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The Use of Displacement Threshold for Switching Frequency Strategy for Structural Vibration Mitigation

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Abstract

This paper presents a study of controllable real-time frequency shift using a fluid pin damper, so called 'smart pin', mounted at a beam-column connection. Unlike the stationary frequency shifter, the pin can increase or decrease the rotational stiffness of the connection, leading to an actively adjustable structural frequency due to real-time responses of polarised magneto-rheological (MR) fluid, whose rheological properties can change in milliseconds. The feedback to the pin damper governs the structural frequency changes. To demonstrate this concept, a single storey plane steel frame model with one hinge and one 'smart pin' damper, mounted at each beam-column connection and subjected to two scaled earthquake excitations, namely El-Centro 1940 and Northridge 1994, which respectively represent near- and far-field excitations, was tested using the shake table at the University of Technology, Sydney (UTS) structures laboratory, for 'proof-of-concept' investigation. Further, the dynamic performance of the model using a proposed switching strategy with a displacement threshold as an indicator for alternately supplied current level (flip-flop) was examined, assuming the earthquake records were known. The results showed some potential use of this control technique for structural vibration mitigation, however, further study to optimize the performance of the switching strategy is still required.

Keywords: Fluid damper; Structural vibration mitigation; Switching frequency strategy

1. Introduction

The stationary frequency shift technique, employing changes of stiffness or mass is very effective for vibration mitigation of structural systems, excited by harmonic or narrow band frequency excitations. The technique, however, performs poorly to random excitation with broad band frequency content. This shortcoming, can be overcome if the structural frequency can be real-time shifted away from its excitation frequency. For this case, using a 'smart pin' integrated with a structural system will be one ideal solution.

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Different to bolted structural systems with a fixed frequency and passively non-adjustable friction, the frequency of 'smart' pin-frame system can be real-time adjusted or varied for vibration mitigation purpose, due to rapid changes of MR fluid rheological properties, which uniquely transforms the fluid from liquid into semi-solid state or vice versa in milli-seconds. The material state changes are exhibited by the increase of torque and the decrease of rotational motion (Samali *et al.,* 2003 ; Widjaja *et al.,* 2003 ; Widjaja *et al.,* 2005a), leading to 'locked' or 'semi-locked' condition of the 'smart' pin.

It is known that the pins at beam-column connections play an important role to reduce vibration levels, for instance, due to the presence of dry friction in bolted beam-column connections with high strength bolts. This phenomenon can be imitated by the 'smart' pin, which can generate fluid shear forces of magnetised MR fluid between two magnetic poles, developing either Pin-Pin ('P-P') or Pin-Rigid ('P-R') beam-column connections of the integrated system. The dynamic performance of both integrated systems with different dynamic characteristics shown in Amplitude Frequency Characteristics (AFC) of the system (Widjaja *et al.,* 2005b), were examined in reducing displacement responses.

2. Dynamic analysis

The 'smart'-pin-frame system can be set to either 'P-P' or 'P-R' beam-column end conditions, if no or maximum direct current (DC) is respectively supplied to the 'smart' pin. The 'smart' pin' will 'release', 'brake' or 'lock' the relative rotation between the beam and the column, which in turn leads to either reduction or enhancement of rotational stiffness of beam-column end. Viscous damping contributed by 'smart' pin is negligible as the pin is operated in shear mode, while the MR fluid is in semi-solid state.

The 'proof-of-concept' tests used a single storey, one bay steel plane frame model with a real pin and a smart pin mounted at each beam-column connection. The lateral stiffness of this model is real-time electronically adjusted by varying the supplied DC current level to the smart pin, leading to varying system frequency of the model.

3. Structural model

Depending on the smart pin 'locked', 'braked' or 'released' state, the 'smart' pin-frame system, can be simulated with a structural model as shown in Fig. 1. The tested model, utilising the large torque capacity and small viscous force generated by polarised MR fluid in the fabricated 'smart' pin, introduces the system damping $c_{f\theta}$ c_θ and magnetic field-induced or static friction f_d (Eq. 1). To accommodate the DC current induced property change, the 'smart' pin is simulated with a model having a rotational viscous dashpot, a magnetic-field adjustable rotational spring and a rotational friction element as shown in 'zoomed' smart pin model.

In view of 'P-P' or 'P-R' model, the equation of motion of this 'smart'-pin-frame model (Fig. 1) can be generally expressed as

$$\begin{bmatrix} m_f+\Delta m & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{r}_c \end{Bmatrix}+\begin{bmatrix} c_{ff}(i) & c_{f\theta}(i) \\ c_{f\theta}(i) & c_\theta(i) \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{r}_c \end{Bmatrix}$$
$$+\begin{bmatrix} k_{ff} & k_{fc} \\ k_{cf} & k_{cc}+k_\theta(i) \end{bmatrix}\begin{Bmatrix} x \\ r_c \end{Bmatrix}=f_d\begin{Bmatrix} -1 \\ 0 \end{Bmatrix} sign(\dot{x})\delta(i=0)$$
$$+\begin{Bmatrix} -1 \\ 0 \end{Bmatrix}(m_f+\Delta m)\ddot{x}_g \tag{1}$$

In Eq. 1, m_f, Δm, c_{ff}, $c_{f\theta}$, c_θ, k_{ff}, k_{fc}, k_{bb}, k_{cc}, k_θ, f_d, $\delta(*)$, i, $\ddot{x}_g$, x and r_c are lumped mass of P-P integrated system; additional mass; system damping of 'P-P' integrated system; system damping due to one unit rotation at smart pin mounted column end; smart pin damping; lateral stiffness coefficient of 'P-R' integrated system; lateral stiffness coefficient due to one unit rotation at smart pin mounted column end; rotational stiffness coefficient at smart pin mounted beam end; rotational stiffness coefficient at smart pin mounted column end; magnetic field induced rotational stiffness contributed by energised smart pin; static friction of system smart pin; Dirac delta function; DC current level (Ampere); earthquake ground acceleration; lateral displacement and 'smart' pin rotation, respectively.

4. SIMULINK model

SIMULINK model for physical 'smart'-pin-frame system, a tool to 'dialogue' between analytical and physical tested model, is used to provide an electronic interface, signal acquisition and processing with a computer system. The SIMULINK model is represented by a discrete-time state-space model rather than a continuous-time state-space model.

5. Switching strategy

The inability to predict instantaneous frequency of a real excitation leads to the use of a different 'tool', an available instantaneous kinematic quantity. In this case, the model instantaneous lateral displacement is selected, as it is measured at every discrete time step. Meanwhile, the law for switching the system frequentcy in relation to the model lateral displacement is not fully known as yet due to inestimable instantaneous frequency. A simple switching law is proposed using a displacement threshold as an

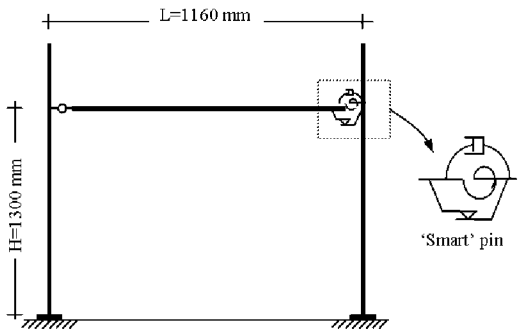

Fig. 1. Structural model of 'smart'-pin-frame system.

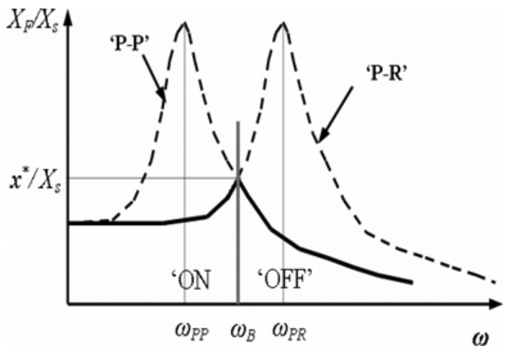

Fig. 2. Switching strategy implementation.

indicator, which if exceeded, the law will alternately 'flip-flop' the system frequency by supplying either zero or 1.8 Ampere DC current to the 'smart' pin.

Two solid lines in Fig. 2, where the line changes at bifurcation frequency ω_B, can be mathematically expressed using the dynamic amplification factor for base excitation as

$$\frac{x(t,i)}{X_s} = \frac{(\omega/\omega_s(i))^2}{\left[\left(1-(\omega/\omega_s(i))^2\right)^2 + \left(2\xi(i)(\omega/\omega_s(i))\right)^2\right]^{1/2}} \tag{2}$$

In Eq. (2), x and X_s are the instantaneous displacement response and the static displacement, respectively. The instantaneous ground-induced forcing frequency ω can be varied in broad or narrow band range depending on the nature of excitation. The proposed switching algorithm, for instance, can be simple for harmonic excitation due to its constant forcing frequency and similarly for narrow band frequency excitation. On the other hand, the instant-taneously time-based information of forcing frequency, which is unavailable for the broad-band frequency excitations, such as earthquakes may be simply overcome using a displacement threshold. The proposed switching law, in voltages, can be expressed as

$$V_c = \delta(x - x^*)\left(V_0\,\delta(V_m - V_c) + V_m\,\delta(V_0 - V_c)\right) + \delta(x^* - x)V_c \tag{3}$$

In Eq. (3), V_c, V_m, V_0 and x^* are the command voltage; the maximum voltage; the initial voltage; and the displacement threshold, respectively. The required current input i to the 'smart pin'-Wonder Box-computer system supplied by the Wonder Box powered by a DC power supply unit can be computed using the following relationship which is obtain from calibration.

$$V_c = 2.0757i + 0.511 \tag{4}$$

The use of this proposed switching law (Eq. 3) by alternately switching the current level between 0 or 1.8 Ampere, when the selected displacement threshold of 10 mm is exceeded by the displacement response, transforms the 'smart pin'-frame system into two systems either with lowest or highest system frequency, associated with 'P-P' or 'P-R' system.

6. Experimental set-up

The 'smart'-pin-frame model shown in Fig. 3, was built by the UTS Engineering workshops for 'proof-of-concept' tests, and consists of a steel plane frame with a real pin and a 'smart' pin, instrumented with a dynamic LVDT with a maximum stroke of 75 mm and an accelerometer 'Crossbow' having the capacity range of +/- 1.0 g and sensitivity of 2.01 g/Volt. It is electronically interfaced with a power supply unit, a muxed AD/DA port, a dSpace board equipped computer system, a 166 Hz. Pentium 1, configured with 256 MB of RAM; and a LORD Wonder Box.

The steel plane frame model, a single storey, one bay plane frame with beam ends of a real pin connection and a prototype 'smart' pin fixed with two 8 mm diameter bolts each, has two flat bar column sections of 1300 × 100 × 5 mm each, and a hollow section steel beam of 75 × 25 × 2 mm spanning 1160 mm. The total mass of the frame together with the 'smart' pin is 32.50 (=21.50+11) kg. The maximum displacement response was limited to approximately 4% of column height due to the constraint of prototype 'smart' pin rotation, which consists of a steel bracket for beam end connection and a 6 mm thick steel boxed casing with dimensions of 312 (H) ×

Table 1. Experimental cases.

Case No's	Excitations	DC Current (Ampere)	Shake table Span (mm)	Time scale factor
1	El Centro 1940	0 or 1.80	3.5; 9.0	3.0
2	Northridge 1994	0 or 1.80	3.5; 9.0	3.0
3	Sudden release	0 or 1.80	-	-

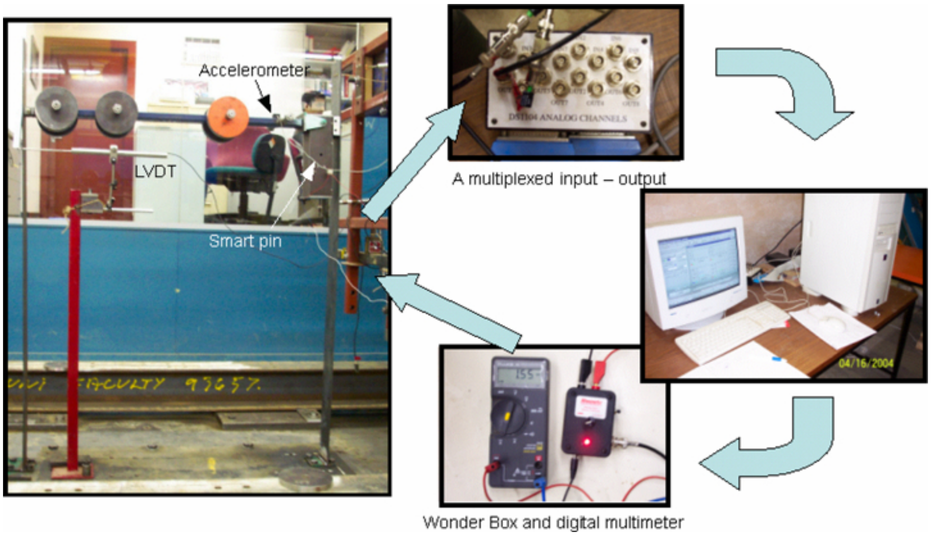

Fig. 3. Experimental set-up of 'smart'-pin-frame system.

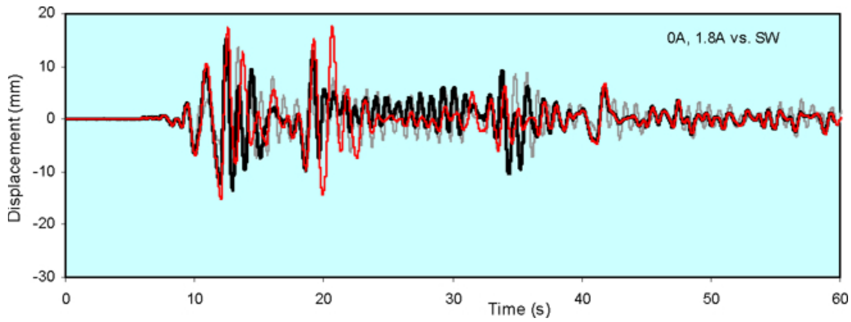

Fig. 4. Time history displacement responses of 'smart pin'-frame-system due to scaled El Centro earthquake (thin solid line –0A, thin dotted line –1.8A, thick solid line –SW).

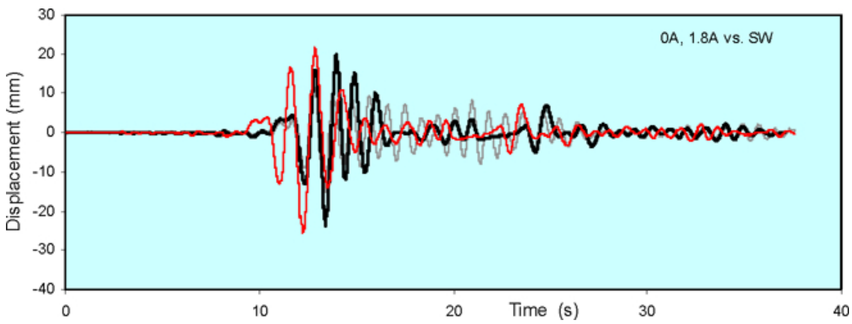

Fig. 5. Time history displacement response of 'smart pin'-frame-system due to Scaled Northridge earthquake (thin solid line – 0A, thin dotted line –1.8A, thick solid line –SW).

90 (L) × 85 (B) mm. The pin houses a pair of 6 mm thick turnable plates, a PVC tank and a pair of electromagnetic steel yokes of a pair copper wired coil with 200 turns of 0.5 mm diameter, having an average length of magnetic steel path for each loop of 120 mm. The plates, acting as armatures with a maximum rotation of 5 degrees, are immersed in MR fluid, MRF-132AD, in the gaps between two pairs of magnetic poles providing a net gap of 2 mm between the plates and the pole and a multi-shearing area of approximately 5920 mm^2.

Two shake table tests (Table 1) using the set-up model (Fig. 3), were conducted for 'proof-of-concept' of real-time frequency shift technique, subjected to two shake table displacement cases of 3.5 and 9.0 mm. Table 1 also shows Case 3, corresponding to 'sudden release' tests.

Dynamic performance of 'smart pin'-frame system The dynamic performance of 'smart pin'-frame model for both the 'P-P' and 'P-R' conditions, expressed in term of time history displacement responses as shown in Fig. 4 and 5, was compared using the experimental results of the model with and without the proposed switching strategy (SW). The intensities for both time scaled earthquake records: El Centro NS 1940 and Northridge NS 1994, were scaled due to the constraints of maximum rotation of the 'smart pin' (5 degrees). The scaled intensities of both earthquakes are 0.08 and 0.03, respectively.

Vibration responses for 0 and 1.8 Ampere cases serve as the bounded displacement range of 'smart' pin-frame model, where the ideal SW induced vibration response should be able to trace the minimum displacement track generated either by 0 Ampere ('P-P' system) or 1.8 Ampere ('P-R' system). Figures 4 and 5 show moderately good performance to trace the minimum track of displacement responses. In future, this study can be extended to explore the use of frequency-based indicator rather than time-based displacement threshold.

7. Discussions and conclusion

The use of displacement threshold to indirectly switch the frequency of 'smart' pin-frame model, subjected to random excitations in real application shows potential use for structural vibration mitigation, however it still requires further study, particularly in relation to instantaneous frequency of excitation.

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