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EXPERIMENTAL VALIDATION OF A ROLLING ISOLATION SYSTEM

P.S. Harvey[1], G-P. Zéhil[2], and H.P. Gavin[3]

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An assessment of the ability of lightly- and heavily-damped rolling isolation systems (RISs) to mitigate the hazard of seismically-induced failures requires high-fidelity models that can adequately capture the system's intrinsic non-linear behavior. The light damping of steel bearings rolling between steel plates can be augmented by adhering thin rubber sheets to the plates, increasing the rolling resistance and decreasing the displacement demand on the RIS. The simplified model discussed in this paper is applicable to RISs with any potential energy function, is amenable to both lightly- and heavily damped RISs, and is validated through the successful prediction of peak responses for a wide range of disturbance frequencies and intensities. The damping provided by rolling between thin viscoelastic sheets increases the allowable floor motion intensity by a factor of two-to-three, depending on the period of motion. Acceleration responses of isolation systems with damping supplied in this fashion grow with increased damping, at short-period excitations.

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ABSTRACT

An assessment of the ability of lightly- and heavily-damped rolling isolation systems (RISs) to mitigate the hazard of seismically-induced failures requires high-fidelity models that can adequately capture the systems' intrinsic non-linear behavior. The light damping of steel bearings rolling between steel plates can be augmented by adhering thin rubber sheets to the plates, increasing the rolling resistance and decreasing the displacement demand on the RIS. The simplified model discussed in this paper is applicable to RISs with any potential energy function, is amenable to both lightly- and heavily damped RISs, and is validated through the successful prediction of peak responses for a wide range of disturbance frequencies and intensities. The damping provided by rolling between thin viscoelastic sheets increases the allowable floor motion intensity by a factor of two-to-three, depending on the period of motion. Acceleration responses of isolation systems with damping supplied in this fashion grow with increased damping short-period excitations.

Introduction

Systems that mitigate earthquake hazards by enabling the uninterrupted operation of computing facilities, telecommunication networks, and lifeline systems reduce the potential of property, economic, and human losses. Equipment isolation is a promising solution for protecting mission- critical systems and valuable property from earthquake hazards [1,2]. Various isolation techniques have been developed and utilized on structures and equipment; e.g., friction pendulum isolators [3,4], rolling isolation systems [5], isolation bearings [6], and sliding isolators [7]. All are fundamentally similar—the isolated structure (or object) is mechanically decoupled from horizontal components of ground (or floor) motions via a compliant, sliding, rocking, or rolling interface. In effect, the period of the isolated system is lengthened and shifted away from the predominant periods of the disturbance, reducing resonant effects.

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The suitability of equipment isolation systems for floor motions corresponding to a structure's design-basis earthquake depends substantially on the peak displacement responses to these floor motions. The ability to predict the system's displacement demand associated with a particular hazard level or return period is of particular importance in the probabilistic seismic hazard analysis of contents protected by isolation. Estimating the displacement demand for an equipment isolation system corresponding to a specific installation, building site, and hazard level requires, in part, a predictive model of the isolation system behavior.

To date, researchers have focused primarily on the single-axis behavior of equipment isolation systems, neglecting the coupling between transverse responses. Experimental tests on equipment isolation systems are sparse [4,8,9,10], especially for multi-axis disturbances [11]. The prediction of the response of equipment isolation systems and their ability to protect building contents requires models that can capture the observed non-linear behavior of actual isolation systems subjected to multi-axis shaking. Accordingly, the focus of this paper is on the experimental validation of a multi-axis, non-linear model of a rolling equipment isolation system (RIS) to further attenuate responses.

RISs [12] are widely used to isolate mainframes, LAN racks, electronics enclosures, telecommunications switches, as well as other mission-critical equipment and valuable property. Museums around the world have adopted isolation systems to protect objects (such as The Statue of Hermes and The Gates of Hell) from earthquake-induced floor motions [13]. Presently, the United States and Japan have hundreds of installations. Displacement demands for these systems in the field are large enough (> 3 cm) to invalidate any linear approximation. Harvey and Gavin [14] derived the non-holonomic equations of motion of the RIS, which consist of eleven coupled non-linear differential equations. This paper proposes and validates a simplified mathematical model which preserves the complex non-linear nature of the system.

An illustration of the RIS to be analyzed in this article is shown in Figure 1. The system comprises a pair of rectangular frames, four pairs of shallow bowls, and four rigid steel ball-bearings. The object resting on the top-frame is isolated from the floor motion applied to the bottom-frame through a rolling pendulum mechanism. The bottom- and top-frames contain four concave-up bowls and four concave-down bowls, respectively, at their corners. Four ball-bearings roll between the lower- and upper-bowls (Figure 1) allowing for the top-frame to displace with respect to the bottom-frame. The bowl profiles of the system studied in this paper are approximately quadratic near the bowl centers and are approximately cone-shaped at larger distances from the centers. These bowl profile regimes dictate the restoring forces of the system. At the edge of the each bowl's rolling surface, a lip acts as a stiff limit on the ball-bearing's displacement. The isolation system's displacement capacity is determined by the contact of the ball-bearings with the bowl lips.

Lightly-damped RISs represent a popular method for the seismic protection of fragile objects [15,16], and these systems can perform extremely well when their displacement demands are small (< 10–20 cm) [17,18]. When the isolator's displacement capacity is insufficient to meet the demands of a disturbance, the performance of the isolator is diminished due to impacts, giving rise to potentially high acceleration responses in isolated objects. An RIS designed for strong (infrequent) floor motions would require either (i) a larger displacement capacity, or (ii) supplemental damping to reduce displacement demands. Two methods for adding damping to RISs have been investigated: (i) encasing the ball-bearing with a damping material (e.g. rubber) [9] or (ii) bonding viscoelastic layers to the counter-facing surfaces [19, 20]. Both approaches act to increase the rolling resistance and thus increase energy dissipation, decrease isolator displacements, and improve performance over lightly-damped RISs. The latter approach, referred to hereinafter as a heavily- damped RIS, is a focus of the present study.

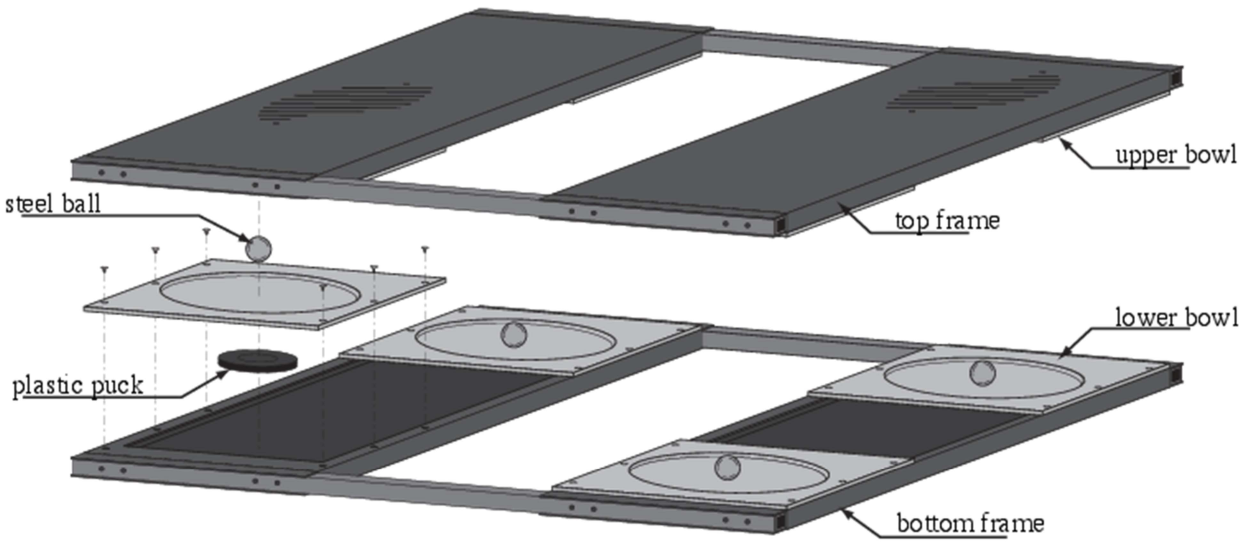

Figure 1. Exploded view of a rolling isolation platform.

Aspects of the Model

The following development is a simplified version of a more complex model [14], which incorporates mass eccentricity and the dynamics of ball-bearings rolling between non-parallel planes. Consider the displaced configuration of an RIS illustrated in Figure 2. The bottom-frame is excited by translational disturbances. Vibration-sensitive equipment is rigidly connected to the top-frame, we assume for simplicity that the equipment's mass is located concentrically. The top-frame undergoes rotation and translational displacement, relative to the bottom-frame.

The top-frame and equipment are mechanically isolated from the bottom-frame via the rolling of large, steel ball-bearings between concave-up lower-bowls and concave-down upper-bowls at the four corners (Figure 1). The bowls and balls are numbered as shown in Figure 2, and their locations are specified in relation to the bowl centers.

The gravitational restoring forces in the system are attributed to changes in the heights at the corners, which depend on the platform displacements and the ball-bearing locations. Figure 2 shows ball-bearing locations with respect to the centers of the lower- and upper- bowls We assume all the bowls are axi-symmetric with radius-dependent bowl-shape function, $\eta(r)$. The height of the top-frame at the center of the each upper-bowl is the sum of contributions from the lower- and upper-bowls.

The ball-bearing coordinates evolve according to a set of non-holonomic constraints prescribed by the condition of rolling without slipping between non-parallel surfaces [14]. The kinematic constraint, relating the ball-bearing velocities to the relative velocities of the upper-bowls at the ball-bearing locations, depends upon the slopes of the upper- and lower-bowls. The ball-bearing velocity is in the direction of the relative velocity between the upper and lower bowl. For shallow bowls, the non-holonomic constraint may be approximated by the condition that the velocity of the ball-bearing center is half of the relative velocity across the isolation system. Thus, eight non-linear first-order ordinary differential equations prescribe the evolution of the four ball-bearings. As such, initial positions for the balls must be specified.

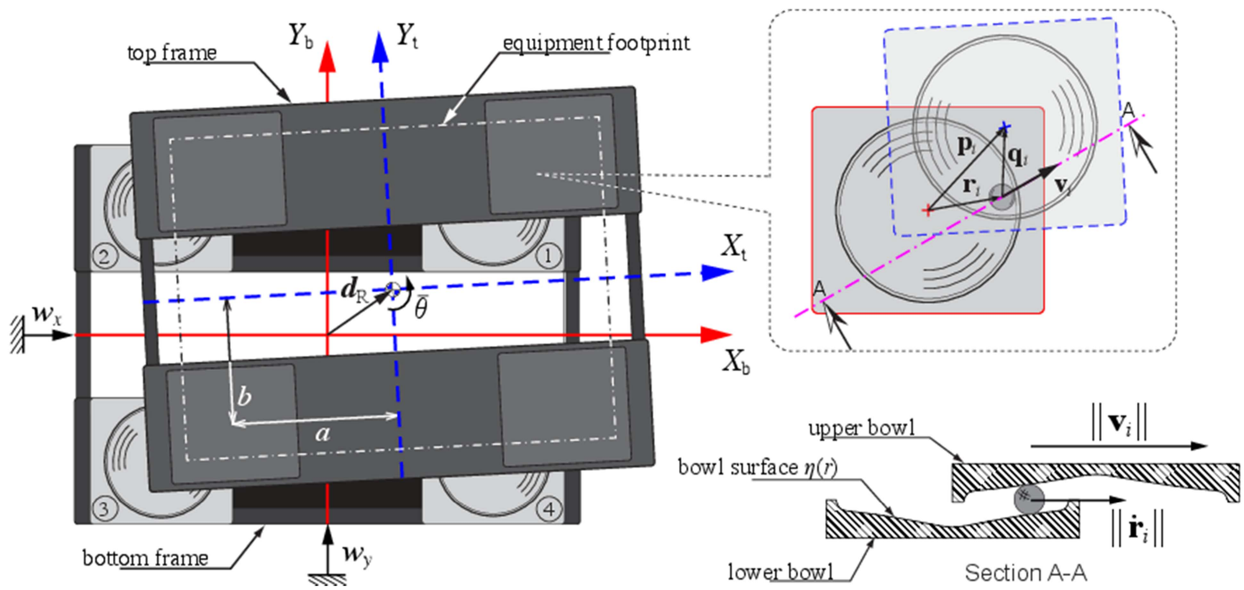

Figure 2. Coordinates of motion for the rolling isolation system, and coordinates of each ball.

The equations of motion then follow from the fundamental non-holonomic form of Lagrange's equation [14].

Dissipative Forces

The dissipative forces in the lightly-damped RIS are assumed to be linearly proportional to the ball-bearing velocities and the damping forces are modeled to act at the ball-bearing locations. Harvey and Gavin [14] fitted the energy decay computed from free-response measurements and suggested a mass-dependent damping rate. The system is very lightly damped; equivalent damping ratios are approximately 0.01 to 0.02.

Dissipative forces in the heavily-damped RIS are also modeled to act at the ball-bearing locations, in the direction of the velocity, but follow a sigmoidal relation with velocity and a power law with the compressive load [21,22].

Experimental Setup

In order to assess the performances of the lightly- and heavily-damped RISs and to validate the simplified models described above, experiments were conducted in which the systems were excited uni-axially, and various response quantities were measured. Experiments were conducted on a single-axis servo-hydraulic shaking table. The table can achieve peak velocities of 50 cm/s and has a stroke of ±7.5 cm. The RIS in this study was loaded with a set of steel plate s with mass of approximately 20 kg and a mass moment of inertia of 1.346 kg sq.cm. Their primary axes were aligned with the top-frame. Two payload masses were investigated: Small (15 steel plates ≈ 300 kg) and Large (30 steel plates ≈ 600 kg).

Bowl Shape Function

The potential energy, and hence the restoring forces, depend explicitly on the bowl-shape function. The bowls are intended to have conical radial profiles [15], but due to the manufacturing process the bowls are not perfectly conical. When installed, the bowls are clamped along two edges and a hard plastic puck is sandwiched within the platform to reduce elastic deformation in the bowls when loaded. Thus, the installed bowl shape is markedly different than the un-installed shape. To determine the deformed shape, controlled free-response experiments were performed with the lightly-damped RIS, and the acceleration-displacement relationship was used to ascertain the bowl slope.

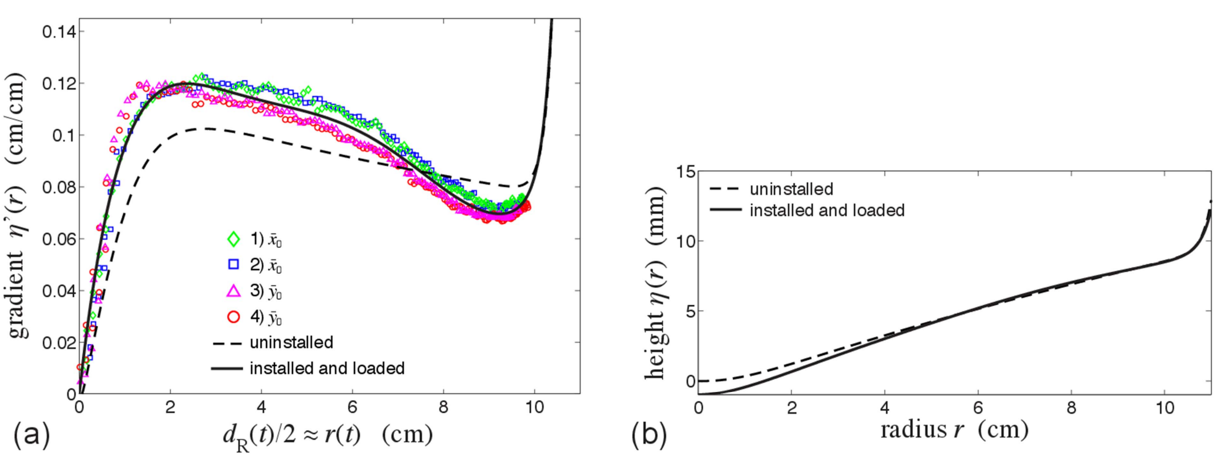

Figure 3: (a) Determination of the gradient of the bowl profiles from direct measurement of (1/4) cycle of free response. (b) Comparison of the associated bowl profiles for installed and uninstalled bowls.

Four sets of free-response measurements were analyzed. The top-frame was displaced to its full capacity—twice in the x-direction and twice in the y-direction, denoted x0 and y0 , respectively—and released from rest. The bowl gradient is computed from the measured free-response accelerations and displacements. Only the first quarter cycle of motion (approximately 0.7 s) is used to estimate the shape of the bowl. Figure 3 shows the four normalized experimental total accelerations versus relative displacements. The dashed line is the un-installed bowl fit from Ref. [14], which shows poor correspondence with the experimental data. The solid line shows a polynomial fit to the experimental data.

Lightly-Damped Model Validation

We now validate the simplified mathematical model of the lightly-damped RIS. The lightly-damped system is known to be chaotic [14,22], and thus one cannot expect to match experimental and numerical trajectories. However, peak response quantities are generally more repeatable.

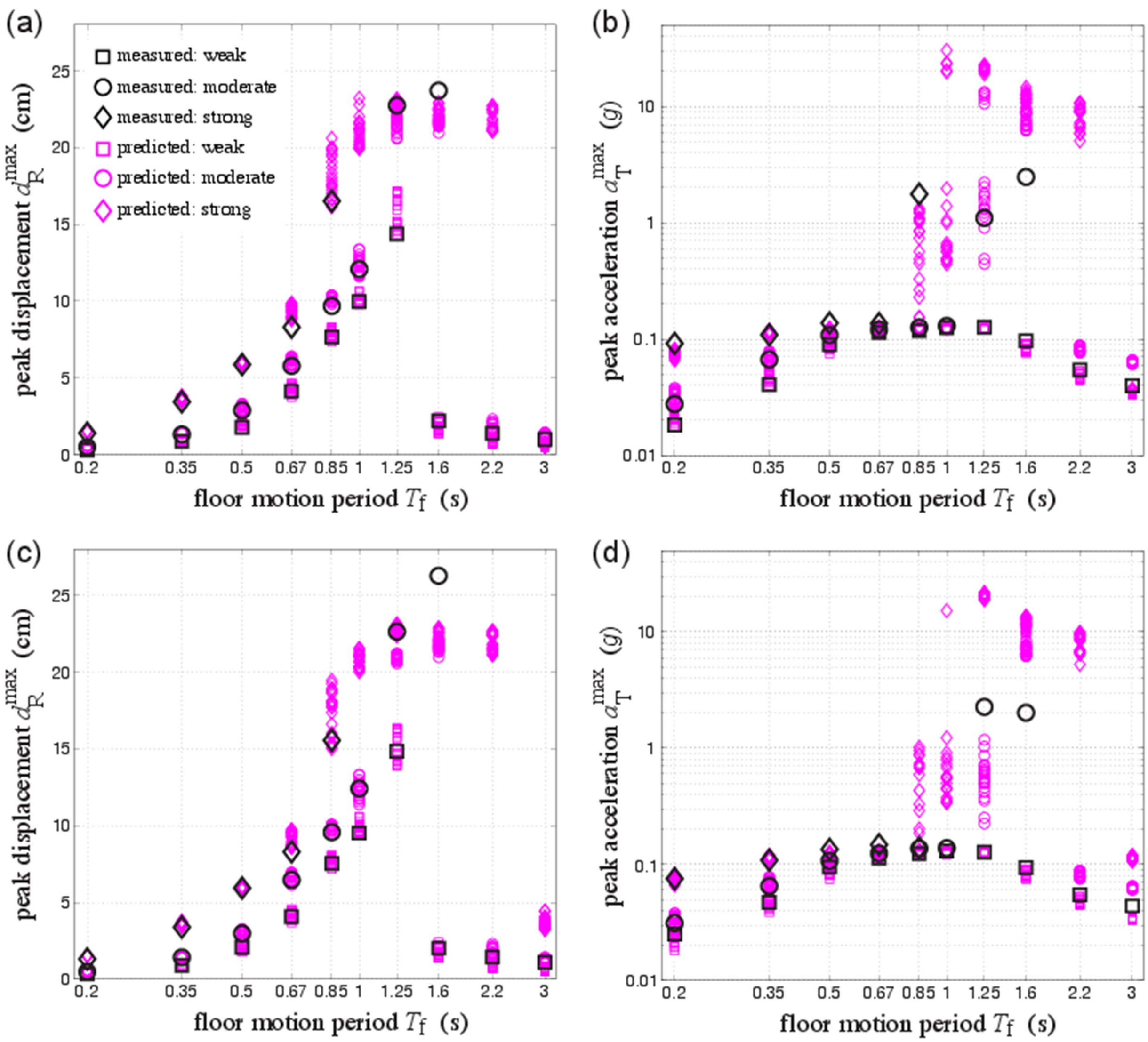

Figure 4: Experimental validation of the lightly-damped rolling isolation system model via prediction of peak response accelerations and peak response displacements for a

set of disturbances of different period and intensity. (a-b) small payload and (c- d) large payload.

The motion of the shake table is controlled to represent an idealization of the motion of a floor of a building subjected to an earthquake ground motion. As such, it is dominated by a single frequency, with amplitude that grows and decays with time.

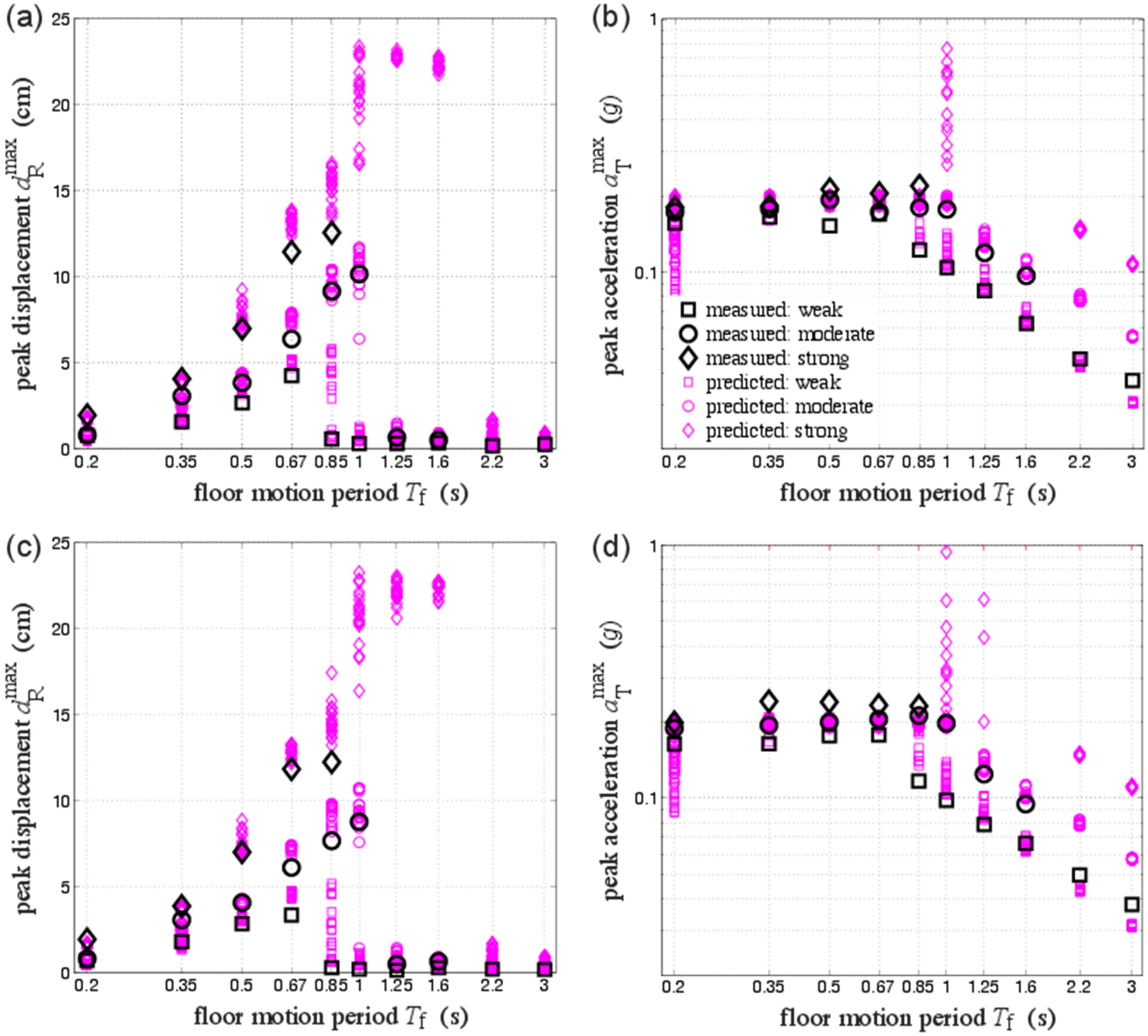

Figure 5: Measured and predicted peak responses of the heavily-damped RIS: (a-b) small payload and (c-d) arge payload. No spikes in acceleration due to impacts were seen experimentally. Large (greater than 1 g) accelerations are predicted for cases not experimentally tested (i.e. strong motions at T f = 1, 1.25, and 1.6 s), but are not shown in the acceleration spectra; these points corresponds to peak displacements greater than 20 cm.

The shaking table disturbances used in this work were designed to represent Weak, Moderate, and Strong motions over a range of periods. The disturbances are parameterized by the peak disturbance velocity and the floor motion period. Acceleration records were scaled to match the prescribed peak velocity values. The experiments were designed to have constant peak table velocities for the three disturbance strengths, but this was not precisely achieved in the laboratory implementation. The response quantities of interest are peak relative displacement and the peak total acceleration of the isolated mass. The experimentally-measured and numerically-predicted peak responses for the small and large payloads can be seen in Figure 4. The disturbance strengths are distinguished by the marker shape with the measured response quantities in black and the predicted response quantities in magenta.

The experimental and numerical peak responses show good agreement. The numerical model predicts the peak acceleration well for cases without impacts, but differing results are seen for tests with impacts since the impacts of the ball-bearings with the bowl lips generate spikes in the acceleration. Elevated peak accelerations are observed in such impacting cases (e.g. moderate periods. See Figure 4(b). Tests with impacts are easy to discern from tests without; in tests with impacts, the peak acceleration can exceed 1 g.

Heavily-Damped Model Validation

Unlike the lightly-damped system [14,22], the heavily-damped RIS is insensitive to initial conditions. Furthermore, lateral translations do not develop as they do in the lightly-damped system [14]. So the model is able to predict forced displacement and acceleration responses. The experimentally-measured and numerically-predicted peak responses for the small and large payloads can be seen in Figure 5. The predicted and measured peak responses show excellent agreement. For the small payload in Figure 5(a), the max peak displacements coincide in nearly all cases, with the numerical prediction being slightly high near resonance. High peak accelerations are predicted when a ball-bearing impacts the lip, but for clarity are not shown in Figures 5(b,d).

Nearly identical results are observed for the small and large payloads. RISs exhibit mass-independent behavior—the natural period is independent of the mass of the isolated equipment. Heavily-damped RISs, as we have shown, exhibit mass-dependent (i.e. load-dependent) rolling resistance, which scales nearly linearly (to the power 1.25) with mass. Thus, the damped isolation behavior is approximately mass-independent, as shown experimentally and numerically.

Conclusions

This paper presents model validation results for a rolling isolation system. The model validated is a simplified version of previously published models, in that the bowls are assumed to be very shallow and that the ball velocity is taken to be always half of the velocity of the upper bowl. Supplemental damping, via rubber-coated rolling surfaces, is capable of decreasing the displacement demands on RISs, thereby increasing the performance of such systems for high-intensity motions. The improvement of isolation performance through added damping is more pronounced at longer period excitations.

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