Vibration Control with Nonlinear Rotating Inertial Mass Device

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1. Introduction

The authors have been carrying out numerical studies on the effect of a passive nonlinear absorber containing a rotating inertial mass (N-RIM). In this paper, the performance of this proposed absorber system when used for the base isolation of a building against strong earthquakes is presented. The N-RIM system consists of a strongly nonlinear stiffness and a rotating inertial mass (RIM). In order to examine the performance of this nonlinear system, numerical continuation techniques are used to examine the resonance curves and also to determine their stability while direct time integration is used to examine the transient behavior of the dynamic system.

The RIM device includes a ball screw that converts the axial oscillation of the rod end into rotational motion of the internal flywheel. The rotating flywheel in the device is able to generate a large inertial force that can exceed 5000 times its real mass.

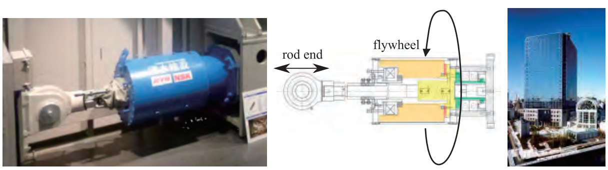

Fig. 1: Photo and cross section of RIM

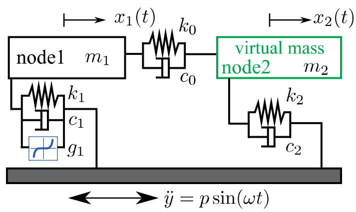

Fig. 2: N-RIM system

2. Dynamics of linear and nonlinear system

A two-degree-of-freedom system consisting of the N-RIM device under harmonic ground motion is considered, as shown in Fig. 2. The governing equations of motion of this system are given by:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_0+c_1 & -c_0 \\ -c_0 & c_0+c_2 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_0+k_1 & -k_0 \\ -k_0 & k_0+k_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{Bmatrix} G_1(x_1) \\ 0 \end{Bmatrix} = -\begin{Bmatrix} m_1 \\ \delta m_2 \end{Bmatrix}\ddot{y} \tag{1}$$

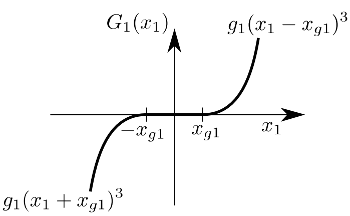

Fig. 3: Cubic nonlinearity

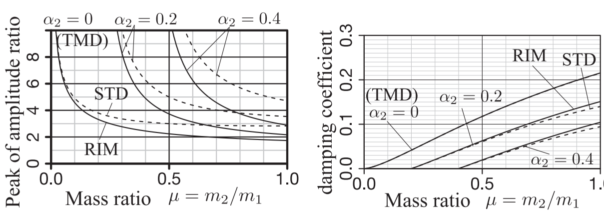

Fig. 4: Optimized parameters of linear systems

First, we derived optimized parameters for linear systems using the fixed-point theory. A standard system (STD) is common type of coupled vibration control structure ($\delta = 1$ in Eq. (1)). A RIM system is a coupled vibration control structure with RIM ($\delta = 0$). Figure 4 shows that the RIM system is more effective than the STD system. Such linear systems require a large amount of damping in the case of a large mass ratio.

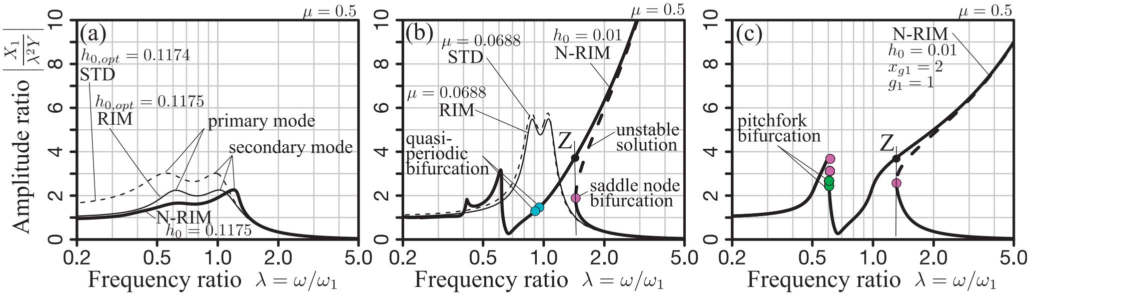

Fig. 5: Resonance curves of STD, RIM, N-RIM

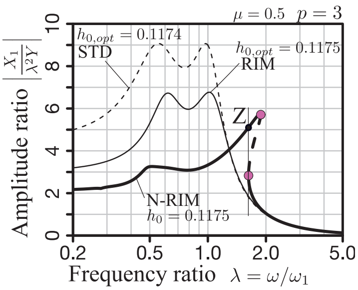

Fig. 6: Resonance curves in case of large input motion (p=3)

The resonance curves of RIM, STD and N-RIM systems for the case of $\mu = 0.5$ are shown in Fig. 5(a). There are two mode peaks in the resonance curve. The RIM system is more effective than the STD system in the low frequency ratio region. The N-RIM system results in a lower primary mode peak. On the other hand, the peak of the secondary mode shifts in the direction of higher frequency. In Fig. 5(b), we investigate a low damping coefficient condition. The optimized parameters of the STD and RIM systems are recalculated. Such a low damping coefficient requires a low mass ratio for optimization using the fixed-point theory. The amplitude ratios of the STD and RIM systems increase to almost 6.0. In comparison with the RIM system, the peak of the primary mode with the N-RIM system is low, but the peak of the secondary mode is much higher. Meanwhile, we can use the lowest stable solution in a case where the initial conditions are zero or small. Therefore, we regard point Z as the maximum amplitude ratio in Fig. 5(b). The effect of the gap in the cubic nonlinearity is shown in Fig. 5(c). The quasi-periodic bifurcations shown in Fig. 5(b) vanish. On the other hand, pitchfork bifurcations emerge near the primary mode. As the two stable solution lines cover the whole frequency range, the pitchfork bifurcations do not result in any divergence phenomenon. Figure 6 shows resonance curves in the case of large input motion. The amplitude ratios of the linear systems (STD, RIM) increase proportionally. By contrast, the N-RIM system restrains the amplitude ratio over a relatively broad frequency range.

3. Conclusions

In this paper, we report on analytical studies of the response characteristics of two-degree-of-freedom systems with a nonlinear rotating inertial mass (N-RIM) under harmonic ground motion. First, we derived optimized parameters for linear systems using the fixed-point theory, showing that the RIM system is more effective than standard coupled vibration control structures. Such linear systems require a large amount of damping in the case of a large mass ratio. Next, we studied N-RIM systems using numerical continuation techniques and direct time integration. Many interesting and complex dynamic phenomena were found, including pitchfork and quasi-periodic bifurcations as well as a saddle node. The N-RIM system is shown not to require a large amount of damping even for a large mass ratio. Furthermore N-RIM systems can restrain the response amplitude over a relatively broad frequency range in the case of a large input motion. In conclusion, the newly proposed N-RIM system is shown to reduce structural response quite effectively.