Spring Loaded Liquid Column Ball Damper for Vibration Control with Forced Vibration

[1]Abhishek Gupta, [2]Manoj Kakulate, [3]Ashish Jopale

[1]Student, Mechanical Engineering Department, Smt. KashibaiNavale College ofEngineering,Pune
abhishekgupta4244@gmail.com
*[2]Student, Mechanical Engineering Department, Smt. KashibaiNavale College ofEngineering,Pune**manojkakulate5@gmail.com***
*[3]Student, Mechanical Engineering Department, Smt. KashibaiNavale College ofEngineering,Pune**ashishjopale123@gmail.com***

ABSTRACT

Tuned Liquid Column Damper (TLCD) is a vibration reducing device by absorbing vibrations for the tall buildings and long bridges vibrating at minute frequencies. Further advancement in tuned liquid column damper (TLCD) is equipped with steel ball attached with steel spring & it is place in the horizontal column of the damper which is called Spring Loaded Liquid Column Ball Damper (SLLCBD). Optimum ball diameter & mass ratio is evaluated for the absorber capacity by the parametric study. Results obtained from numerical simulation are compared with traditional TLCD on the basis of the optimum parameters. Around74% vibration reductions are observed as per the results on improvement of vibration absorbing capacity.

Keywords*: Spring Loaded Liquid Column Ball Damper,Forced Vibration, Ball Diameter Ratio.*

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1. INTRODUCTION

Tall buildings nowadays are having very low vibration absorbing structures due to fact of higher modern construction techniques. Thus vibrations get induced in buildings due to wind and environmental excitation which causes occupant discomfort and thus resulting in structure failure. So it gives the necessity to search for a device to absorb the vibrations of tall buildings. Among these devices is the tuned liquid column damper (TLCD), which initially was proposed by Sakai and his co-authors [1]. It consists of a U-shaped tube, filled with liquid, preferably water. At the center of the horizontal section of tube, steel coated ball attached with spring is kept. The study done byChaiviriyawong et al.[2]so as to find out the liquid dampers effective length by method of numerical potential flow of induced velocity distribution of fluid in the liquid column damper.Xu et al. [5], and Haroun et al.[4]conducted the theoretical and experimental works and reduced structure lateral vibrations by study of TLCD. Xue et al. [3]and Wu et al. [6] studied the TLCD and came to a conclusion that structure torsional vibrationcould reduce under harmonic excitation effectively. Multiple tuned liquid column dampers (MTLCD), which consists of a series of TLCDs has been studied by Gao et al. [7]for lateral vibration reduction and by Shum and Xu[8]and Xu and Shum [9]for structure torsional vibration reduction.

Watikns[10] proposed another variation of TLCD called Liquid column variable absorber. The cross-section of the later is not uniform is the major difference observed between the TLCD and LCVA. Many researchers carried out studies on LCVA. Among them were Hitchcock et al. [11,12], Watkins and Hitchcock [13]and Chang and Hus [14].Gao and Kwok[15] foundthat horizontal tube cross section increase might decrease the vertical tube liquid column and by providing the harmonic vibration to the structure the amplification factor can be reduced so that the optimal parameters can be to obtain. A recent study by Shum [16]proposed the optimal parameters of a TLCD to suppress the vibration caused by harmonic excitation. In his paper, for the case of undamped primary structure closed form solution was developed and for the case of damped primary structure numerical technique was used.

In the current investigation, a modified version of TLCD, which includes a coated steel ball attached with spring inside the horizontal section of the damper, is investigated. It is estimated that ball along with the spring will act as a moving orifice and the absorber performance will get improved by disturbing the flow. Spring loaded LCBD is attached on the model, the model is having single degree of freedom so as vibrating structure gets stimulated. Lagrange's equations are used for deriving the equations of motion. The viscosity of the fluid viscosity is included in the model which contributes to the damping term associated with ball along with the spring. The governing equations are solved numerically by using Runge-kutta method by using MATLAB software and the performance of spring loaded LCBD is compared with that of TLCD. For comparison the optimum design parameters utilized are provided by Wu et al. [6]. In addition to this some optimal design parameters are used to evaluate the performance of the proposed system and to confirm its effectiveness which are taken from Shum [16]. The results obtained are excellent by using the proposed absorber with suppression magnitude exceeding 74% as opposed to the current optimum designs of the TLCD as per the reports of theharmonic excitations literature. The rest of the paper is organized as follows: In Section 2, the equations of motions are derived. In Section 3, numerical simulations are presented to address the effects of varying system's parameters and to assess the effectiveness of the absorber.

Nomenclature			
A	cross-sectional area of the U-tube	G	gravitational acceleration
A_0	orifice area of TLCD	h	undisturbed length of the liquid in the vertical column
A_b	main cross sectional of the ball	K_{eq}	Equivalent stiffness of the two springs
B	length of the horizontal section	I	mass moment inertia of the ball about center of mass
D	diameter of the all	K	fundamental mode stiffness of the structure
d_{eq}	equivalent damping coefficient	L	total length of the liquid in the tube
c_s	viscous damping coefficient of the main structure	m_b	mass of the ball
c_t	equivalent damping coefficient of the LCBD	m_f	mass of the fluid
F_{ext}	external excitation	m_s	fundamental mass of the main structure
x_b	displacement of the ball	Q_i	ith generalized forces
x_s	displacement of the main structure	R	ball-tube diameter ratio
y	displacement of the surface of the fluid	R_b	radius of the ball
α	ratio of the horizontal length to total length of theliquid in the tube	T	Time
		ρ	fluid density
ω_{ex}	external excitation	ω_0	natural frequency of the TLCD
λ	optimal frequency tuning ratio	ω_{st}	natural frequency of the main structure
δ	Optimum head loss coefficient		

2. FORMULATION OF GOVERNING EQUATION OF MOTIONS

Figure shown below illustrates spring loaded liquid column ball damper, provided that structure is subjected to base excitation. It is mainly divided into three parts vibrating structure, oscillating fluid and rolling steel ball with spring.

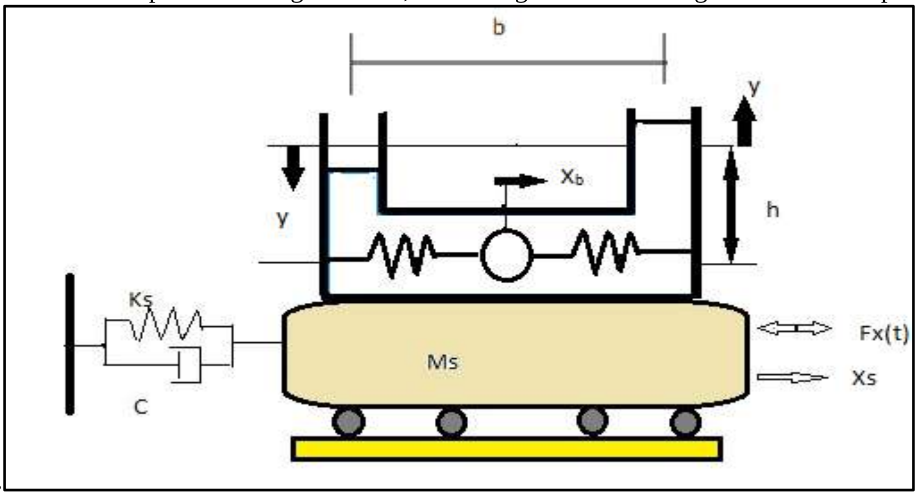

Fig-1 Structure with Spring Loaded TLCD with Force excitation

2.1The kinetic energy of the entire system

$T = T_{fluid} + T_{ball} + T_{structure}$ -----(1)

$T_{fluid} = T_{f1} + T_{f2} + T_{f3}$ -----(2)

Total kinetic energy of fluid is,

$T_{fluid} = \frac{1}{2}\rho A(h-y)(\dot{x}_s{}^2 + \dot{y}^2) + \frac{1}{2}\rho A(h+y)(\dot{x}_s{}^2 + \dot{y}^2) + \frac{1}{2}\rho Ab(\dot{x}_s + \dot{y})^2$ -----(3)

The ball will have two types of kinetic energies- traditional and rotational.

With the assumption of no slipping the two kinetic energies of ball are given as follows,

$T_{ball\_trans} = \frac{1}{2} m_b \dot{x}_b{}^2$ -----(4)

$T_{ball\_rotary} = \frac{1}{2}\frac{I}{R_b{}^2}(\dot{x_b} - \dot{x_s})^2$ -----(5)

Total kinetic energy of the ball is,

$T_{ball} = \frac{1}{2} m_b \dot{x}_b{}^2 + \frac{1}{2}\frac{I}{R_b{}^2}(\dot{x_b} - \dot{x_s})^2$ -----(6)

The kinetic energy of the structure is,

$Ts = \frac{1}{2} m_s \dot{x}_s^2$ -----(7)

Hence total kinetic energy of system is given by

$T = \frac{1}{2} m_s \dot{x}_s^2 + \frac{1}{2}\rho A(h-y)(\dot{x}_s{}^2 + \dot{y}^2) + \frac{1}{2}\rho A(h+y)(\dot{x}_s{}^2 + \dot{y}^2) + \frac{1}{2}\rho Ab(\dot{x}_s + \dot{y})^2 + \frac{1}{2} m_b \dot{x}_b{}^2 + \frac{1}{2}\frac{I}{R_b{}^2}(\dot{x_b} - \dot{x_s})^2$ -----(8)

2.2Potential energy of entire system

The potential energy of the fluid can be expressed as

$U_{fluid} = U_{f1} + U_{f2} = \frac{1}{2}\rho A(h-y)^2 + \frac{1}{2}\rho A(h+y)^2$ -----(9)

Where $U_{f1}$and $U_{f2}$are potential energies of fluid in left and right column respectively

Potential energy of the structure is,

$U_s = \frac{1}{2} k(x_s)^2$ -----(10)

Potential energy of the ball with two springs is,

$U_{ball} = \frac{1}{2} k_{eq}\ (x_b - x_s)^2$ -----(11)

Potential energy of the entire system is,

$U = U_{f1} + U_{f2} + U_s + U_{ball}$

$U = \frac{1}{2}\rho A(h-y)^2 + \frac{1}{2}\rho A(h+y)^2 + \frac{1}{2} k(x_s)^2 + \frac{1}{2} k_{eq}\ (x_b - x_s)^2$

$U = \rho Ag(h^2 + y^2) + \frac{1}{2} k(x_s)^2 + \frac{1}{2} k_{eq}\ (x_b - x_s)^2$ -----(12)

In the proposed research, the governing equations of a vibrating structure have been derived in termz of generalized co-ordinates by using Lagrange's Equations. For that kinetic and potential energy expressions for the entire system have been written.

Lagrange's Equation can be stated as follows

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}i}\right) - \frac{\partial T}{\partial qi} + \frac{\partial U}{\partial qi} = Q_i \qquad \text{--------(13)}$$

The generalized forces are,

$q_1=x_s$, $q_2=x_b$, $q_3=y$

The generalized forces are,

$Q_1= (F_{ext}(t) - C_x\dot{X}_s$, $Q_2=-deq\ (\dot{x}_b - \dot{y}) + 2\rho g y A_b$, $Q_3=-c_t\dot{y}$

By using Langarange's and Energy equations, final equations derived are

Equation for vibrating structure,

$$\left(m_f + m_s + \frac{1}{R_b^2}\right)\ddot{x}_s + C_s\dot{X}_s + \left(K + K_{eq}\right) + \alpha m_f\ddot{y} - \frac{I}{{R_b}^2}\ddot{x}_b - K_{eq}X_b = F_{ext}(t) \qquad \text{-------(I)}$$

Equation for ball attached with spring,

$$\left(m_b + \frac{I}{R_b^2}\right)\ddot{x}_b + d_{eq}\,\dot{x}_b + k_{eq}x_b = \frac{I}{{R_b}^2}\ddot{x}_s + k_{eq}x_s + d_{eq}\dot{y} + 2\rho A_b g y \qquad \text{-------(II)}$$

Equation for oscillating liquid column,

$$m_f\,\ddot{y} + \alpha m_f\ddot{x}_s + 2\rho A_b g y + c_t\,\dot{y} = 0 \qquad \text{--------(III)}$$

3. OPTIMUM PARAMETERS FOR SLLCD

Table1-Damping ratio for different ball tube diameter

Ball tube diameter ratio R	Damping ratio ζ
0.90	0.081
0.79	0.046
0.68	0.044
0.56	0.042
0.45	0.039
0.34	0.039

The damping ratio of SLLCBD is measured for six different ball diameters as listed aboveTable1 [16]. Ball diameter is directly proportional to damping. Due to decrease in cross section between ball and tube fluid experiences a better resistance.Table2 [16] provides different optimum parameters for obtaining numerical stimulation.

Table2-System parameters for LCBD (optimum values)

Parameter	Magnitude
Mass ratio (m_f /m_s)	0.01
Length ratio(α=b/(b+2h))	0.8
Primary structure fundamental frequency ω_s(HZ)	0.93
Optimum Frequency Tuning Ratio($\lambda= \omega_t/\omega_s$)	0.986
Primary structure damping ratio(ζ_s)	0.03
Optimum head loss coefficient δ	21.9

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4. SIMULATION

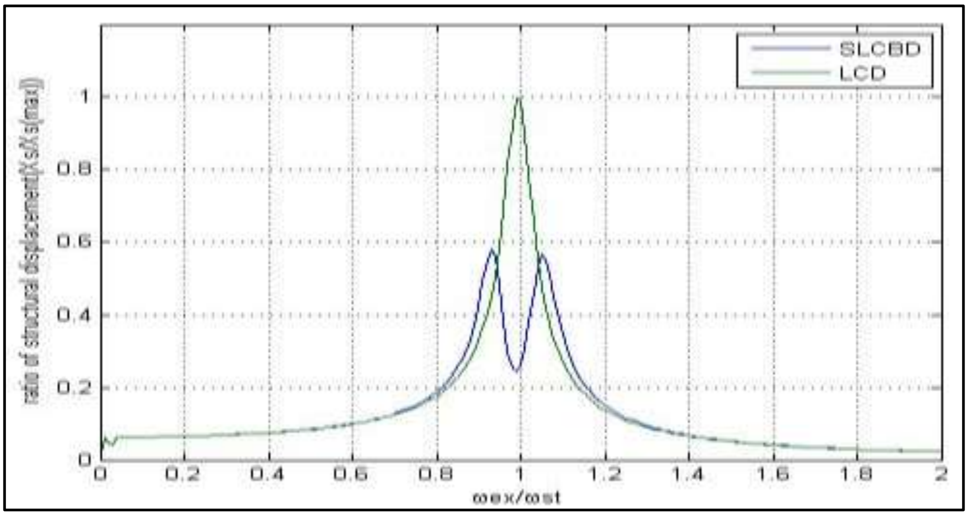

Fig2- Normalised frequency response of structure with spring loaded TLCBD and TLCD

ωs=0.93 HZ , R=0.822 and ζ_s=0.03

RungeKutta method is used for Numerical simulation. So that performance of TLCD and spring loaded TLCBD can be compared for their optimum cases. Frequency response of structure with TLCD and Spring loaded TLCBD of is shown in figure below. Ball tube diameter ratio is 0.822(Optimum) which is used for simulation. Time history response curve for above values is obtained at tuning ratio 1 is shown in figure for spring loaded tuned liquid column ball damper. It is observed that performance of spring loaded TLCBD is very favorable within resonance reason; however, both responses are similar outside the region.

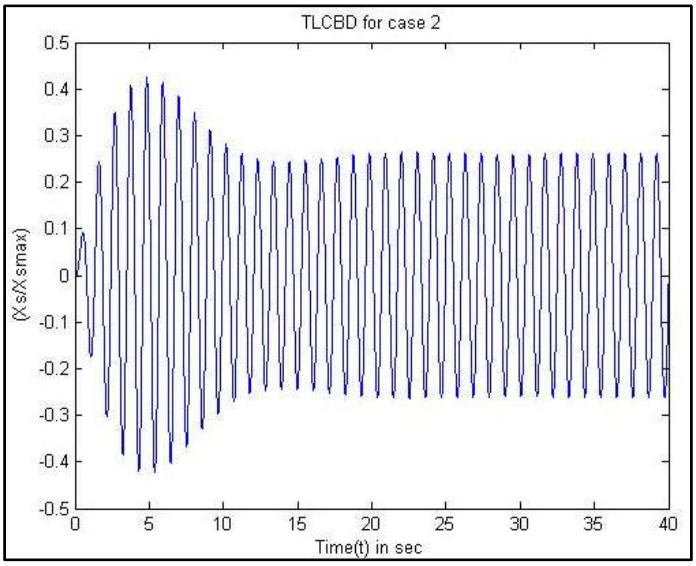

Fig3-Time history of response of structure with spring loaded TLCBD for ζ=0.03

4.1. Effect of ball tube diameter ratio on response

Amplitude ratio, damping ratio and Fundamental natural frequency are some of the parameters based on which the effect of ball diameter is investigated. For several ball tube diameter ratio response of structure is calculated and plotted in dimensionless form as shown in figure. For R=0.778 at which response of structure becomes minimum.

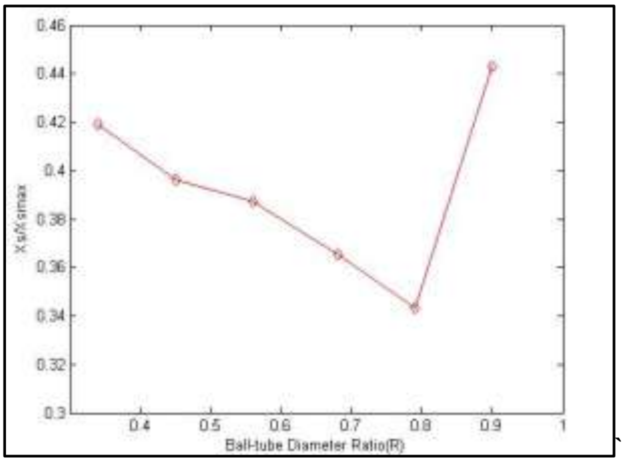

Fig4-Steady state response of the structure for different values of R

5. CONCLUSION

The current analysis deals with the newer version of tuned liquid column damper. The mathematical modeling of damper attached to single degree of freedom is developed. Viscosity of fluid along with the stiffness of spring is taken into consideration. A comparison is done on TLCD and spring loaded TLCD. Around 74% of vibration reduction is absorbed from the analysis. The main influencing parameters on the performance of the absorber are ball-tube diameter ratio and mass ratio. Further more performance of the absorber can be improved by selecting the optimum ball-tube diameter ratio and mass ratio up to a particular limit.

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