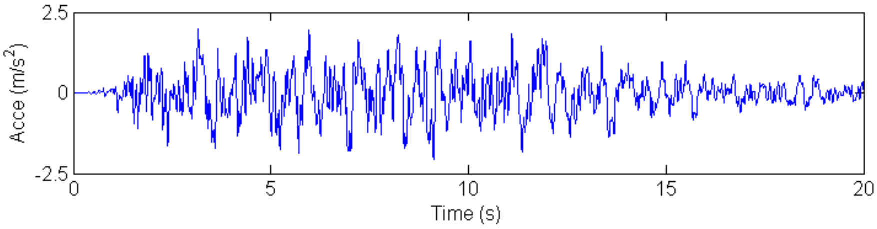

Figure 7. Simulated earthquake time history

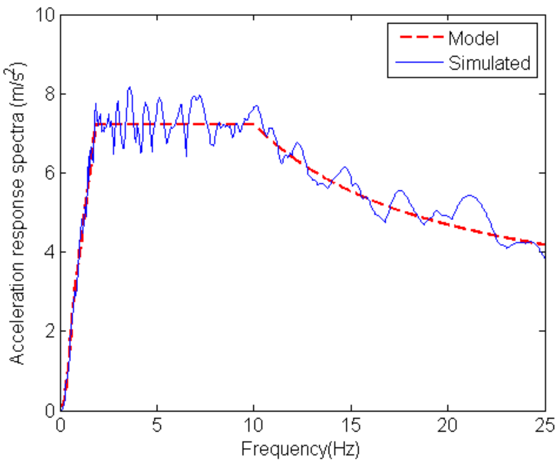

Figure 8. Comparison of the simulated and target response spectra

4 NUMERICAL RESULTS

The free span vibration of the subsea pipeline belongs to a general class of structure-water interaction problem. It is important to correctly assess the reactive force generated between the pipe and the surrounding water during vibration. This reactive force is mainly due to the inertia and pressure drag effects. The inertia effect is considered by the added mass as mentioned in Section 2.2. The drag effect was found not to be substantial (Nath and Soh 1978) and is neglected in the present study.

To investigate the effectiveness of the proposed pipe-in-pipe system to mitigate seismic induced vibrations of a subsea pipeline with a free span, the seismic response of the proposed pipe-in-pipe system subjected to the simulated earthquake loading as shown in Figure 7 is investigated. For comparison, the seismic response of the traditional pipe-in-pipe system is also calculated.

Figure 9 shows the transverse displacement time histories of the outer pipe at the middle of the free span when the proposed and traditional pipe-in-pipe systems are subjected to the transverse earthquake loading. The corresponding results for the inner pipe are shown in Figure 10. The blue curves are the results obtained based on the traditional PIP and the red curves are from the proposed system. As can be seen from the figures, it is quite effective to use the proposed pipe-in-pipe system to mitigate seismic induced vibrations of the free span. The proposed system not only significantly suppresses the vibration of the main system (outer pipe) but also obviously reduces the vibration of the TMD system (inner pipe). Table 1 tabulates the peak responses. The corresponding ratios between the responses of the proposed system and the traditional system are also given in the table. As shown, the ratios of the outer and the inner pipes are 0.402 and 0.503 respectively. These results demonstrate that properly designing a pipe-in-pipe system can greatly reduce pipeline vibrations. The proposed system is more effective in reducing the vibration of the outer pipe compared to the inner pipe. This is because the optimum values of the TMD system are estimated based on the structure-TMD concept, in which normally only the vibrations of the main system is of interest. For the proposed system, due to the large mass ratio, the vibrations of both the outer and inner pipes are evidently suppressed. This is, actually, a very favourable property for the proposed pipe-in-pipe system, since as mentioned above, the inner pipe is used to transport the hydrocarbons, the safety of the inner pipe is as important as the outer pipe.

Figure 11 shows the relative displacement between the inner and outer pipes at the middle of the free span when the proposed pipe-in-pipe system is subjected to the transverse earthquake loading. Very small relative displacement (stroke of the TMD) is obtained as shown in the figure. This property makes the pipe-in-pipe system very suitable to be designed as a TMD system considering the stroke of the TMD can only be developed in the annulus between the outer and inner pipes. It is also noted that no additional mass is needed for the proposed system, which means the proposed system will not significantly increase the cost of the pipe-in-pipe system. These properties make the proposed system have great application potential to mitigate subsea pipeline vibrations induced by various sources, and therefore can lead to better pipeline design.

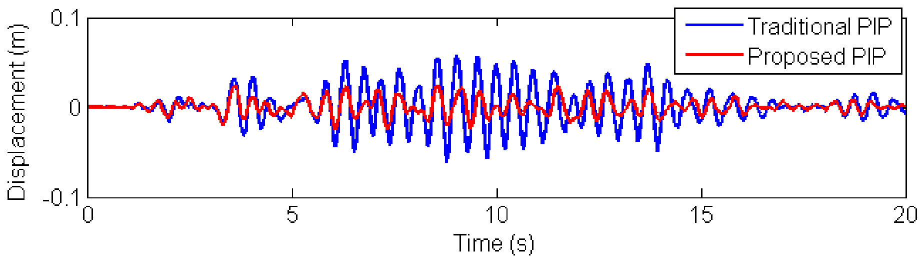

Figure 9. Transverse displacements of the outer pipe at the middle of the free span when the proposed and traditional pipe-in-pipe systems are subjected to the transverse earthquake loading

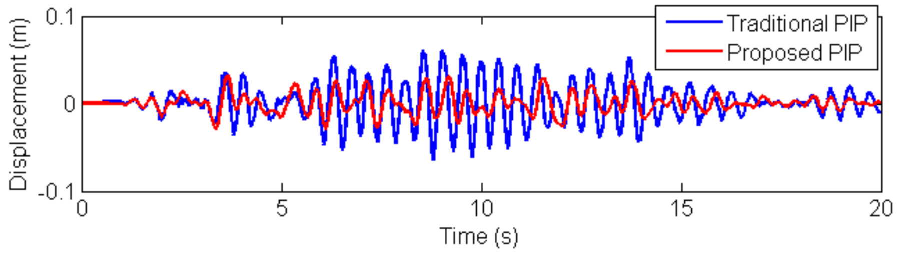

Figure 10. Transverse displacements of the inner pipe at the middle of the free span when the proposed and traditional pipe-in-pipe systems are subjected to the transverse earthquake loading

Table 1. Peak displacements of the outer and inner pipes at the middle of the free span of the pipe-in-pipe systems and corresponding response ratios.

Different PIP systems	Traditional PIP (m)		Proposed PIP (m)		Ratio	
	Outer	Inner	Outer	Inner	Outer	Inner
Displacement	0.0604	0.064	0.0243	0.0322	0.402	0.503

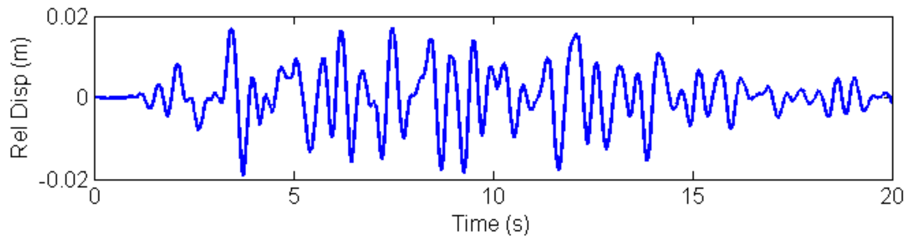

Figure 11. Relative displacement between the inner and outer pipes at the middle of the free span when the proposed pipe-in-pipe system is subjected to the transverse earthquake loading

5 CONCLUSIONS

This paper proposes using pipe-in-pipe system to mitigate seismic induced vibrations of subsea pipeline with a free span. This system takes advantage of the special structural layout of the pipe-in-pipe system and it can be designed as a non-conventional structure-TMD system. The Outer pipe acts as the main system and the inner pipe performs as the TMD mass. The optimized springs and dashpots are installed in the annulus between the outer and inner pipes and provide stiffness and damping to the TMD mass. Detailed three dimensional numerical analyses are carried out to examine the effectiveness of the proposed system. Numerical results show that the proposed system can significantly supress the vibrations of both the outer and inner pipes. The proposed system has great application potential to mitigate subsea pipeline vibrations induced by various sources, and leads to better pipeline design.

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