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TWO-AXIS VIBRATION RESPONSE ATTENUATION OF BUILDING STRUCTURE USING ROLLING CYLINDER DYNAMIC VIBRATION ABSORBER

*Lovely Son[1], Mulyadi Bur[1], Bima Anugrah Saputra[1], Eka Satria[1] and Zeki Midi[1]

[1]Mechanical Engineering Department, Engineering Faculty, Andalas University, Indonesia

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ABSTRACT: This study proposes a novel two-axis dynamic vibration absorber designed to mitigate building vibrations in two axes of motion. The dynamic vibration absorber comprises two cylinders rolling along a circular curved track, each aligned orthogonally to reduce vibration responses along separate axes. Both absorbers are placed on the upper floor of the building and the natural frequencies of the cylinders are tuned to match the two lowest natural frequencies of the building's bending modes. Several simulation studies in frequency and time domains are performed to evaluate the damper performance in reducing the building structural response under seismic excitation. The simulation data shows that the proposed dynamics vibration absorber can effectively reduce the seismic response of the building structure. Additionally, an experimental set-up is built and tested to validate the simulation outcomes. Experimental findings reveal a 70% reduction in structural vibration, with close agreement between empirical and simulation results, confirming the DVA's efficacy.

Keywords: Vibration, Dynamics, Building, Absorber, Structure

1. INTRODUCTION

Buildings are continuously subjected to various dynamic loads such as wind, earthquakes, traffic, machinery, and human activities, which can induce vibrations that affect structural integrity, occupant comfort, and serviceability. As modern buildings become taller, lighter, and more flexible, their susceptibility to vibration-related problems has increased significantly. Excessive vibrations can lead not only to structural damage but also to discomfort, reduced productivity, and even long-term health issues for occupants.

Vibrations of building structures due to earthquakes have become the focus of attention of researchers in recent decades. This is because earthquakes are natural phenomena that are difficult to predict accurately both in terms of time and place of occurrence [1,2]. Besides that, earthquakes with large energy can cause damage and even collapse of building structures.

The dynamic response of buildings during earthquakes depends on several factors, including structural configuration, material properties, mass distribution, stiffness, and damping characteristics. When the frequency content of ground motion approaches the natural frequencies of a structure, resonance may occur, significantly amplifying structural response and increasing the likelihood of damage. Therefore, anticipating the effects of earthquakes on building structures is very important in designing earthquake-resistant building structures.

To mitigate undesirable vibrations, various control strategies have been developed, including passive, semi-active, and active vibration control systems. Passive devices are widely used due to their reliability and low maintenance requirements. Recent research has focused on improving the effectiveness, adaptability, and cost-efficiency of these systems, as well as developing innovative damping mechanisms tailored to specific structural applications.

Dynamic vibration absorbers (DVAs) are proven passive solutions for mitigating structural vibration. Many researches have been conducted to investigate diverse DVA configurations for structural application such as pendulum absorbers [3], U-shaped water tanks [4], and tuned mass dampers TMDs [5]. DVA can be tuned to minimize vibration amplitudes and even harness energy from structural oscillations, offering dual-functional benefits [6]. Design of multiple DVAs that simultaneously absorbs vibration energy from a high-speed train that enabling streamlined performance assessment have been established [7]. Recent studies investigate the application of Genetic Algorithm (GA) to optimize vibration suppression in a Two-DOF structure model subjected to seismic load [8]. For high-rise structures, advanced numerical models are essential to accurately evaluate DVA effectiveness, as oversimplified two-degree-of-freedom models fail to capture real-world complexities. Research related to the application of DVA for multidirectional vibrations has been carried out by several researchers. Qin et al. [9] apply multiple DVA in reducing a floor-like lightweight joist structure vibration. Yin et al. [10] propose a technique to control multi-directional vibration of marine pipe system using mistuned cyclic symmetric structure as DVA. Bur et al. [11] develop a DVA system consist of two pendulums connected by helical spring to control vibration of shear structure model.

The effectiveness of a dynamic vibration absorber (DVA) depends largely on the appropriate selection of its natural frequency, and damping parameters. A DVA functions by transferring vibrational energy from the primary structure to a secondary system, thereby reducing the response of the main structure. To achieve optimal performance, the absorber must be properly tuned to the dynamic characteristics of the structure it is intended to protect.

A critical factor in selecting a passive DVA for practical use is the ease with which its parameters can be tuned. Rolling cylinder-based DVAs distinguish themselves by allowing for simple natural frequency adjustments, achieved by modifying the cylinder's radius as it traverses a circular path. This mechanism is also easily integrated into multi-degree-of-freedom structures. In addition, the damping value of rolling cylinder-based DVAs can easily varied using friction or magnetic damping mechanism.

Previous research has investigated the efficacy of rolling cylinder-based DVAs; for instance, Shiryayev and Vahdati [12] compared the rolling cylinder vibration absorber performance on flat versus curved paths, while Ito and Aida [13] utilized magnetic damping on the rolling pendulum type dynamic absorber to address rocking vibrations. Investigation of vibrational energy dissipation by tuned rolling-cylinder dampers was performed by Tsuda and Saeki [14]. Building on these foundations, this study proposes a vibration control strategy for spatial structures using a rolling cylinder DVA. Using a two-story building model as a case study, we demonstrate how two perpendicular cylinders mounted on the top floor can effectively suppress bending-mode vibrations along both the x and y axes.

2. RESEARCH SIGNIFICANCE

Research on the application of rolling cylinder–based dynamic vibration absorbers (DVAs) in spatial structures remains limited. To the best of the author's knowledge, existing studies have largely been confined to single-degree-of-freedom vibration systems. This study presents the development of a rolling cylinder–based DVA for spatial structural applications. The key contribution of this work is its ability to attenuate structural vibrations in two orthogonal directions, specifically along the x- and y-axes. Moreover, the installation of the damper in two perpendicular orientations on the building roof further differentiates this study from previous research. Furthermore, the proposed method can be experimentally validated on laboratory-scale structural models.

3. METHODOLOGY

3.1 One Degree of Freedom System with a Rolling Cylinder DVA

A single-degree-of-freedom (One-DOF) vibration system integrated with a rolling cylinder dynamic vibration absorber (DVA) is shown in Fig.1. The primary system is defined by mass *M*, stiffness *k*, and damping coefficient *c*. The DVA consists of a cylinder with mass *m* and radius *r*, which rolls along a circular track of radius *R*

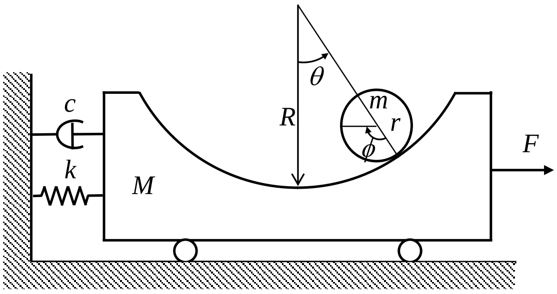


Fig.1 One degree of freedom system with rolling cylinder DVA

The moment balance on the cylinder at the contact point between the cylinder and the pad results in:

$$J_G\left(\ddot{\phi}-\ddot{\theta}\right)+mr\left(R-r\right)\ddot{\theta}+m\ddot{x}r\cos\theta+mgr\sin\theta$$
$$+C_r\dot{\theta}=0 \qquad (1)$$

In the case of without slip $\phi=\frac{R}{r}\theta$ and $\ddot{\phi}=\frac{R}{r}\ddot{\theta}$, therefore Eq. (1) can be simplified by:

$$L\left(\frac{J_G}{r^2}+m\right)\ddot{\theta}+m\ddot{x}\cos\theta+mg\sin\theta+\frac{C_r}{r}\dot{\theta}=0 \qquad (2)$$

Where $L=R-r$ and *L* denotes the pendulum length. Applying a force balance to the main mass yields:

$$M\ddot{x}+c\dot{x}+kx+m\ddot{x}+mL\ddot{\theta}\cos\theta-mL\dot{\theta}^2\sin\theta=F \qquad (3)$$

Eq. (2) and (3) are the governing equations of 1-DOF vibration system with rolling cylinder DVA.

3.2 Building Structure Model with Two Rolling Cylinder DVA

A building structure model incorporating two rolling cylinder dynamic vibration absorbers (DVAs) as shown in Fig.2 is utilized to evaluate the damper performance on the spatial structure. The structure represents a two-story building model, comprising a basement floor, a first floor, and a second floor. Each floor is supported by six vertical columns, as illustrated in Fig.2. Two rolling cylinder DVAs are positioned atop the second floor. These absorbers are designed to mitigate the two lowest bending mode vibrations of the structure in the x- and y-directions

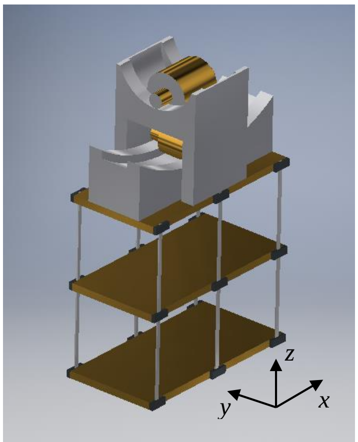


Fig.2 Building structure model with two rolling cylinder DVA

3.2.1 Governing equation

To derive the governing equations for the space structure equipped with absorbers, the system is modeled using the finite element method (FEM). The coupled differential equations governing the absorber and the structure are formulated as:

$$L_i\left(\frac{J_{Gi}}{r_i^2}+m_{di}\right)\ddot{\theta}_i+m_{di}\ddot{x}_{di}\cos\theta_i+m_{di}g\sin\theta_i$$

$$+\frac{C_{ri}}{r_i}\dot{\theta}_i=0\ \ ,i=1,2 \tag{4}$$

$$[\mathbf{M}]\{\ddot{\mathbf{x}}\}+[\mathbf{C}]\{\dot{\mathbf{x}}\}+[\mathbf{K}]\{\mathbf{x}\}=\{\mathbf{B_u}\}f_{ext}$$

$$+\{\mathbf{B_v}\}f_{in} \tag{5}$$

were
$[\mathbf{M}]$, $[\mathbf{C}]$ and $[\mathbf{K}]$ are the structural mass, damping and stiffness matrix calculated by FEM, respectively. $\{\mathbf{B_u}\}$ and $\{\mathbf{B_v}\}$ in Eq. (5) are the row matrices that contain delta functions $\delta_{i,j}$ as follows:

$$\{\mathbf{B_u}\}=\{\delta_{u,1}\quad \delta_{u,2}\quad \cdots\quad \delta_{u,j}\quad \cdots\quad \delta_{u,NDOF}\} \tag{6}$$

$$\{\mathbf{B_v}\}=\{\delta_{v,1}\quad \delta_{v,2}\quad \cdots\quad \delta_{v,j}\quad \cdots\quad \delta_{v,NDOF}\} \tag{7}$$

In Eq. (6) and (7), subscript u and v denote position of the external forces and the interaction forces between DVA and structure. $\delta_{i,j}$ denotes delta function that can be expressed by:

$$\delta_{i,j}=\begin{cases}1, & \text{if } i=j\\ 0, & \text{if } i\neq j\end{cases} \tag{8}$$

The external and interaction force between structure and DVA are expressed as:

$$f_{ext}=F \tag{9}$$

$$f_{in}=mL\dot{\theta}^2\sin\theta-mL\ddot{\theta}\cos\theta-m\ddot{x} \tag{10}$$

Eq. (5) can be expressed in modal coordinates as follows:

$$\ddot{q}_i+2\zeta_i\omega_i q_i+\omega_i^2 q_i=\mathbf{\Psi_i}\left[\{\mathbf{B_u}\}f_{ext}+\{\mathbf{B_v}\}f_{in}\right],$$

$$i=1,2,\cdots,\infty \tag{11}$$

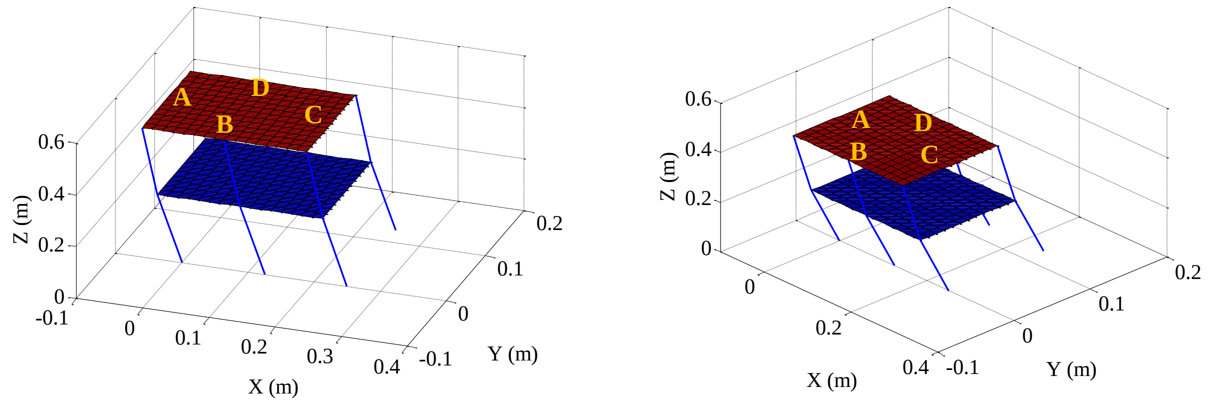
3.2.2 Frequency response function (FRF)

The frequency response function (FRF) of the space structure model integrated with two cylindrical DVAs is calculated under the assumption of linear system behavior. For small cylinder displacements, linear approximations are applied to the cylinder's rotational motion and translational dynamics. Using this assumption, the governing equations of the system (Eqs. (4) and (5)) are linearized as follows:

$$[\mathbf{M}]_{\mathbf{lin}}\{\ddot{\mathbf{x}}\}+[\mathbf{C}]_{\mathbf{lin}}\{\dot{\mathbf{x}}\}+[\mathbf{K}]_{\mathbf{lin}}\{\mathbf{x}\}=\{\mathbf{B}\}_{\mathbf{lin}}F \tag{12}$$

4. RESULTS AND DISCUSSION

The vibration attenuation performance of the building structure model equipped with two rolling cylinder dynamic vibration absorbers (DVAs) is numerically evaluated using the nominal simulation parameters listed in Table 1. In the simulation study, the DVAs are positioned at the center of the second floor.



f_1 = 1.77 Hz

f_2 = 2.65 Hz

Fig.3 Two Lowest natural frequencies and mode shapes of the structure model

Table 1 Nominal simulation parameters

No	Parameters	Value
1	1st floor dimensions	(250 × 125× 8) mm
2	2nd floor dimensions	(250 × 125 × 8) mm
3	Columns dimensions	(2 × 3 × 125) mm
4	Columns modulus (E_c)	69×10^9 N/m^2
5	Plate modulus (E_c)	120×10^9 N/m^2
6	1st pendulum mass (m_{d1})	0.35 kg
7	2nd pendulum mass (m_{d2})	0.09 kg
8	1st pendulum inertia (J_{G1})	3.5×10^{-5} kg m^2
9	2nd pendulum inertia(J_{G2})	3.7×10^{-6} kg m^2
10	Structural damping ratio (ζ)	1×10^{-3} Ns/m
11	1st pendulum length (L_1)	0.08 m
12	2nd pendulum length (L_2)	0.033 m
13	1st cylinder radius (r_1)	0.01 m
14	2nd cylinder radius (r_2)	0.005 m
15	Damping (C_{r1} and C_{r2})	1×10^{-4} Nms

The two lowest natural frequencies of the structure (1.77 Hz and 2.65 Hz) and their corresponding mode shapes, derived from numerical simulations is depicted in Fig.3. The first and second mode shapes represent the structure's lowest bending modes in the x- and y-directions. Two cylindrical DVAs are tuned to these two natural frequencies to target vibration mitigation in these critical modes. Two rolling-cylinder dynamic vibration absorbers (DVAs) are designed to suppress vibrations in the building structure along two orthogonal axes (x and y directions). Both devices are mounted on the top floor of the building, as shown in Fig. 2. Their effectiveness is assessed through the structure's frequency response functions (FRFs) in the x–z and y–z planes. The FRF in the x–z plane is obtained using excitation at point A and response measurements at point C, whereas the FRF in the y–z plane is determined from excitation and measurements taken at points B and D (see Fig. 3).

4.1 Variation of Pendulums İnertia (J_{G1}, J_{G2})

The effect of varying J_{G1} on the frequency response function (FRF) in the x-z plane is shown in Fig.4(a). The results demonstrate that reducing J_{G1} from its nominal value enhances the damper's effectiveness in suppressing vibrations near the natural frequency of the first bending mode in the x-z plane. Conversely, as shown in Fig.4(b), variations in J_{G1} exhibit negligible impact on the FRF in the y-z plane. The impact of J_{G2} variations on the FRF in the x-z and y-z planes (Fig.5) reveal that the x-z plane FRF exhibits little to no sensitivity to J_{G2} adjustments. In contrast, deviations in J_{G2} affect the y-z plane FRF, though the effect remains relatively minor.

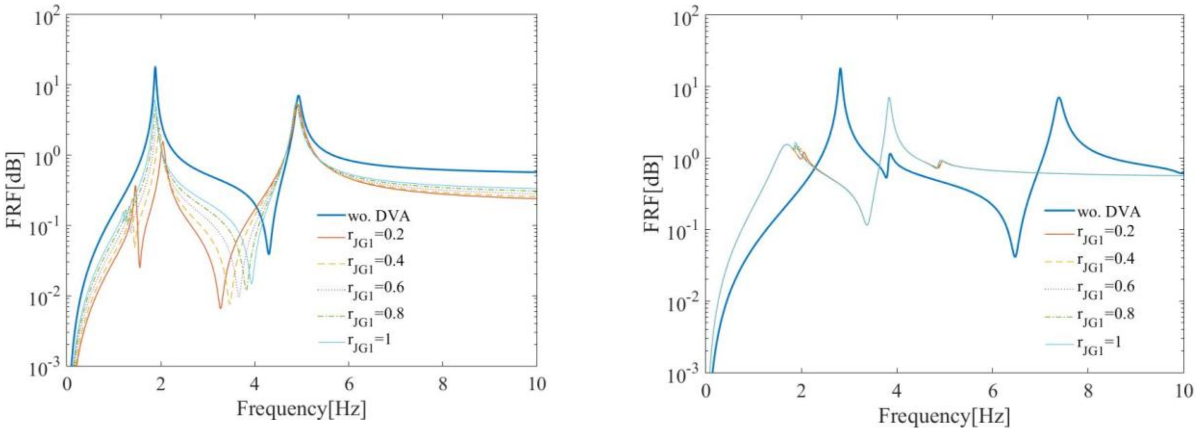


Fig. 4 Variation of FRF vs J_{G1} (a) x-z plane (b) y-z plane

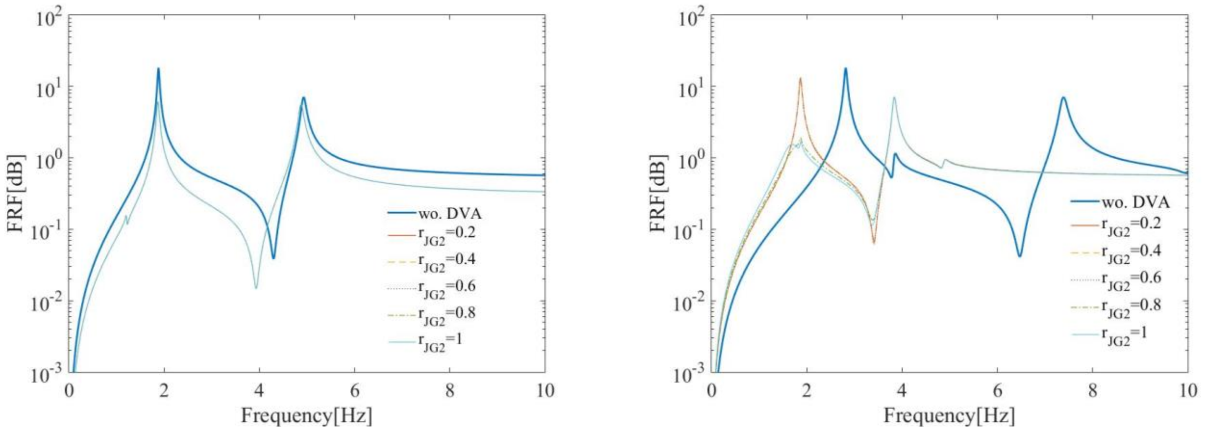


Fig. 5 Variation of FRF vs J_{G2} (a) x-z plane (b) y-z plane

4.2 Variation of Circular Track Radius (L_1, L_2)

The effect of increasing L_1 on the FRF of the structure in the x-z and y-z planes is shown in Fig.6. It is shown that variations in L_1 markedly influence the FRF in the x-z plane. Notably, reducing L_1 below its nominal value enhances the DVA's effectiveness in mitigating structural vibrations in this plane. In contrast, the y-z plane FRF exhibits negligible sensitivity to changes in L_1.

Relationship between L_2 adjustments and the FRF of the structure in the x-z and y-z planes is evaluated by varying the ratio between L_2 to its nominal value as shown in Fig.7. The results reveal that increasing L_2 has negligible impact on the x-z plane FRF. Conversely, elevating L_2 introduces a slight but measurable effect on the y-z plane FRF.

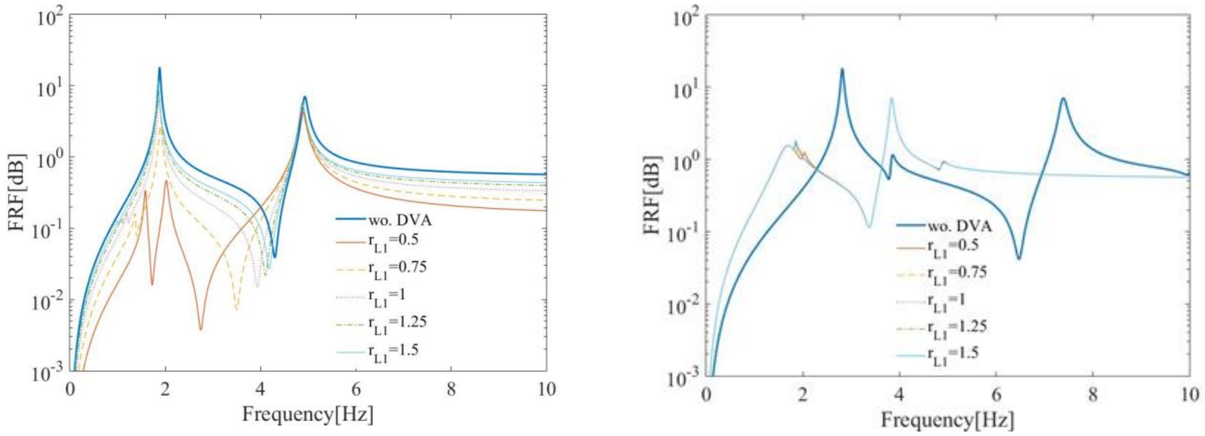


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Fig. 6 Variation of FRF vs L_1 (a) x-z plane (b) y-z plane

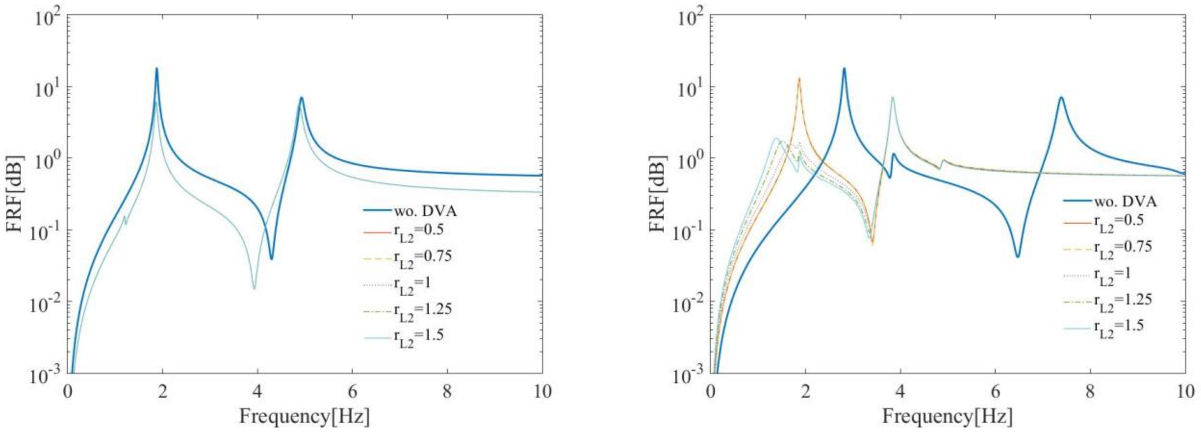

Fig.7 Variation of FRF vs L_2 (a) x-z plane (b) y-z plane

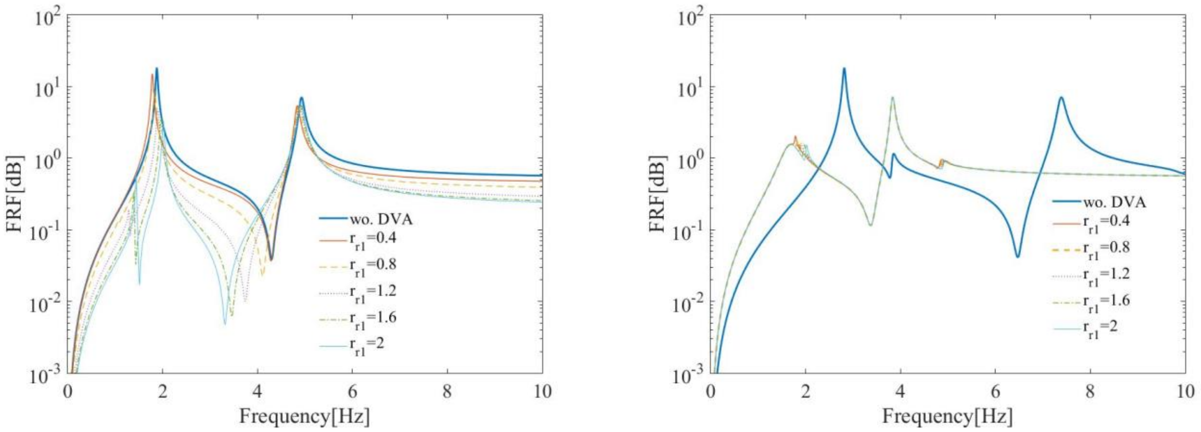

Fig. 8 Variation of FRF vs r_1 (a) x-z plane (b) y-z plane

4.3 Variation of Cylinder Radius (r_1, r_2)

Fig.8 demonstrates the influence of the first cylinder radius (r_1) on the FRF of the structure in the x-z and y-z planes. Enlarging r_1 enhances the dynamic absorber's vibration mitigation performance in the x-z plane. Conversely, increasing r_1 exerts minimal influence on the y-z plane FRF.

Time-domain responses simulation of the structure in x-z plane and y-z plane at two distinct measurement points are shown in Fig.9. The external excitations are applied at points A (x-direction) and B (y-direction), with the Kobe earthquake signal serving as the disturbance input. The structural response is measured at points C and D. It is shown that both dynamic absorbers significantly mitigate structural vibrations in the x-z and y-z axis. Compared to conventional DVA which is only able to reduce vibrations in one axis [9], rolling cylinder DVA developed in this study has the ability to dampen vibrations in both directions of the vibration axis.

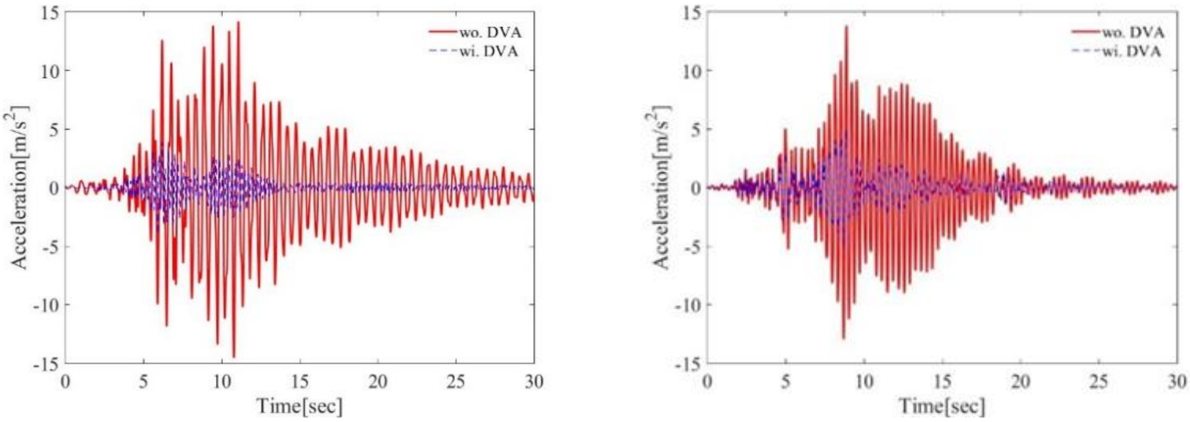

Fig. 9 Time response calculated in (a) x-z plane (b) y-z plane

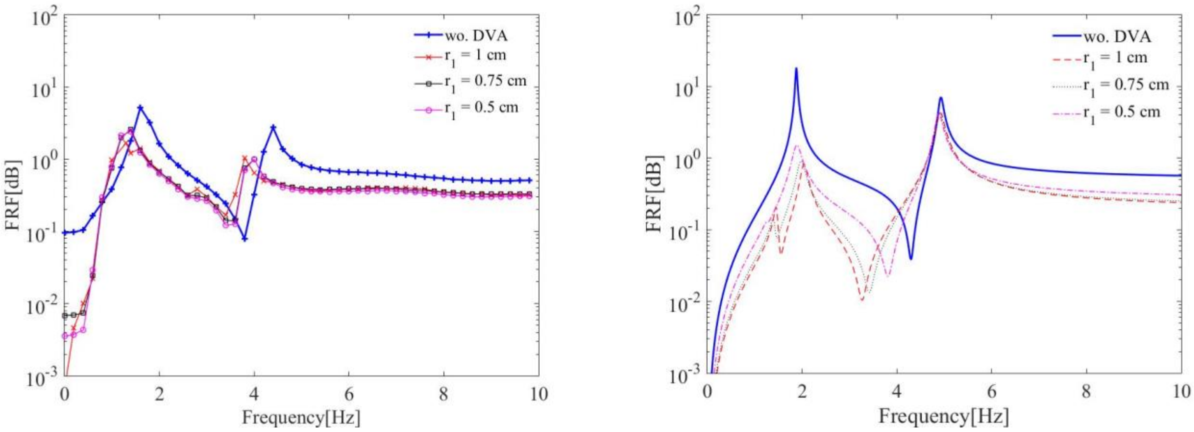

Fig. 10 Comparison of FRF in x-z plane (a) experiment (b) simulation

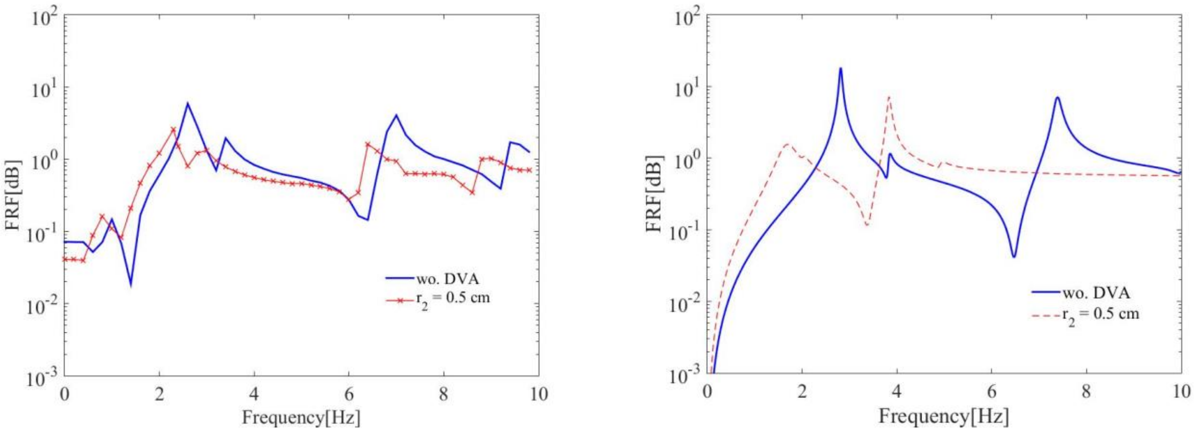

Fig. 11 Comparison of FRF in y-z plane (a) experiment (b) simulation

5. EXPERIMENTAL VALIDATION

For the FRF measurement in the x-direction, an impact hammer is used to apply shock excitation at point A, and the acceleration response is recorded at point C. For the FRF in the y-direction, excitation is applied at point B, and the response is measured at point D.

The excitation force is applied using OMEGA's IH101 Impulse Hammer and the acceleration data are collected using B&K accelerometer type 4507. Fig.10 and 11 shows the comparison of the experimental FRF and the simulated FRF in the x-z and y-z planes. Experimental data can validate simulation results. The difference in the peak FRF is likely arise from uncertainties in modeling parameters, particularly the moment of inertia and damping coefficient.

6. CONCLUSION

This study proposes a concept for space building structural vibration attenuation using two cylinder dynamic vibration absorber. Both absorbers are placed on the top floor of the building and are used to dampen vibrations in the x-z and y-z planes. The simulation results show that there are a number of parameters that significantly affect the performance of the dampers. Furthermore, employing optimal DVA parameters can reduce the structural response by as much as 70%. Experimental studies show that the simulation results can be validated experimentally.

7. ACKNOWLEDGMENTS

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