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Experimental and numerical investigations on the performance of particle dampers attached to a primary structure undergoing free vibration in the horizontal and vertical directions

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ABSTRACT

Particle damping (PD) has been well known for its simplicity and high efficiency in attenuating structure vibration. Recent studies on PD have focused mainly on new types of dampers and applications. Meanwhile, excitation applied to the primary structure is still limited to either horizontal or vertical direction, perpendicular or parallel to gravity. In this study, the characteristics of PD under horizontal–vertical excitations (HVE) are investigated numerically and experimentally. The particle damper, which is attached to the top free end of an L-shaped cantilever beam, is simultaneously excited in the horizontal and vertical directions in the context of free decay. An equivalent model capable of motion in both the horizontal and vertical directions is generated. Given an initial displacement disturbance, this model starts vibrating freely in the vertical plane. A code based on the 3D discrete element method is programmed, and the high coincidence between the numerical and experimental results shows that this equivalent model is capable of high-fidelity simulation for PD under HVE.

Parametric studies have been implemented to characterize the basic nonlinear damping capacity of particle dampers under this new operating condition. The effects of seven dimensionless independent parameters on the specific damping capacity (SDC) are investigated, including dimensionless acceleration amplitude, particle mass ratio, dimensionless horizontal and vertical impact clearances, coefficients of friction and restitution, and amplitude ratio of the horizontal excitation to the vertical excitation. The results show that the basic damping properties of PD under HVE are similar to those of PD under only vertical excitation. However, PD under HVE signifies its own characteristics because of the existence of horizontal excitation: (1) The impact clearances in both the horizontal and vertical directions have significant effects on the SDC because of the significant increase in oblique impacts. (2) The shape and dimensions of a damper cavity should be designed according to the acceleration amplitude. If the amplitude is relatively low (such as $\Gamma < 3$ in this study), the optimum shape of the damper cavity tends to be flat. By contrast, if the amplitude is high (such as Γ close to 10), the optimum shape tends to be elongated. The damping differences between PD under HVE and vertical excitation are also investigated. For PD under HVE, the kinetic energy is mainly dissipated by friction rather than inelastic collision for PD under vertical excitation. In addition, by use of

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different amplitude ratios of the horizontal excitation to the vertical excitation, it is found that the total ratio of energy dissipation for the particle dampers under HVE generally becomes higher, and the optimum Γ region for high SDC is also expanded.

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1. Introduction

Particle damping (PD) is an effective passive damping technique wherein multiple small metallic or other types of particles are placed inside one damper cavity attached to the high vibration amplitude location of a primary structure. As the primary structure vibrates, kinetic energy is dissipated because of the combined effects of inelastic collisions, frictional losses, and momentum exchange when particles in the cavity collide and rub with themselves and the cavity walls. As the damping mechanism does not rely on viscoelasticity, the particles can be made from thermally stable materials, such as metals or ceramics, because their performance is insensitive to temperature. This feature allows PD to be used even in harsh environments, such as rocket motors and gas turbine engines [1,2].

To date, extensive numerical simulation methods have been proposed in the field of PD. Two of them are still mainly in use. The first method can be called “equivalent single mass” method, in which all particles are modeled as a single mass and all the massive mechanisms of energy dissipation are “wrapped” into an “effective coefficient of restitution” [3–7]. Although a reasonable correlation with the experimental results can be obtained for a specific class of damper designs [5], it may not work well if significant particle–particle loss mechanisms exist, such as friction among the particles, or for the cases where geometry significantly affects the motion of particles. The other numerical method is called “discrete element method (DEM)”, which is also alternatively referred to as the particle dynamics method. In this method, individual particles are modeled and their motions are tracked in time. As a result, the resultant force on any particles at any time is determined by its interaction with particles and cavity walls. Compared with other numerical methods, DEM makes it possible to follow the nonlinear interaction of a large number of particles. Much of the pioneering work using DEM simulates the behavior of granular materials [8–13]. However, Olson [14,15] first conducted DEM with attention focused on the effectiveness of using particle dampers to attenuate the oscillations of a vibrating structure. He generated a horizontal single-degree-of-freedom (SDOF) model to predict the performance of a particle damper attached to the free end of a horizontally vibrating cantilever beam, and the numerical predictions generally agree well with the experimental results.

Based on this horizontal SDOF model, the performance of particle dampers attached to the beam-like structure and other similar continuous structures, which can be reduced to the SDOF model, has been extensively investigated [16–20]. In addition, the dynamic loads vary. The study of PD under the condition of free vibration is perhaps not, in itself, as important as the study of forced vibration. However, a free decay study has its own value in this nonlinear problem. First, the results have intrinsic value in showing the rate of recovery from a transient disturbance. More importantly, PD has been known for its amplitude-dependent behavior in forced vibration [21,22], and a single transient decay can elicit an amplitude range covering over at least one order of magnitude. A particle damper attached to the free end of a vertically vibrating cantilever beam is often used to investigate the damping performance of PD under vertical excitation [23–26]. With horizontal response neglected, the primary structure is modeled by a vertical SDOF model. Since the vibrating motion is parallel to gravity, PD demonstrates even more nonlinear characteristics. For PD under horizontal excitation, particles are able to come into contact with both side walls of the cavity (both-sides collision) because only one contact criterion is used to describe the relative position of particles and the cavity [19]. However, for PD under vertical excitation, a separation criterion [23] is added, except for the contact criterion: the separation of particles and the cavity floor occurs when the vertical acceleration of the cavity exceeds the acceleration due to gravity, $(-a)>g$; whereas the separation of particles and the cavity ceiling occurs when $(-a)<g$. In other words, both-sides collision occurs if the acceleration amplitude of the primary structure increases to a specific value, which is able to supply sufficient kinetic energy for the particles to impact the cavity ceiling. If not, the particles are just launched off the floor, then fall freely under gravity and impact with the floor again (one-side collision). Therefore, two collision manners (one-side collision and both-sides collision) exist for PD under vertical excitation, which makes this nonlinear problem even more complex [23].

Recent studies on PD have focused mainly on new types of dampers and applications [27,28]. However, the vibrating motion of the primary structure is still limited to either horizontal or vertical direction, perpendicular or parallel to gravity. PD has shown its utility in gas turbine engines [2,29]. Typical components, such as bladed disks whose vibration are to be damped, vibrate at least in two directions physically. In addition, the horizontal and vertical vibrating motions are in phase with each other because of the geometry. Thus, the situation can be simplified to motion in one direction but at different angles to gravity. Relevant research has been conducted by Els [30,31]. He developed a test bench, which consisted of a rotating cantilever beam with a particle damper at the tip, and adjusted the angle of motion to “gravity” by changing the rotating velocity. Although the damper vibrates freely in the vertical direction, the analysis of PD in the horizontal motion perpendicular to gravity is more appropriate to understand the damper characteristics in this case. When the centrifugal acceleration exceeds 1g, the particles are no longer free to bounce up and down, but tend to move along the sidewall. If the centrifugal acceleration is further increased, then the particles move in a “sloshing” motion along the wall until the centrifugal forces become too high to allow any relative motion between the particles. A simplified vertical SDOF model filled with particles was also developed [31]. Using DEM, gravity and centrifugal acceleration were