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Influence of mechanical layout of inerter systems on seismic mitigation of storage tanks

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ABSTRACT

Investigations concerning impact of the mechanical layout of two typical inerter systems on mitigation of seismic response of a base-isolated storage tank are reported. To this end, parameter assessment was first performed to determine impact of the mechanical layout of inerter systems on the sloshing height, isolation displacement, base shear force, and overturning base moment of the storage tank. Conditions favorable for the design suitable of each inerter system were identified based on results of parametric analysis performed as per design guidelines. In addition, the study proposes a demand-oriented optimum design method for determining design parameters of the bearing and inerter systems to meet target performance levels of the storage tank. The proposed method facilitates design of inerter systems with different mechanical layouts. Under the same target level of vibration mitigation in storage tanks, two typical inerter systems have been designed to further explore the impact of inerter-system mechanical layouts. Finally, frequency-domain and time-history analyses were performed on numerical cases of storage tanks with above-designed inerter systems. Analyses results demonstrate that a suitable inerter-system mechanical layout can be selected in accordance with design guidelines prior to design optimization of an inerter system. Using the proposed optimum-design method, inerter systems could be designed to realize target performance levels of the storage tank. In addition, the impact of the inerter-system mechanical layout on mitigation of seismic response of a base-isolated storage tank has been appropriately considered in the proposed demand-oriented optimum-design method.

1. Introduction

Storage tanks are socially important and strategically significant as liquid-storage terminals, which find wide utility in civil- and industrial-engineering applications, such as water-supply systems, liquefied-gas-supply systems, and chemical industries. However, tank failure under seismic excitation is a common problem [1,2], which may lead to disastrous consequences. To reduce the damage caused to a storage tank under seismic excitations, numerous theoretical studies and experiments [3–5] have been performed to investigate tank reinforcements, tank-isolation technologies [6–8], and tanks with baffles [7,9,10]. Traditional measures enhance cross-sectional dimensions of specific tank components, which serve to increase the carrying capacity of storage tanks. With the use of isolation technologies, a certain number of bearings are set between the bottom of the tank and underground foundation [11,12], so that natural frequency of the impulsive component in tanks can be shifted away from the dominant frequency of ground motion. Consequently, the base shear force and overturning base moment of an isolated tank can be reduced. However, in the condition that the isolation period is close to the sloshing period, use of base-isolation technologies might cause an increase in the sloshing height of tanks [13]. In accordance with extant researches performed concerning tank damage, tank failure can also result from strong sloshing of the liquid [4,14]. Use of a baffle represents a direct method for controlling the sloshing height within a value that effectively dissipates the vibration energy of a wave and adjusts structural damping [4,15]. Use of baffles, however, makes it difficult to use the tank and causes an increase in the value of base shear [16]. A hybrid control system comprising rubber bearings and an inerter system was proposed [17] in order to reduce the seismic response of storage tanks from the outside.

Typical inerter systems comprise three basic mechanical elements—the inerter, damping, and spring elements [18–21]. Towards the end of the last century, to amplify the viscous-damping force, Arakaki et al. [22] made use of a ball screw to transform linear motion into high-speed rotation. The mentioned ball-screw damper utilized

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inerter mechanism. In 2002, Smith [18] introduced the concept of inerter systems by means of the mechanical–electrical analogy and proposed a gear rack mechanism for inerter realization. Based on this concept, many researches have been performed to develop inerter systems with different layouts for vibration mitigation and proper implementation of the inerter concept [23–26]. The damping element in inerter systems has been proven to be more effective compared to viscous dampers with the same damping coefficient for vibration-energy dissipation [20]. The base-isolation system used in conjunction with an inerter comprising a tuned-mass damper has been employed in the reduction of seismic response of the structure under representative ground motions [27]. The effectiveness of incorporating inerter and base-isolation systems within a parallel layout has been demonstrated, for mitigating the seismic response of storage tanks [17], wherein a parallel inerter system (PIS), the inerter and damping elements of which are set in parallel, is used to absorb and dissipate vibrational energies. However, the vibration-mitigation effect of a series inerter system (SIS) was not considered. Further, the impact of the mechanical layout of an inerter system on seismic-response mitigation has also been ignored. Research related to these topics is, therefore, necessary to identify differences in control characteristics between SIS and PIS. In addition, determination of optimum design conditions for a base-isolated tank comprising an inerter system requires further investigation.

The proposed study investigates the impact of two basic mechanical layouts of inerter systems on mitigation of the vibration response of storage tanks. To this end, mechanical models of isolated tanks equipped with PIS and SIS were respectively built, and parametric analyses were performed to assess impacts of the two inerter-system layouts on the sloshing height, isolation displacement, base shear force, and overturning base moment of storage tanks. Subsequently, a demand-oriented optimum-design method has been proposed to design the bearing and inerter systems. Under the same target level of vibration mitigation effect for storage tanks with different aspect ratios, bearings, SIS and PIS were designed to further explore the impact of inerter-system layout. Lastly, frequency- and time-history analyses were performed concerning numerical cases of storage tanks equipped with SIS/PIS in conjunction with optimum bearings for validation of the proposed method.

2. Theoretical analysis of storage tanks equipped with inerter system

In this study, an inerter system was designed with bearings to reduce the seismic response of a storage tank; the bearing, designed to isolate the tank and inerter system, was installed to absorb and dissipate the vibration energy [17].

2.1. Inerter system model

An inerter is a type of two-terminal inertia element such that movements of both terminals are unrestricted. The reaction force of an inerter is proportional to relative accelerations of the two terminals and its apparent mass m_d. Using the mechanisms, such as the ball screw, gear rack, liquid, and so on, mass of an inerter system can be amplified by up to thousands times and be defined as apparent mass [20]. Supposing accelerations of the two inerter terminals to be denoted by $\ddot{u}_1$ and $\ddot{u}_2$, as depicted in Fig. 1, the reaction force F_{in} of the inerter could be expressed as

$$F_{in} = m_d(\ddot{u}_2 - \ddot{u}_1). \tag{1}$$

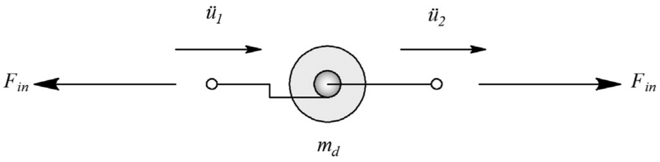

Fig. 1. Mechanical model of inerter.

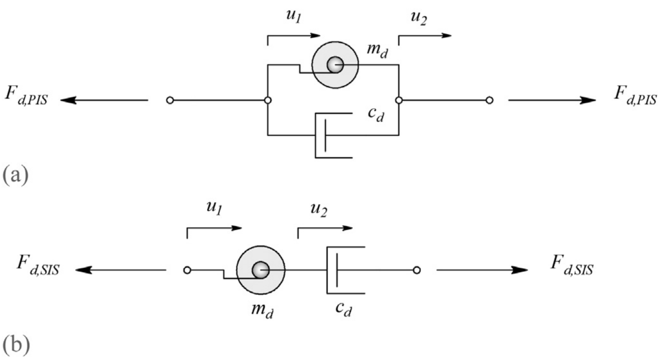

Fig. 2. Basic mechanical layouts of inerter systems for storage tanks—(a) PIS; (b) SIS.

Two basic mechanical layouts could be implemented using an inerter along with a damping element, as depicted in Figs. 2(a) and 2(b). One possible layout is the PIS, wherein the inerter element m_d is placed parallel to the damping element c_d; in the second layout—the SIS—the inerter element m_d can be placed in series with the damping element c_d.

The mechanical principle of elements in an inerter system has been investigated by many researchers [20,21,24,28], and output forces corresponding to the SIS and PIS could be expressed as under.

$$F_{d,SIS} = m_d(\ddot{u}_2 - \ddot{u}_1), \quad F_{d,PIS} = m_d(\ddot{u}_2 - \ddot{u}_1) + c_d(\dot{u}_2 - \dot{u}_1), \tag{2}$$

where $\dot{u}_1$ and $\dot{u}_2$ denote velocities of two terminals of the inerter element.

2.2. Rubber bearing model

Bearing used in inerter systems comprise a spring and dashpot connected in a parallel layout. Let k_b and c_b denote the spring stiffness and damping coefficient of the dashpot, respectively. The output force F_{rb} exerted by the bearing can, therefore, be expressed as $F_{rb} = k_b x_b + c_b \dot{x}_b$, wherein x_b and $\dot{x}_b$ denote the isolation displacement and velocity, respectively. In addition, the isolation period and damping ratio of the overall storage tank could be expressed as follow [17].

$$T_b = 2\pi\sqrt{m_l/k_b}, \tag{3}$$

$$\xi_b = c_b/(2\sqrt{m_l k_b}), \tag{4}$$

where m_l represents total mass of the storage-tank assembly.

2.3. Tank model

In this study, an incompressible liquid was assumed to be contained within in a storage tank with rigid walls. The classical lumped-mass model was used to evaluate the dynamic response of the tank [29]. The stored liquid in the tank could be divided into two components—impulsive and convective [21,29,30]. Veletsos [29] proposed a practical and accurate liquid-storage-tank model by considering the first three order modes of a sloshing liquid. Sloshing motion of a storage tank can be expressed as a linear combination of these modes. Fig. 3(a)–(c) depict schematics of tanks equipped with PIS (Tank I) and SIS (Tank II) and without any control system installed (Tank III), respectively. As depicted in the figure, the rigid cylindrical tank was considered as a four-lumped-mass model. D denotes diameter of the rigid tank while H denotes the height of the liquid contained within the tank; m_b and h_b represent mass and height of the impulsive component, respectively, whereas m_j, k_j, c_j, and h_j denote the mass, stiffness,