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Experimental and theoretical investigation on dynamic properties of tuned particle damper

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ABSTRACT

Aiming at solving the ineffectiveness of conventional particle damper (PD) at vibration acceleration less than the acceleration of gravity (1*g*) in vertical vibration, based on tuned mass damper and particle damper, a new type of damper, tuned particle damper (TPD), is introduced and tested in this work. The TPD can work as a conventional tuned mass damper as well as a particle damper. Due to the vibration of the TPD is amplified because of its vibration absorber function, the particles in the TPD can be easily driven into a state in which the acceleration is higher than 1g even though the master structure's acceleration is much lower than 1g. As well known, when the acceleration of a particle damper is less than 1*g*, the particles will behave like a lump of mass and provide no damping to the system. Therefore, the TPD might find a solution for the particle damper to function under small vibration acceleration. When the master structure's acceleration is higher than 1g, the damping from the TPD can be enhanced even more. In addition, the TPD's particle damping does not depend on the relative velocity between the master structure and absorber, but on the acceleration of the absorber only. Unlike the viscous damping in tuned mass damper, heavy particle damping will not affect the TPD's main dynamic properties as a vibration absorber. Furthermore, a 2-Degree-Of-Freedom (2-DOF) model was firstly developed to approximate the nonlinear behavior of the PD. The model prediction is consistent with the measured experimental results. This 2-DOF model can also be applied to simplifying the conventional PDs installed on any structures.

1. Introduction

Vibration control technology has been increasingly applied in wide range of industrial sectors, particularly in aerospace engineering, mechanical engineering, marine engineering etc. Due to hostile environment (low or high temperature, corrosion, radiation etc.), conventional damping materials, such as viscoelastic materials, will fail to function properly. Damping materials must be heat, radiation, aging and corrosion resistant. Non-obstructive particle damping (NOPD) technology [1,2] is a derivative of impact damping with several advantages. NOPD is used to fill the particles of various shapes, sizes, and materials in an enclosure attached to a structure. As a result of the collisions, momentum is exchanged between the structure and the particles, and kinetic energy is converted to heat. Additional energy dissipation can also occur due to particle-to-particle collisions and frictions and particle-to-wall frictions.

In past decades, particle dampers (PDs) have been studied and documented extensively with experimental and numerical method. Experimental studies [3–10] have shown that a PD offers several advantages due to its conceptual simplicity, potential effectiveness over broad frequency range, temperature and duration insensitivity and very low cost. There are three main simulation methods: Particle Dynamic Method [11]; Discrete Element Method (DEM) [12–14] and Multiphase Flow Method [15]. And DEM is the most widely used in previous works.

The damping performance of PDs depends on many factors [3–9,12–14], such as particle material, shape, packing ratio, vibration acceleration etc., which make the PD a very complicated nonlinear system, so that it is very hard if not impossible to establish a theoretic model for PDs dynamics analysis, which make it difficult to design PDs. Some researchers [7,16] consider that a PD attached to the principal system acts as a small oscillator with equivalent viscous dampingc_{eq}, equivalent linear stiffness k_{eq} and equivalent mass m_{eq}; see Fig. 1. However this equivalent approach cannot exhibit PD's characteristics of energy dissipation when $c_{eq}$is large. Because in this model, high damping can glue the PD to the principal system, which will never happen for PDs.

Previous research [7,8] have shown that vibration acceleration is one of the most important factors for PD's damping performance. As the excitation acceleration is increased in the case of vertical vibration, the particles in the PD undergo three

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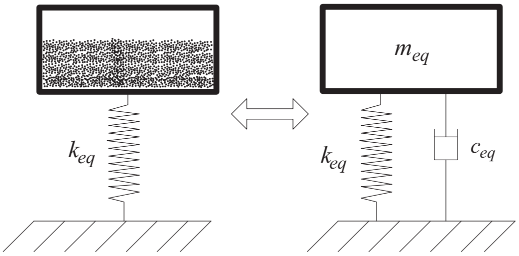

Fig. 1. Particle damper and equivalent dynamic model: (a) undamped DVA and (b) damped DVA.

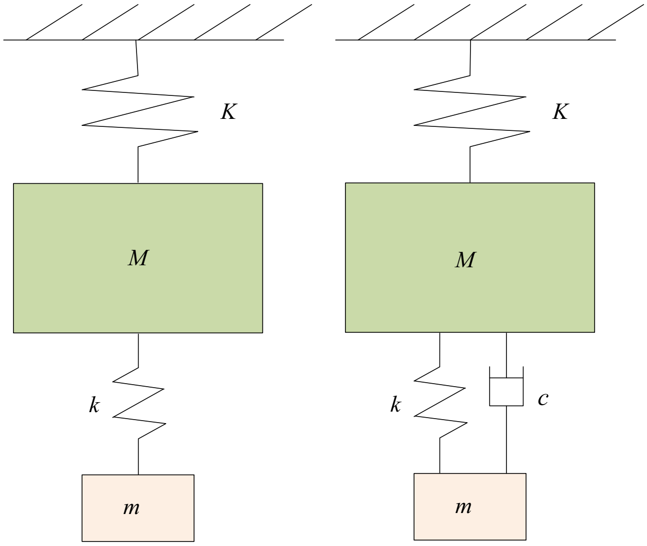

Fig. 2. Dynamic Vibration Absorber.

stages: 'solid-like', 'liquid-like' and 'gas-like'. At very low vibrating acceleration ($<1g$), particles remain locked together (solid-like) and move together with PD container. In this stage, PD hardly has damping performance. As the excitation is increased, some particles start to slide over one another dissipating energy via friction between particles. At higher vibration levels, particles begin to roll over one another resulting in the fluid-like convection occurring within the damper. At very high excitation amplitudes, particularly when particles occupy only a small fraction of the container volume, the particles move in a gas-like manner. And highest levels of damping have been reported for the transition between solid-like and fluid-like behavior. So the main drawback hampering application of NOPD technology in real structure is that: when the acceleration is lower than the gravity acceleration ($1g$), the PDs will provide no damping at all. Low acceleration vibration appears in large scale structures, or softly-supported precision equipment which needs further vibration suppression although its vibration level is already very low because of the rigorous requirements from the equipment such as navigation apparatus. In another word, low acceleration vibration control must be dealt with.

Dynamic Vibration Absorber (DVA) has been successfully used to attenuate the vibration of many structures [17–19]. DVAs are widely used for the control of structural vibration and noise radiation owing to their simplicity, effectiveness and inherent stability characteristics. An undamped DVA is an auxiliary mass-spring system which, when correctly tuned and attached to a vibrating body subject to a harmonic excitation, eliminates steady-state motion of the point to which it is attached shown in Fig. 2(a). A damped DVA has a damper added between the absorber mass (tuned mass) and the primary mass as shown in Fig. 2(b) to dissipate the energy transferred from the master structure.

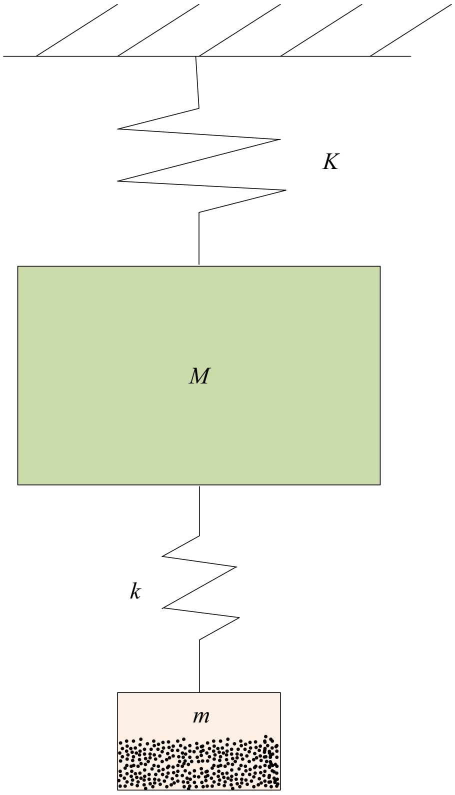

Fig. 3. Tuned particle damper.

In this paper, a new vibration damper—tuned particle damper (TPD) was firstly proposed to improve the traditional PD's damping performance at low vibrating acceleration ($<1g$) based on classic DVA. As shown in Fig. 3, the mass of DVA is turned into a particle damper to form a TPD. Simply, the TPD is built by making a cavity in the slavery mass, filling the cavity with particles and sealing it off. Apparently, the TPD's vibration acceleration would be more likely much higher than the master structure so that the particles would be easily enter liquid-like or gas-like state, which would be significantly increase the damping effect from the moving particles. In general, TPD can suppress vibration of structure though two ways: first, TPD acted as an undamped DVA absorbing vibration energy of master system. Second, consume the energy as a PD.

The motivation of this work was to present an experimental study on the TPD and built an approximate theoretical model for PD. It was found that the TPD could significantly improve the damping behavior of particles in low vibrating acceleration ($<1g$). And compared with traditional PDs, TPDs have much better performance on dissipating energy of primary system. To estimate the damping effect, a 2-Degree-Of-Freedom (2-DOF) model was introduced to approximate the nonlinear behavior of the PD. It was applied to the test rig for comparison between the theoretical and measured results. And reasonable consistence was found between experimental results and the model prediction.

2. A 2-DOF model to approximate the particle damper

The PDs dissipate structural vibration energy though impact and friction of particle-to-particle and particle-to-wall. Because the quantity of particles dissipating energy depends on the vibration acceleration, only part of the particles move around and dissipate energy at certain acceleration level. The higher the acceleration is, the more particles are in motion. Based on above