LETTERS TO THE EDITOR

EXPERIMENTAL VERIFICATION OF SHOCK REDUCTION ACHIEVED THROUGH NON-LINEAR LOCALIZATION

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1. INTRODUCTION

Over the past several decades, new methods have been proposed, and in some cases implemented, for reducing the transient responses of large structures, particularly those induced by earthquakes [1–4]. The most successful of these to date are the passive devices such as viscoelastic and viscous dampers which can be installed throughout the structure, base isolators, and tuned mass absorbers [5–12]. These are particularly advantageous as they do not require an energy source; however, their characteristics are fixed making them unable to adapt to changing conditions. More recently, semi-active or "intelligent" devices have been proposed for seismic response reduction. These are typified by devices such as variable orifice dampers and controllable fluid dampers, the properties of which can be continuously varied with minimal energy requirements. An example of the former has been implemented with success in a highway bridge in Oklahoma in order to reduce the response due to traffic loads with a concurrent increase in bridge life [13]. Magnetorheological devices appear to be quite attractive, with a 20 t device currently undergoing testing at the University of Notre Dame [14].

In a recent paper [15], a theoretical investigation on the use of non-linear localization for reducing the transmitted vibrations in structures subjected to transient base motions has been presented. The key idea of that work was the introduction of a localized non-linear normal mode [16] centered on a secondary substructure away from the main structure to be isolated. The design relied upon the excitation of this localized mode by the base motion, so that the major portion of the input-induced energy was transferred to the preassigned substructure, instead of the primary structure to be isolated. The present work aims to experimentally verify the theoretical localization concepts presented in

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reference [15]. To this end, a special experimental fixture was built and tested in order to verify base isolation due to non-linear localization.

2. NON-LINEAR LOCALIZATION FOR SHOCK REDUCTION

The shock reduction system that we are proposing combines the properties of two well-known techniques: base isolation and localization. Structural base isolation systems for seismic protection have been successfully implemented for nearly 20 years, both in this country and overseas. Currently, more than 40 base-isolated structures exist, with more in progress. The concept of base isolation is simply the absorption and dissipation of input energy through the use of large rubber–metal bearings introduced between the foundation and ground. To enhance performance when large events occur, the bearing generally encompass a lead core which acts as an efficient energy dissipator. The structure and foundation essentially float on the bearing system thereby minimizing the deformations and stresses in the structure itself. However, as the foundation and structure undergo potentially large motions with respect to ground, core deformations can lead to permanent offset of the foundation which can affect subsequent performance during aftershocks. Localization, in the linear sense, is a phenomenon that occurs in nearly periodic systems. The sensitivity of the modes of the system to small asymmetries is known to cause local confinement of the response. However, it is difficult to achieve ideal levels of confinement due to tolerances, parameter uncertainties, and so forth. The fact that similar but more robust effects are achievable through the exploitation of non-linear behavior, and that the potential for breakthrough passive performance is significantly enhanced by combining base isolation with localization ideas, are the primary motivations for this proposal. The following represents a concise exposition of these ideas, applied to a simple representation of a base-isolated structure–foundation system, where the addition of a secondary structure to the base isolator provides the needed non-linear tuning mechanism.

Consider the one-dimensional model of a base-isolated structure, shown in Figure 1. The primary structure to be protected is represented here as a slender cantilever beam-column with uniform mass distribution ρ, and constant load P at its free end. The column carries n concentrated masses $M_1, \ldots, M_n$ (with corresponding moments of inertia $J_1, \ldots, J_n$) attached at points $x = a_1, \ldots, a_n$, with $a_n = l$. The column is flexibly connected to the foundation, mass M_0, through a linear rotational spring with rate c_3. The foundation is connected through a linear translational spring with rate c_2 to a secondary mass m_1 which is connected to ground through a translational bilinear spring $F(u)$. Note that the mass m_1 acting through the non-linear spring represents the secondary structure which acts as the non-linear vibration absorber. The main goal of the non-linear design is to localize the main portion of the base motion-induced energy to the secondary substructure m_1, and allow only a small part of this energy to be transferred to the primary cantilever structure. In reference [15], it was demonstrated through this simple representation that this system is indeed capable of localizing vibratory energy away from the primary structure over a wide range of frequencies. Once localized,
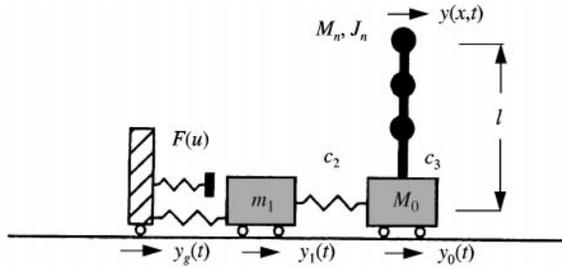
Figure 1. Schematic of a structure with a compound non-linear base isolation system.
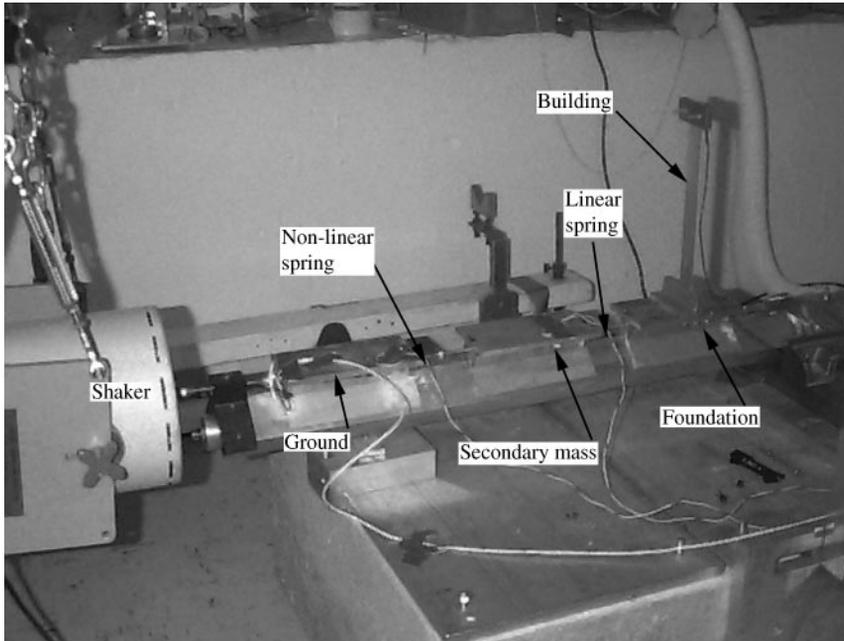
Figure 2. Experimental apparatus.

this energy can be effectively dissipated. It must be pointed out that the mechanism for inducing the non-linear localization in the system is the non-linear spring $F(u)$, and a 1:1 internal resonance between the secondary substructure m_1 and the second mode of the main structure. The system of Figure 1 is shown forced by a prescribed ground motion $y_g(t)$ representing the shock excitation.

3. EXPERIMENTAL VERIFICATION

An experiment to verify the previously mentioned theoretical concepts was built and tested in the Linear and Nonlinear Dynamics Laboratory (LNDL) at the University of Illinois. A photograph of the apparatus is shown in Figure 2. It consisted of an electromagnetic shaker, mounted horizontally, connected through
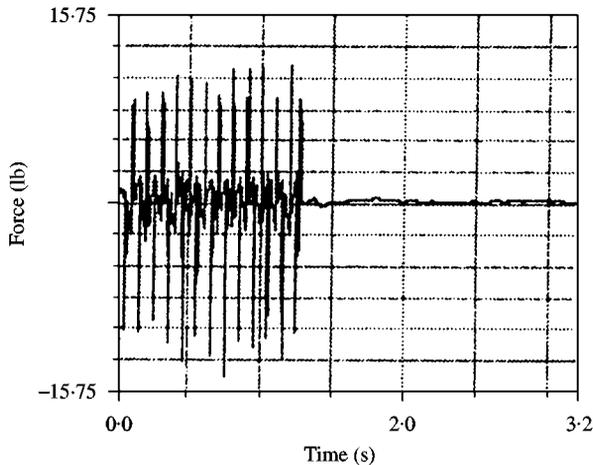
Figure 3. Time history of forcing input.

a stinger to a rigid block representing the ground. This was connected to an intermediate rigid mass (the secondary mass m_1 of the theoretical model of Figure 1) through a linear spring with clearance non-linearity; this mass, in turn, was connected through a linear spring to a third rigid mass (the foundation) which carried the flexible structure to be isolated. The sensing mechanism consisted of a force transducer disposed between the stinger and ground block, an accelerometer mounted to the secondary mass, and an additional accelerometer mounted to the top of the flexible structure. The blocks rested on a rigid air table and were supported on a cushion of compressed air forced through and out of the table. This eliminated dry friction forces and enabled the accurate determination of energy transfer between the various substructures.

The experimental results were found to be in satisfactory support of the theoretical predictions. The system was forced by the shaker with a series of shock pulses simulating a transient input. In Figure 3, the time history of the input corresponding to the experimental measurements presented herein is depicted. In contrast to the theoretical model, the experimental model contained a one-sided (rather than two-sided) clearance non-linearity in the secondary mass. In Figure 4, we present the tip accelerations of the flexible structure together with the accelerations of the secondary mass for systems with and without the clearance non-linearity. We observed at least a 40% reduction in the maximum positive amplitude and a 20% reduction in the maximum negative amplitude of the tip mass acceleration. Similar repeatable reductions in maximum acceleration amplitudes were observed over a range of input magnitudes. Clearly, this reduction in maximum acceleration amplitude is due to the presence of the clearance non-linearity, as predicted in reference [15].

This was verified by the Fourier spectra of the accelerations, depicted in Figure 5. Both the accelerations of the tip of the flexible structure and the secondary substructure are shown for linear and non-linear cases. The maximum non-linear acceleration peaks refer to motion in the vibro-impact regime, not in the ensuing
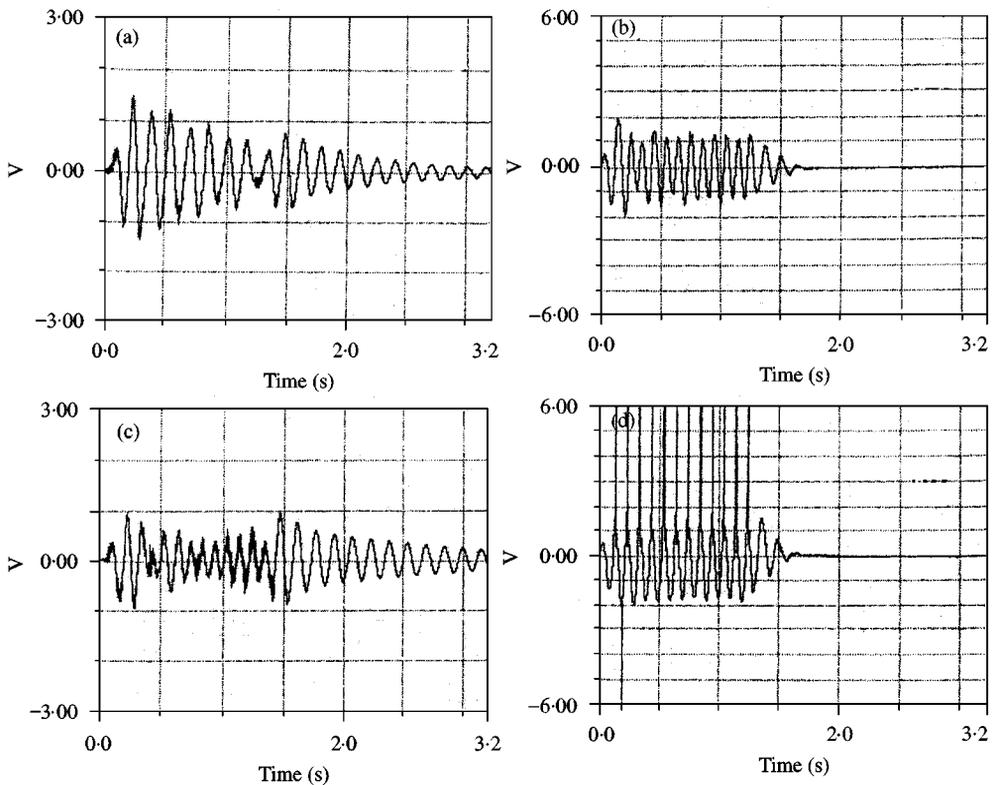
Figure 4. System response showing (a) tip acceleration and (b) secondary mass acceleration for the linear system; (c) tip acceleration and (d) secondary mass acceleration for the system with clearance non-linearity.

free oscillation. Comparing the spectra of the tip acceleration for both the linear and non-linear cases, we observed a reduction of the harmonic associated with the second flexible mode (of about 45%) and a redistribution of energy toward higher frequencies. By contrast, comparing the acceleration spectra of the secondary mass, we observed an increase of the amplitude of the harmonic associated with the mode of vibration of the secondary mass for the non-linear case (of about 50%). This indicates that, due to the clearance non-linearity, energy gets transferred from the second mode of the flexible structure to the secondary mass, i.e., energy localizes in the secondary mass in agreement with the theoretical prediction. A video showing the performance of systems with and without clearance non-linearities is posted at the world wide web site *http://www.seas.cive.wustl.edu/research/quake/nnmbase/*, where the actual experiments, together with an additional series of tests, can be viewed.

In Figure 6, we depict the maximum positive and negative amplitudes of tip accelerations for a series of tests performed at different levels of forcing input. At relatively low forcing amplitudes, where the effects of non-linearity are small, no significant reduction of tip acceleration amplitude is observed. By contrast, at higher forcing amplitudes, significant non-linear effects are present through the
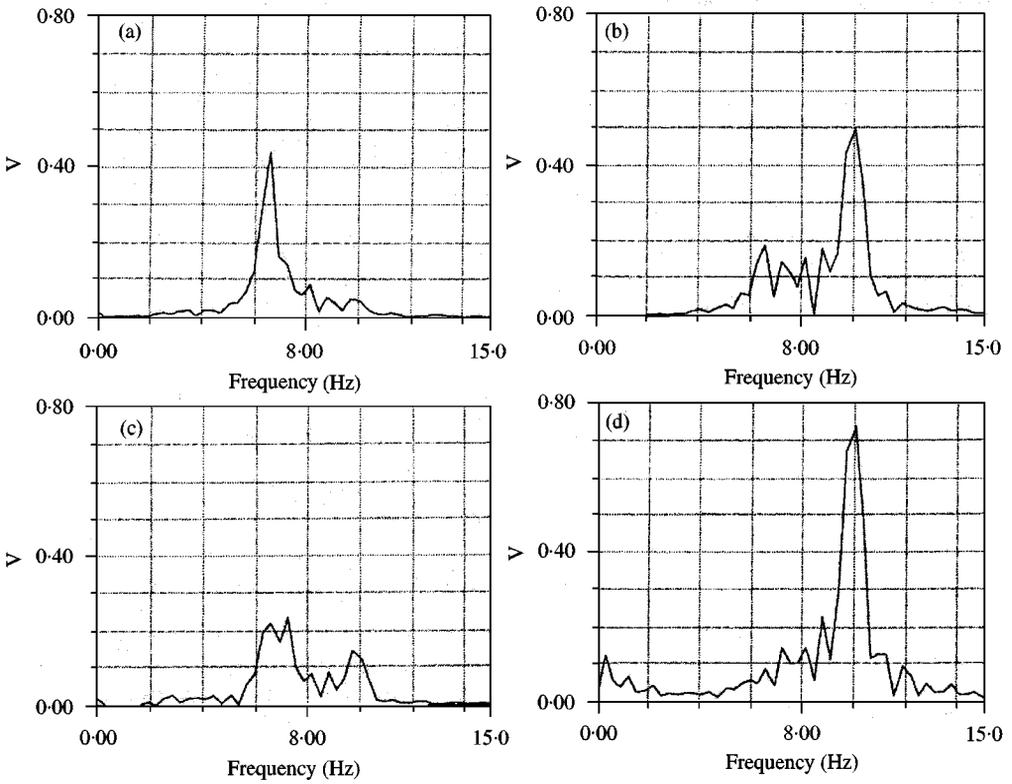
Figure 5. Fourier spectra showing (a) tip acceleration and (b) secondary mass acceleration for the linear system; (c) tip acceleration and (d) secondary mass acceleration for the system with clearance non-linearity.
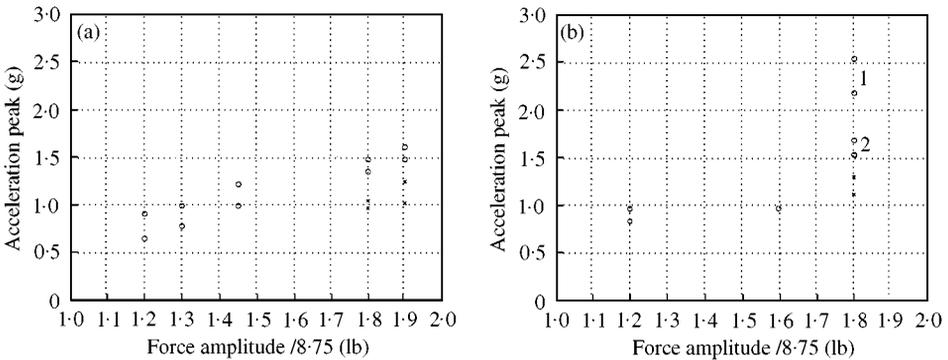
Figure 6. Maximum tip acceleration versus forcing amplitude for two different sets of experiments, (a) and (b); "○" linear and "×" nonlinear. Numbers "1" and "2" refer to two tests with different system initial conditions.

backlash non-linearity, and as a result significant reduction in the maximum tip acceleration amplitude is observed. This is in accordance with the theoretical prediction of reference [15]. The two different levels of measured tip accelerations in the two series of experiments depicted in Figure 6 are due to the change in the

initial configuration of the system (i.e., initial pretension in the coupling springs) at the instant of application of the force excitation.

4. SUMMARY AND CONCLUSIONS

The concept of non-linear localization has been successfully applied to the problem of base isolation of a flexible structure subject to shock-type ground motion through a series of small-scale tests. Observed behavior is consistent with theoretical predictions. Application of this method to full-scale structures in a multi-dimensional environment such as earthquake will obviously require a significant amount of additional analysis and testing.

ACKNOWLEDGMENT

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