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Comparison of semi-active control strategies for rocking objects under pulse and harmonic excitations

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ABSTRACT

Recently, a considerable literature has grown up around the theme of seismic protection of rigid blocks, with a special focus on strategies to reduce the overturning vulnerability due to rocking motion. The present paper investigates a semi-active control method for rocking blocks and compares different strategies for its implementation. In more detail, a feedback control algorithm was developed to adjust the stiffness of the restraints placed at the two lower corners of the block. The utility of the proposed control was quantified through “ad hoc” indices derived from overturning spectra. The performance of a feedback strategy was numerically investigated and specific simulations were performed to quantify the control method degradation when implemented for a real-world application. Finally, the stability of the block controlled with the proposed strategy is compared with the stability of the block whose anchorage is set according to different control strategies.

1. Introduction

The mitigation of the overturning vulnerability due to rocking motion is a thriving research area in the recent years. Overturn vulnerability is a concern for electronic equipment, storage tanks and art objects whose seismic behaviour can be analyzed, from a structural point of view, within the context of the dynamic response of a rigid body.

Rocking is only one of the possible types of motion that a rigid body on a rigid base can experience during a seismic event [1,2]. To mitigate the damage due to the rocking response and to limit the probability of overturning, several passive control strategies were proposed and investigated in the past years. The oldest strategies are based on very simple and intuitive countermeasures, such as lowering the gravity centre of the body [3–8] or fixing the object to the support [3,9–12]. These interventions modify the dynamic behaviour of the body, which is forced to bend and deform instead of oscillating rigidly. As a consequence, the body may be exposed to excessive stresses.

The use of base isolation has been proposed in the last decade to reduce the effective seismic action without inducing high stresses in the bodies, which are thus free to rock on the isolation device [13–18]. Two strategies other than base isolation were recently proposed to reduce the overturning vulnerability while allowing the object to rock [19,20]. More specifically, De Leo et al. proposed a passive tuned mass damper hinged at the top of the block [19], while Ceravolo et al. proposed a semi-active anchorage positioned at the base of the body [20].

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This paper investigates the performance of a semi-active control that employs a feedback strategy to adjust the stiffness of two anchorages placed at the lower corners of the block. The performance of the feedback control strategy was evaluated with reference to a benchmark block subjected to pulse and harmonic excitations. The dynamic behaviour of the block was investigated numerically using a 2D model derived from the Housner model and based on the same assumptions [6]. In order to quantify the efficacy of the control strategy two "ad hoc" utility indices were inferred from the overturning spectra. Thus, it has been possible to compare the feedback control performance to the one of the feedback-feedforward strategy introduced in [20] and the performance of passive control systems. Finally, the influence of timing on the two control strategies was investigated and quantified.

2. Analytical model of the controlled block

A rigid block on a rigid plane, anchored by unilateral restraints placed at the two lower corners of the body, as depicted in Fig. 1, is characterised by the body and the anchorage parameters. More specifically, the body is characterised by the size parameter $R = \sqrt{h^2 + b^2}$, i.e. the distance between the corner of rotation to the centre of mass of the body, and by the slenderness $\lambda = h/b$. Similarly, the semi-active anchorage is characterised by: (i) the two values that the stiffness can assume during the rocking motion, namely K_{max} and K_{min}; (ii) the influence factor q; and (iii) the strength parameter σ. Parameters q and σ reflect, respectively, the maximum elongation of the restrainers at their failure Δ_u and the maximum intensity of the total load transmitted by the anchorage F_u.

The governing equation of the 2D model reported in Fig. 1 is obtained modifying the analytical model of Makris and Roussos [21] and Dimitrakopoulos and DeJong [12] so as to account for the adjustability of the anchorage stiffness. The analytical model of the controlled block is based on the same hypotheses of Housner's model [23]. In detail, these hypotheses are: (a) the body behaves as a rigid body with respect to the excitation; (b) the base support is infinitely rigid; (c) the mass centre of the body is equidistant from the two corners of rotation; (d) the impact is punctual; (e) the impact time Δt_I is infinitely small and the body occupies the same position during the impact; (f) no loss of contact occurs between the body and the support during the rocking motion and at the impact; (g) the coefficient of friction is large enough to prevent sliding, and (h) the impact causes the rotation corner to switch without bouncing.

The governing equation of rocking motion of the rigid block anchored with a semi-active restraint system reads:

$$\ddot{\theta}(t) + \frac{1}{I_0}\{M_g(\theta) + M_{ex}(\theta) + M_{K,TOT}(\theta, K(t))\} = 0 \tag{1}$$

where I_0 is the moment of inertia of the block about the rotation corner, equal to $I_0 = 4mR^2/3$ for a rectangular block, $M_g(\theta)$ and $M_{ex}(\theta)$ are the moments due to the block self-weight and the external excitation, respectively, while $M_{K,TOT}(\theta, K(t))$ is the restoring moment exerted by the anchorages. The three moment terms read respectively:

$$M_g(\theta) = mgR\sin(\mathrm{sgn}[\theta(t)]\alpha - \theta(t)) \tag{2}$$

$$M_{ex}(\theta) = m\ddot{X}_g(t)R\cos(\mathrm{sgn}[\theta(t)]\alpha - \theta(t)) + m\ddot{Y}_g(t)R\sin(\mathrm{sgn}[\theta(t)]\alpha - \theta(t)) \tag{3}$$

$$M_{K,TOT}(\theta, K(t)) = M_K(\theta, K(t))f_{K,R}(\theta_{min}(t))f_{W,R}(\theta(t)) + M_K(\theta, K(t))f_{K,L}(\theta_{max}(t))f_{W,L}(\theta(t)) \tag{4}$$

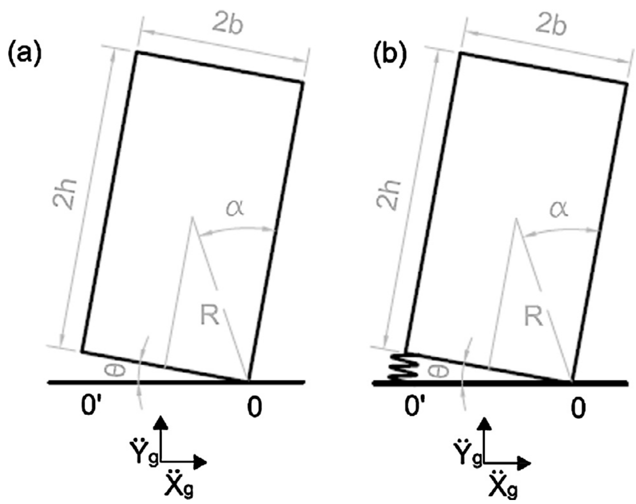

Fig. 1. A rocking block subjected to horizontal and vertical excitation (a) unanchored and (b) anchored.