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Short Communication

On tuned liquid column dampers mounted on a structural frame under a non-ideal excitation

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1. Introduction

The current trend towards buildings of ever increasing heights and the use of light-weight, high-strength materials and advanced construction techniques have led to increasingly flexible and lightly damped structures. Understandably, these structures are very sensitive to environmental excitations such as wind, ocean waves and earthquakes. This causes unwanted vibrations inducing possible structural failure, occupant discomfort, and malfunction of equipment. Hence it has become important to search for practical and effective devices for suppression of these vibrations. An option used to mitigate structural vibrations are the passive control devices, more details on which can be found in Ref. [1]. One of them is the tuned liquid column damper (TLCD) that is a special type of tuned liquid damper (TLD) relying on the motion of the column of liquid in a U-tube-like container to counteract the forces acting on the structure, with damping being introduced through a valve/orifice in the liquid passage [2]. The damping is amplitude dependent since the valve/orifice constricts the dynamics of the liquid in a nonlinear way. Sakai and Takaeda [3] proposed a new type of liquid damper which was termed as a tuned liquid column damper (TLCD) and described its application for cable-stayed bridge towers. TLCDs were studied for

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wind-excited structures by Xu et al. [4]. The performance of TLCDs for seismic applications has been studied by Won et al. [5].

The motivation of this paper is in the works of Yalla and Kareem [6,7], in which we investigate the dynamical behavior of a TLCD coupled with a structural frame under excitation of an unbalanced DC motor with limited power supply; both the motor and the damper attached to a horizontal beam.

The structural frame and DC motor system is considered as a non-ideal system [8–12]. It means that the excitation is influenced by the response of the supporting structure and that the energy source has a limited power supply (non-ideal excitation). The dynamics and control of structural frames under one and two non-ideal excitations was studied by Palacios et al. [13–18].

2. Analyzed mathematical model

As shown in Fig. 1, the non-ideal TLCD system under investigation consists of a structural frame model with a concentrated mass M on the horizontal beam and two identical columns assumed as linear elastic and with negligible mass. A small mass m_0 is placed on the eccentric shaft of the rotor r. When the exciter is in rotational motion counterclockwise from the horizontal direction, the frame is capable only of horizontal motion. The TLCD is also mounted on the frame, its fluid has density ρ, the cross-sectional area of the tube is A, the total length of the liquid column l, the horizontal length of the column b and the coefficient of head loss of the orifice is ξ.

The governing equations of motion of the non-ideal TLCD system are

$$(M_s + m_f)\ddot{X}_s + C_s X_s + K_s X_s = m_0 r(\ddot{\varphi} \sin \varphi + \dot{\varphi}^2 \cos \varphi) - \alpha m_f \ddot{x}_f(t), \tag{1}$$

$$J\ddot{\varphi} - m_0 r \ddot{X}_s \sin \varphi - m_0 r g \cos \varphi = \Gamma(\dot{\varphi}) - H(\dot{\varphi}), \tag{2}$$

$$m_f \ddot{x}_f + \frac{m_f \xi}{2l} |\dot{x}_f| \dot{x}_f + k_f x_f = -\alpha m_f \ddot{X}_s, \tag{3}$$

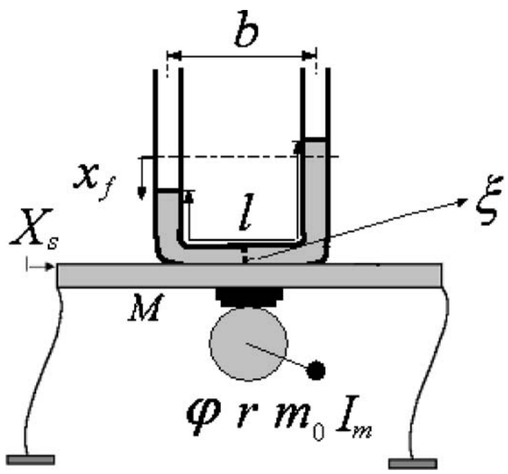

Fig. 1. Structural frame–non-ideal excitation–TLCD system.

where X_s is the response of the structural frame in the horizontal motion, x_f is the response of the liquid damper (TLCD), φ is the rotational coordinate of the DC motor, $\dot{\varphi}$ is the rotational speed of the motor, J is the moment of inertia of the rotor, m_0 is the unbalanced mass of the rotor, r is the eccentricity of the unbalanced mass, $\Gamma(\dot{\varphi})$ is the controlled torque of the unbalanced rotor, $H(\dot{\varphi})$ is the resistance torque of the unbalanced rotor, g is the gravitational constant, M_s is the total mass of the structural frame and motor, K_s is the stiffness of the structural frame, C_s is the damping in the structural frame, α is the length ratio, m_f is the mass of fluid in the tube, k_f is the stiffness of the liquid column.

Eqs. (1) and (2) may be simplified when the model of the DC motor is simplified by removing the effect of the inductance and we obtain

$$\Gamma(\dot{\varphi}) - H(\dot{\varphi}) = a - b\dot{\varphi}, \tag{4}$$

where a represent, the control parameter (voltage or constant torque) and b a constant for each type of motor.

Hence, Eqs. (1)–(3) in their simplified form are

$$(1+\mu)\ddot{X}_s + 2\omega_s\zeta_s\dot{X}_s + \omega_s^2 X_s = q_2(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi) - \alpha\mu\ddot{x}_f, \tag{5}$$

$$\ddot{\varphi} - q_1\ddot{X}_s\sin\varphi - q_3\cos\varphi = \hat{a} - \hat{b}\dot{\varphi}, \tag{6}$$

$$\ddot{x}_f + \frac{\omega_f^2\xi}{4g}|\dot{x}_f|\dot{x}_f + \omega_f^2 x_f = -\alpha\ddot{X}_s, \tag{7}$$

where $\mu = m_f/M_s$, $\omega_s = \sqrt{K_s/M_s}$ (structural frame frequency), $\omega_f = \sqrt{2g/l}$ (liquid damper frequency), $\alpha = b/l$, g is the gravitational constant, $\zeta_s =$ structural frame damping ratio, $q_1 = m_0r/J$, $q_2 = m_0r/M_s$ and $q_3 = m_0rg/J$.

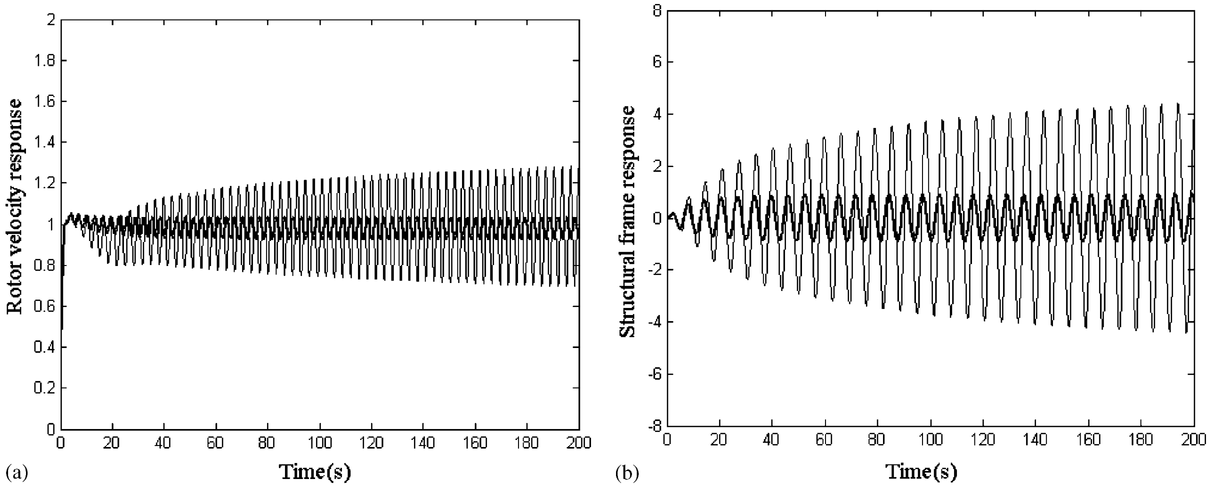

Fig. 2. Response of (a) motor, (b) structural frame for $\mu = 0.01$, $\alpha = 5$, $\hat{a} = 1.6$ and $\xi = 15$: the thin line representing the uncontrolled system and the thick line representing the controlled system.

For the numerical simulations we used a block diagram that represents the equations of motion of the dimensionless non-ideal TLCD system (5)–(7) in a implementation by SIMULINK of MATLAB^{TM}. For numerical integrations we used the variable-step fourth-order Runge–Kutta method (ODE45).

3. Numerical simulations results and discussions

We carried out a number of numerical simulations, in order to show some properties of the considered model and we have taken constant torques or voltage control parameter $\hat{a}$ in conditions of post-resonance and capture resonance regions. The initial conditions are: $\dot{\varphi}(0) = 0.0$, $\varphi(0) = 0.0$, $X(0) = 0.0$, $\dot{X}(0) = 0.0$, $x_f = 0.0$, $\dot{x}_f = 0.0$. Furthermore, we considered

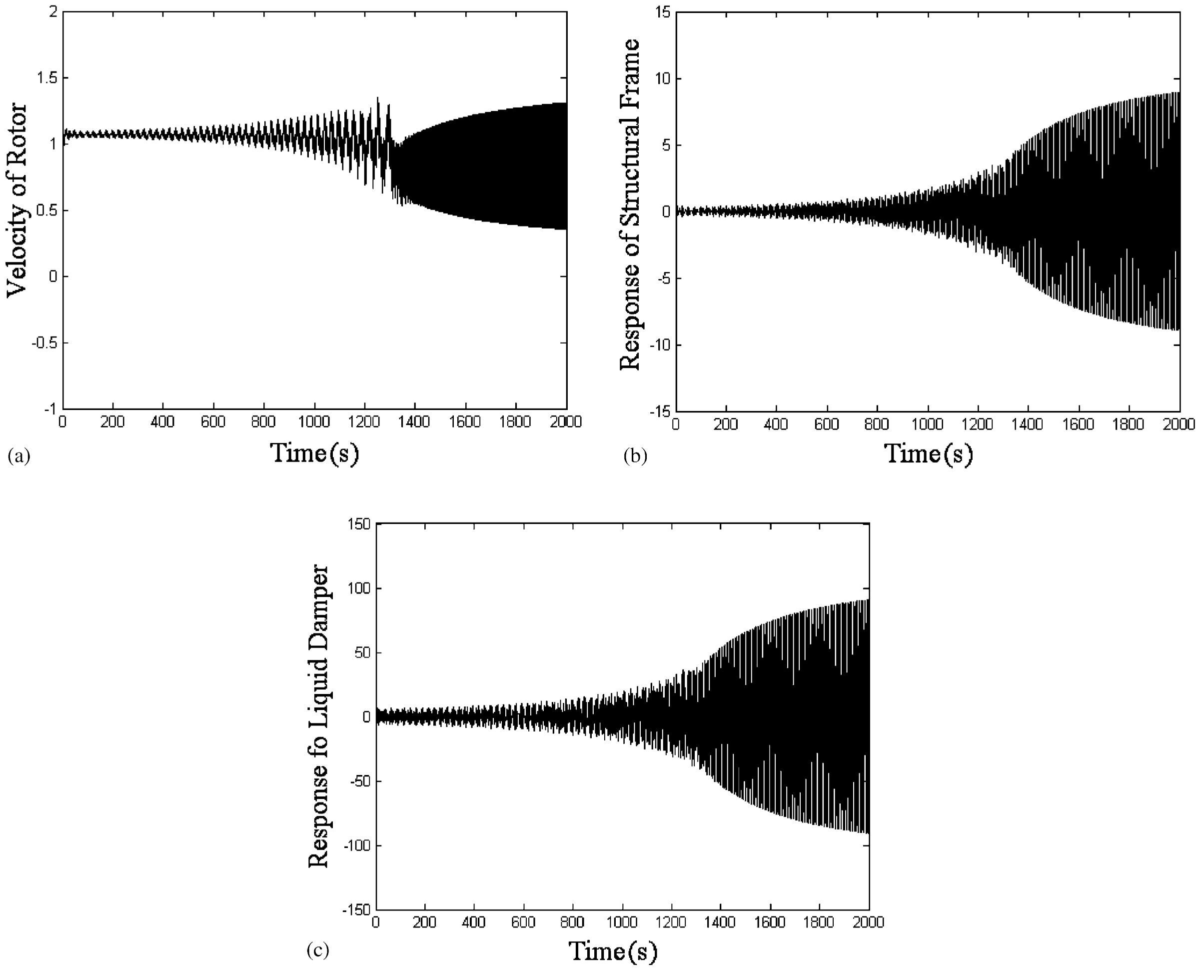

Fig. 3. Response of (a) motor, (b) structural frame, (c) liquid damper for $\xi = 0$, $\hat{a} = 1.6$, $\alpha = 5$ and $\mu = 0.01$.

$\zeta_s = 0.001$, $q_3 = 0.0$, $\hat{b} = 1.5$, $\hat{a} = 1.6$, $q_1 = 0.3$, $q_2 = 0.2$ and $\omega_s = 1\,\text{rad/s}$. For TLCD we considered $\mu = 0.01$, $\alpha = 5$, $\xi = 15$ and $\omega_f = 0.99\,\text{rad/s}$, $g = 9.81\,\text{m/s}^2$.

Next we present a number of numerical simulations, in order to better understand the problem.

In the first numerical simulation, shown in Fig. 2, we show the uncontrolled and controlled response of the non-ideal system coupled with TLCD. When the excitation frequency is near the structural frame frequency, Fig. 2(b), the amplitudes of the uncontrolled structural frame oscillation increase tending to a periodic and stable regime in steady-state motion.

When we take $\mu = 0.01$, $\alpha = 5$, $\xi = 15$ and $\hat{a} = 1.6$ (resonance region), Fig. 2(a) shows the effectiveness of the TLCD to suppress the vibrations of the frame.

For the second numerical simulation, shown in Figs. 3–5, we show different regimes of the interaction of the liquid damper and non-ideally excited frame when we vary parameters ξ, α, μ and control the parameter $\hat{a}$.

Fig. 3 shows an interesting dynamical behavior when we consider the head loss coefficient $\xi = 0$. We observe that the angular velocity of the rotor is captured in resonance causing instability in the motion of the coupled system between the liquid damper and no-ideal structural frame.

Fig. 4 shows a different behavior when we consider $\mu = 0.13$ and $\alpha = 0.6$ with $\xi = 15$ and $\hat{a} = 1.6$. We observe that when the angular velocity of the rotor is captured in the resonance region, the TLCD shows its effectiveness by a stable motion.

Fig. 5 shows an interesting dynamical behavior. When we consider $\xi = 0.078$ with $\mu = 0.13$, $\alpha = 0.6$ and $\hat{a} = 1.6$, the beat phenomenon and stability is present (see Fig. 5(c,d) and the phase plane in Fig. 2(b)). Furthermore, we observe that the angular velocity of the rotor is above the resonance region (due to the influence of the interaction TLCD); see Fig. 5(a). The TLCD demonstrates its effectiveness to suppress the vibrations of the structural frame; see Fig. 5(c).

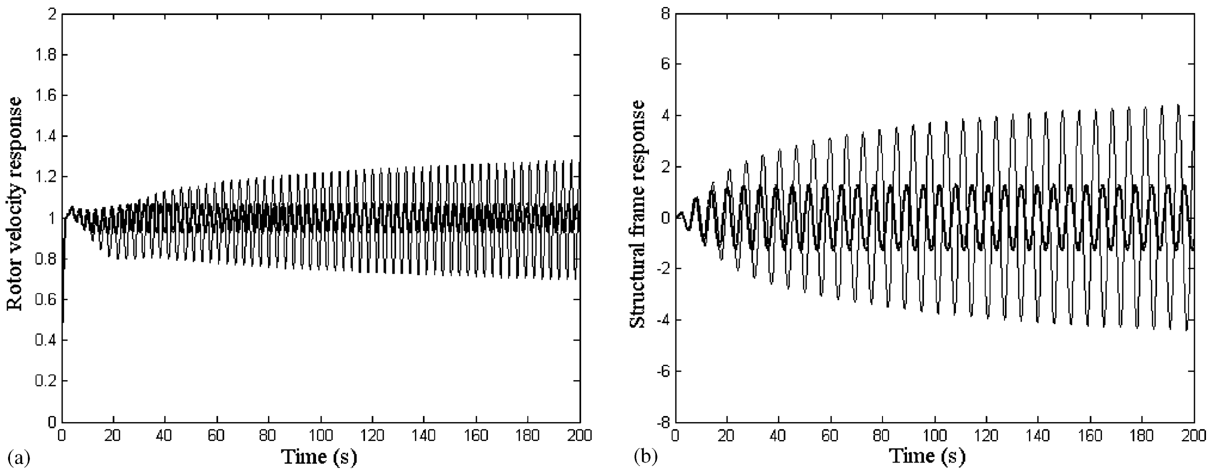

Fig. 4. Response of (a) motor, (b) structural frame for $\mu = 0.13$, $\alpha = 0.6$, $\hat{a} = 1.6$ and $\xi = 15$: the thin line representing the uncontrolled system and the thick line representing the controlled system.

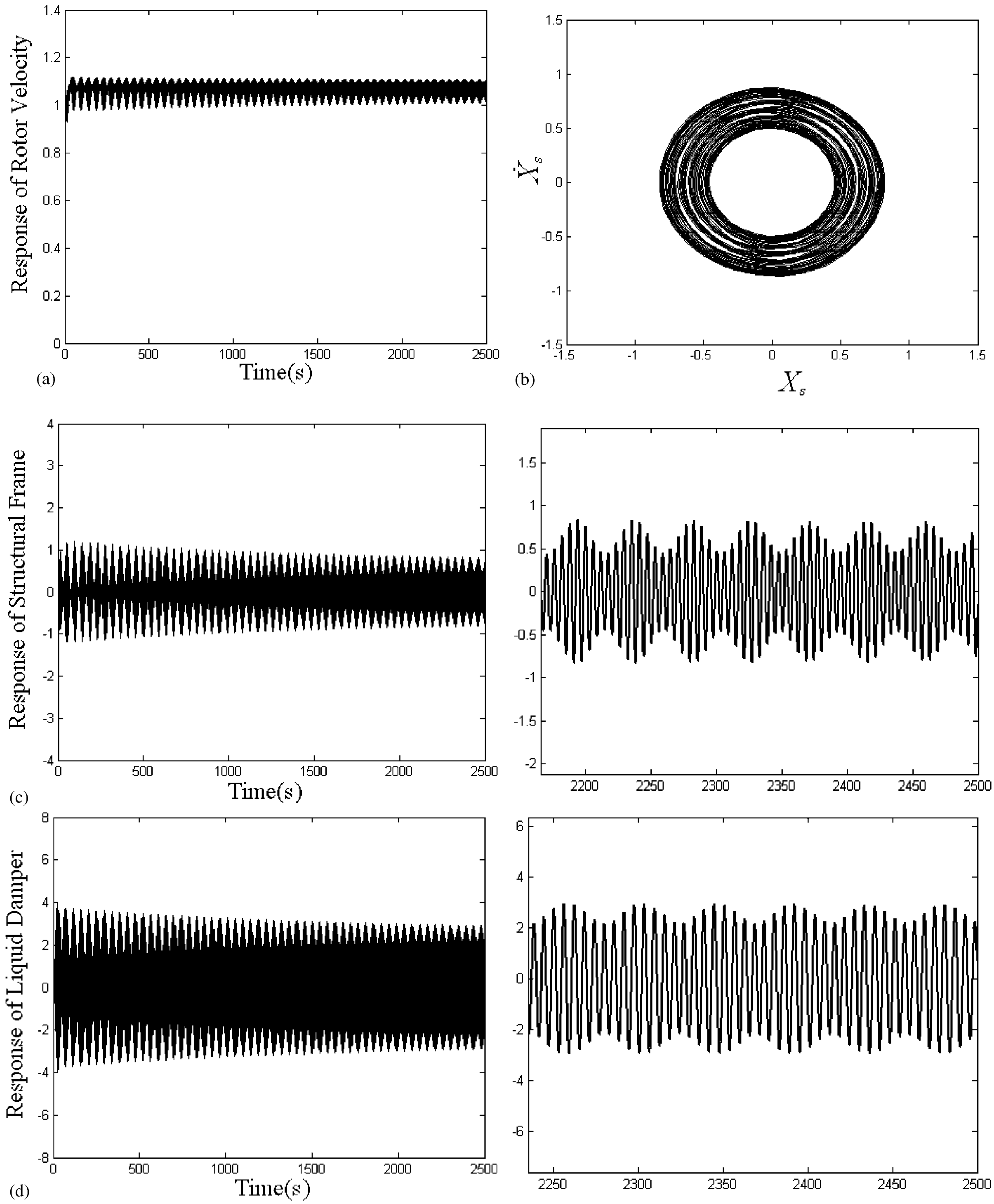

Fig. 5. (a) Motor response, (b) phase plane, (c) structural frame response, (d) liquid damper response for $\mu = 0.13$, $\alpha = 0.6$, $\hat{a} = 1.6$ and $\xi = 0.078$.

4. Conclusions

The modeling and numerical analysis of a vibration control liquid damper for a structural frame under non-ideal excitation using SIMULINK of MATLAB™ is presented. We considered a portal frame with concentrated mass on the horizontal beam and two identical columns assumed as linear elastic and with negligible mass, one non-ideal source (DC motor of limited power supply and unbalanced) and a TLCD mounted on the structural frame. The effectiveness of the TLCD depends on the variation of parameters ξ, μ and α.

Future work will study the optimal selection of parameters ξ, μ, α and the experimental implementation.

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