Intermodal targeted energy transfer in a blast-excited 2D linear system with an elliptical hole

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Summary. This work explores the implementation of the intermodal targeted energy transfer (IMTET) concept for passive mitigation of a 2D linear oscillator subjected to blast excitation in its weak direction. The considered model contains 3 degrees-of-freedom, namely, two directions of translation (i.e., horizontal and transversal), and rotational direction. The passive mitigation here is achieved by inducing extreme, fast time scale energy transfers from weak structural mode (characterized by lower-frequency and large amplitude) which was initially excited by the blast excitation to strong structural modes (i.e., higher-frequency ones with a small amplitudes). These targeted (directed) energy transfers are governed by a non-resonant nonlinear dynamical mechanism induced by vibro-impacts between the main structure and a rigid barrier which constrained the structure to move within an elliptical hole. By redistributing the blast energy from low- to high-frequency structural modes the amplitude of the overall structural response is reduced in an extremely fast time scale, and the intrinsic dissipative modal capacity of the structure itself is better utilized. Additional blast energy dissipation is achieved by inelastic vibro-impacts.

Introduction

Passive mitigation of engineering structures subjected to extreme loads is of considerable interest in real life applications for preventing structural damage and human loss. Several linear and nonlinear absorbers have been investigated in the literature for this purpose [1,2]. Recently, a new concept was introduced [3] for blast mitigation through intermodal targeted energy transfer (IMTET) mechanism which based on irreversible nonlinear non-resonance energy scattering that passively transfers a significant portion of the blast energy from low-frequency structural modes (in particular, the fundamental mode) to high-frequency modes of the structure. Such passive IMTET was achieved by introducing local strong nonlinearities, in the form of vibro-impacts. The IMTET concept was first implemented on a benchmark blast-excited two-degree of freedom (DOF) linear system by introducing to the system a single impact clearance [3]. Then, an extension of IMTET mechanism in multi-DOF systems was conducted in [4], in which a computationally study to explore the concept of IMTET to mitigate the effect of blast loading on a nine-story steel structure was performed.
Here in this study, the IMTET concept will be extended to two-dimensional structures, with the rationale of channeling energy from "weak" to "strong" direction, thus utilizing much more effectively the intrinsic dissipative capacity of the structure itself.

Model description and governing equations

Here we consider a 3DOF oscillator with two directions of translation (i.e., horizontal and transversal) and one of rotational direction. The oscillator consists of a mass m with moment of inertia I moving on both horizontal and vertical directions. The mass is connected to two linear dampers with coefficients c_1 and c_2, and a torsional dumper with coefficient γ. Two linear springs with stiffness k_1 and k_2 and a torsional spring with stiffness k_3 are attached to the mass as well. The mass movement is constrained by a rigid element, in center of an elliptical hole going throw the mass, with width $2a$ and height $2b$, and rotated by an angle α, as shown in Figure 1.

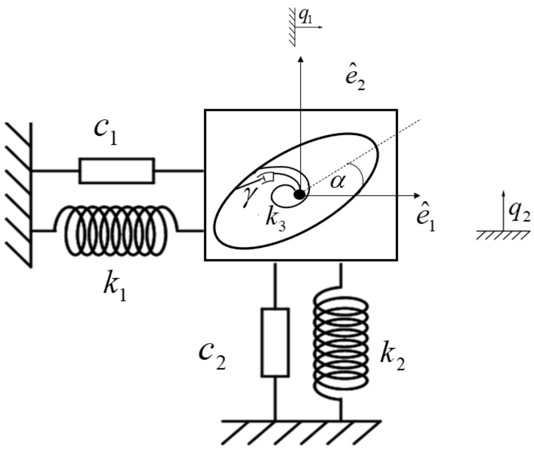

Figure 1: Schematic of the considered system

Let q_1 and q_2 denote the horizontal and the transversal displacements, respectively, the equations of motion between the impacts are given by:

$$m\frac{\partial^2 q_1}{\partial t^2} + c_1\frac{\partial q_1}{\partial t} + k_1 q_1 = 0 \tag{1}$$

$$m\frac{\partial^2 q_2}{\partial t^2} + c_2\frac{\partial q_2}{\partial t} + k_2 q_2 = 0$$
$$I\frac{\partial^2 \theta}{\partial t^2} + \gamma\frac{\partial \theta}{\partial t} + k_3\theta = 0$$

When the rigid element location satisfies the equation of the ellipse in respect to the center of mass, collision happens and the mass changes its velocity instantaneously according to the Newtonian impact law. The collision is defined using coefficient of restitution and coefficient of friction and take under consideration angular impulse. After numerically solving the equations of motion we can explore the efficiency of the mechanism. The simulation parameters are chosen with respect to a real steel beam with rectangular cross section. We have simulated the system for different coefficients of restitution, namely, $r = 0.6{,}1$ and compared the results with the linear case, i.e., without the constraint, for an equal initial condition of impact. To explore the efficiency here we the normalized energy η as the ratio between the instantaneous energy $E(t)$ and the initial energy $E(0)$:

$$\eta(t) = \frac{E(t)}{E(0)} \tag{2}$$

We define the characteristic damping time of the system τ as $\ln(\eta(\tau)) = -1$, in other words, it is the time in which the energy drops by a factor of 1/e of its initial value in a time inverse to the damping coefficient.

Results

As a preliminary results, the horizontal and transversal responses subject to initial conditions that excite only the horizontal direction are shown in Figure 2(left). It is clear that when the vibro-impacts occur, the modes interact immediately, and a substantial amount of energy is transferred from the horizontal to the transversal mode. The latter is characterized by a substantially higher modal dissipative capacity. Thus, an enhancement of the damping properties of the system is realized through utilization of the intrinsic modal structure and excitation of the higher-frequency transversal mode. Figure 2(right) shows the logarithm of the normalized energy as a function of time for the following three cases: linear, nonlinear with purely elastic impacts, and nonlinear with inelastic impacts. It can be seen that the presence of the impacts in the system leads to a significant decrease in the characteristic damping time, even when purely elastic impacts are considered.

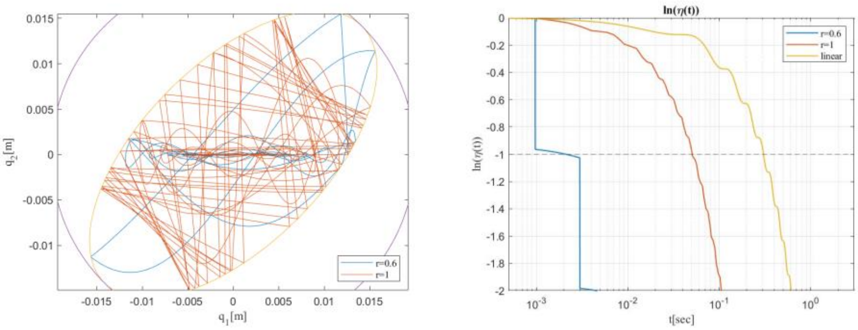

Figure 2: The center of mass trajectory in the $q_1 q_2$ plane (left); The instantaneous energy of the system (right)

Conclusions

In this work, the non-resonance nonlinear mechanism for efficient and rapid low- to high-frequency energy scattering, which is referred to as intermodal targeted energy transfer—IMTET, is implemented for passive mitigation of a 2D linear oscillator subjected to blast excitation in its weak direction. The numerical exploration revealed that channeling the blast energy, within the modal space, from low- to high-frequency structural modes enables an extremely fast mitigation of the overall structural response, and a drastic reduction of the characteristic damping time in the benchmark system.
Such observations open up an entirely new domain of research on constructive utilization of different directions for possible displacement of the structure, in particular channeling energy from “weak” to “strong” direction by means of the IMTET.

References

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