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DEVELOPMENT OF VIBRATION CONTROL SYSTEM USING U-SHAPED WATER TANK

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ABSTRACT

This report summarizes an application of a bi-directional vibration control system (tuned Liquid Column Damper with Period Adjustment equipment : LCD-PA) which can be used to provide reductions in the movements of high-rise buildings loaded by wind or earthquakes of medium strength. Good vibration control effect was confirmed through experimental investigations and the results of wind and earthquake observations.

KEYWORDS

vibration control ; Tuned Liquid Column Damper ; period adjustment ; high-rise building ;
wind observation ; earthquake observation

INTRODUCTION

It is well known fact that stability or dynamic response problems in structural systems are in most cases directly related to resonance of the system. Tuned Mass Dampers (TMD), Tuned Liquid Damper (TLD), and tuned Liquid Column Damper (LCD) are effective in suppressing the vibration resonance motions of flexible high-rise structures which are subjected to wind or earthquake excitation. These TLD and LCD have a number of advantages, such as the use of safe water, low cost, almost zero trigger level, and so on. However, the size of the tank which has been used up to the present is small because of the need to tune its frequency to the natural frequency of building. It is necessary to study frequency adjustment system under a varying size of the tank in order to apply the system to building with different characteristics. This paper summarizes a series of experimental and theoretical studies for the realization of bi-directional Liquid Column Damper with Period Adjustment equipment (LCD-PA). And application of this system to a steel high-rise building is also reported. There has been gained good vibration control effects by experiment as well as wind and earthquake response observations.

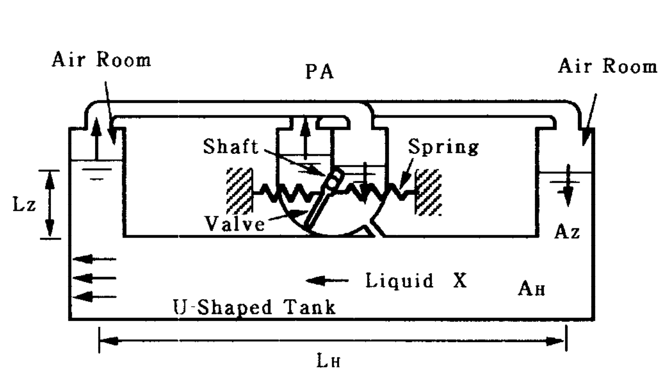


Fig.1 Sectional view of LCD-PA

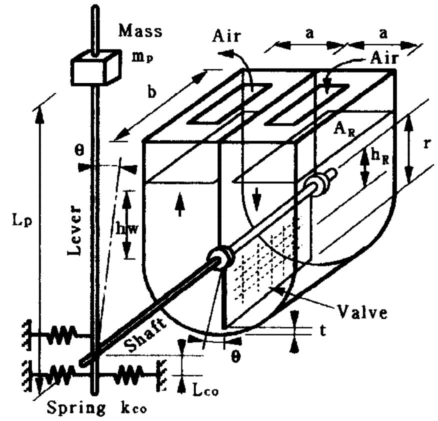


Fig.2 Detail of PA

CONCEPT OF THE LCD-PA

Fig.1 shows a sectional view of the LCD-PA which consists a rectangular bi-directional U-shaped tank (LCD), a pair of air rooms, and period adjustment equipment (PA), while Fig.2 shows the PA in detail. When the tank is moved in the horizontal direction, fluid travels in both horizontal and vertical directions. Accordingly, at one side air is compressed, while at the other side the air pressure reduced. The air pressure drives a fluid movement in PA, resulting in the movement of the valve and shaft, and movements in the springs. By changing the stiffness of the springs, the fluid movements and consequently the natural frequency of the LCD-PA can be controlled.

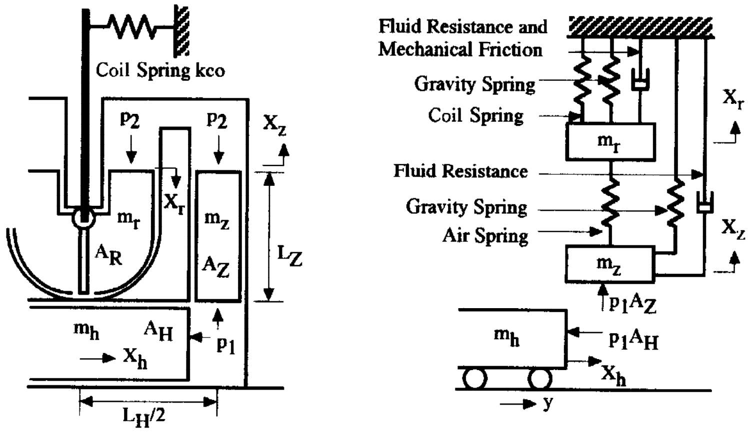
EQUATIONS OF MOTION FOR STRUCTURE WITH LCD-PA

In the U-shaped water tank, water can be considered to move as masses under basement oscillation. As shown in Fig.3(a), water in the LCD-PA can be lumped into three masses such as horizontal, vertical part in the U-shaped water tank and the water mass of the PA. Therefore, the dynamical model of the LCD-PA is described as a mass-spring model shown in Fig.3(b). In addition, using the continuity of the fluid, the vertical displacement of water in the U-shaped tank is replaced by the horizontal displacement and the LCD-PA can be expressed as two degrees of freedom system. The equation of motion of LCD-PA is expressed as follows.

$$\begin{bmatrix} m_m & 0 \\ 0 & m_r \end{bmatrix}\begin{Bmatrix} \ddot{x}_h \\ \ddot{x}_r \end{Bmatrix}+\begin{bmatrix} c_m & 0 \\ 0 & c_r \end{bmatrix}\begin{Bmatrix} \dot{x}_h \\ \dot{x}_r \end{Bmatrix}+\begin{bmatrix} k_m & -k_{mr} \\ -k_{mr} & k_r \end{bmatrix}\begin{Bmatrix} x_h \\ x_r \end{Bmatrix}=-\begin{Bmatrix} m_h \\ 0 \end{Bmatrix}\ddot{y} \tag{1}$$

Here,

$$\begin{gathered} m_m=\rho A_H L_H+2\rho A_Z L_Z\left(\frac{A_H}{A_Z}\right)^2 \qquad m_h=\rho A_H L_H \qquad m_r=\rho A_R L_R+m_P\left(\frac{L_P}{h_R}\right)^2+m_V \\ k_m=2\rho g\frac{A_H^2}{A_R}+\frac{2np_0}{Q}A_H^2 \qquad k_{mr}=\frac{2np_0}{Q}A_H A_R \\ k_r=2\rho g A_R+\frac{2np_0}{Q}A_H A_R+\frac{m_V g}{h_R}-\frac{m_P g L_P}{h_R^2}+k_{co}\left(\frac{L_{co}}{h_R}\right)^2 \\ c_m=\frac{8}{3\pi}\frac{\rho A_H}{2}\zeta_H V_H \qquad c_r=\frac{8}{3\pi}\frac{\rho A_R}{2}\zeta_R V_R+C \end{gathered} \tag{2}$$



(a) Modeling (b) Mass-spring model

Fig.3 Dynamical model of LCD-PA

Where,

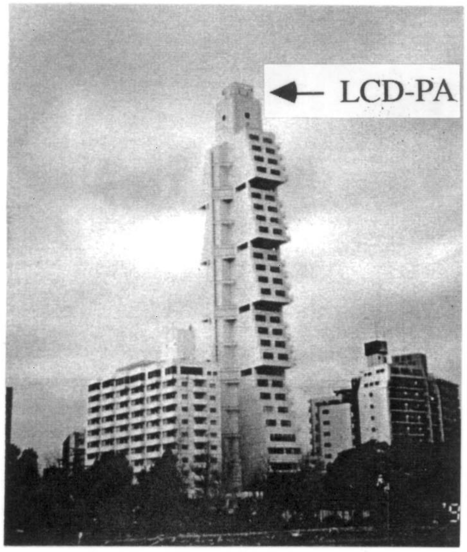
ρ = unit mass of fluid
g = the gravity acceleration
n = the specific heat of air
p_0 = an atmospheric pressure
Q = air volume.
A_H = cross-sectional area of the horizontal portion
A_Z = cross-sectional area of the vertical reservoirs
A_R = cross-sectional area of PA
L_H = length of the horizontal portion
L_Z = length of the vertical reservoirs
L_R = length of PA
ζ_H = fluid resistance factor of LCD
V_H = fluid velocity in the horizontal portion
ζ_R = fluid resistance factor of PA
V_R = fluid velocity in PA
C= damping coefficient by mechanical friction
$k_{co}, L_{co}, m_P, L_P, m_V, h_R$ are described in Fig.2.
And $\ddot{y}$ denotes the base acceleration where the LCD-PA is placed.

For dynamic systems with a larger number of degrees of freedom, such as flexible structures, assuming a modal response, the N different equations of motion become uncoupled from one another and each one describes as a single, separated "spring-mass-damper" vibrational system. The interaction vibration model of structure and LCD-PA is shown as following equation.

$$\begin{bmatrix} m_1+m_h & m_h & 0 \\ m_h & m_m & 0 \\ 0 & 0 & m_r \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_h \\ \ddot{x}_r \end{Bmatrix} + \begin{bmatrix} c_1 & 0 & 0 \\ 0 & c_m & 0 \\ 0 & 0 & c_r \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_h \\ \dot{x}_r \end{Bmatrix} + \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_m & -k_{mr} \\ 0 & -k_{mr} & k_r \end{bmatrix} \begin{Bmatrix} x_1 \\ x_h \\ x_r \end{Bmatrix} = -\begin{Bmatrix} m_1+m_h \\ m_h \\ 0 \end{Bmatrix} \ddot{y} \tag{3}$$

Where, m_1, k_1, c_1 and x_1 are the generalized mass, stiffness, damping, and displacement related to eigenmode of the structure and $\ddot{y}$ denotes the amplitude of the input acceleration.

Tuned optimum values for frequency and critical damping ratio ($h = c/c_c$) of the LCD-PA are found by simulations using above equation and also using the conventional tuned mass theory.



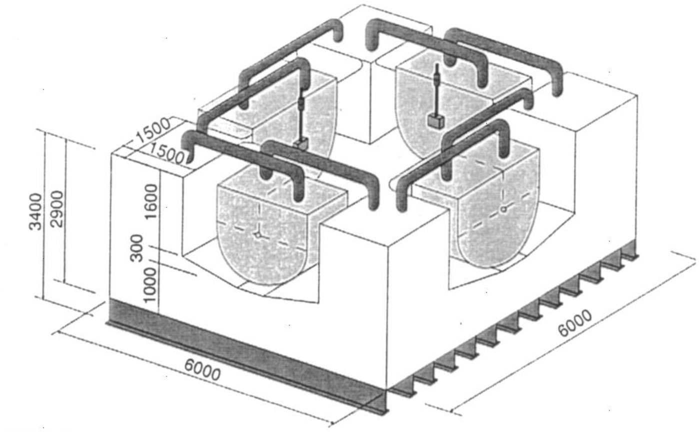


Fig.4 Side view of the high-rise hotel

Fig.5 The employed vibration control system LCD-PA

OUTLINE OF THE REALIZED STRUCTURE AND LCD-PA

Fig.4 shows a concerning building located in Tokyo JAPAN, which is a 26 story hotel with a height of 106m and weight of about 4600 ton. This high-rise building of which the main structure is a steel structure has a high height to width ratio and accordingly resembles a tower. As vibration control system, a LCD-PA is installed on top of the building. The purpose of installing this LCD-PA is to improve the human comfort by reducing the vibration during strong wind, earthquake of small and medium strength, and daily occurring slight vibration such as traffic loads. Furthermore, the tank of LCD-PA is also used as reservoir tank of emergency sprinkler system.

The LCD-PA shown in Fig.5 consists of horizontal part with size of 6 x 6 x 1.3m, four vertical parts at corners with size of 1.5 x 1.5 x 1.6m, and four PAs. The vertical part of the U-shaped tank is filled with water to half depth. Accordingly, the stroke of the water movement is 0.8m which is the enough value to achieve sufficient reduction of the displacements and accelerations under earthquake load with a maximum velocity of 25 cm/sec. A total liquid weight of LCD-PA is 58ton, which value satisfy the regulated water volume as reservoir tank of emergency sprinkler system. Fig.6 shows the natural period characteristics of the LCD-PA. As shown this figure, the natural period of the LCD-PA is adjustable by changing the parameters of PA such as stiffness of the coil spring, the weight of the pendulum, and its length. After investigation of the natural period of the building, that of LCD-PA is tuned to the first natural period of transverse and longitudinal directions of the building. Fig.7 shows the damping characteristics of LCD-PA. Although the critical damping ratio h slightly depends on the water velocity, the optimum damping is almost achieved.

EXPERIMENTAL INVESTIGATIONS

In order to understand the moving characteristics of this structure, a forced vibration experiment was conducted. The results of the experiment were used to investigate the following characteristics.

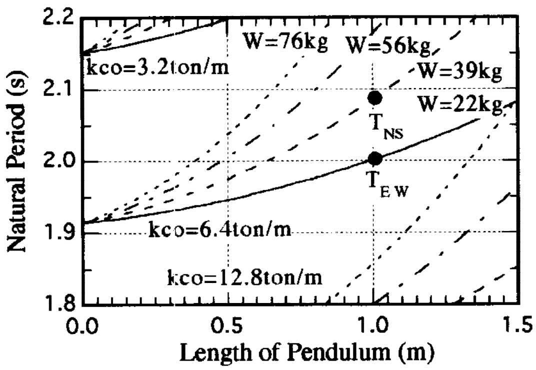


Fig.6 Natural period characteristics of LCD-PA

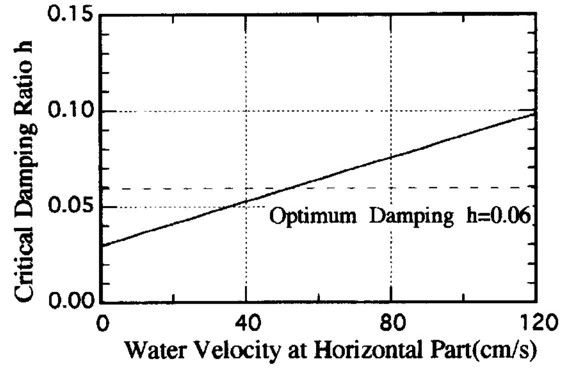


Fig.7 Damping characteristics of LCD-PA

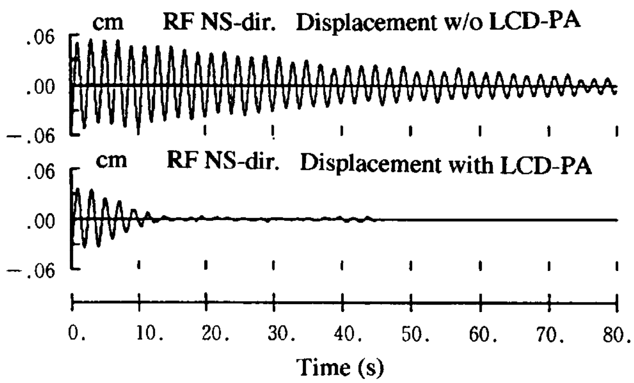


Fig.8 Time-displacement measurement of free vibration experiment

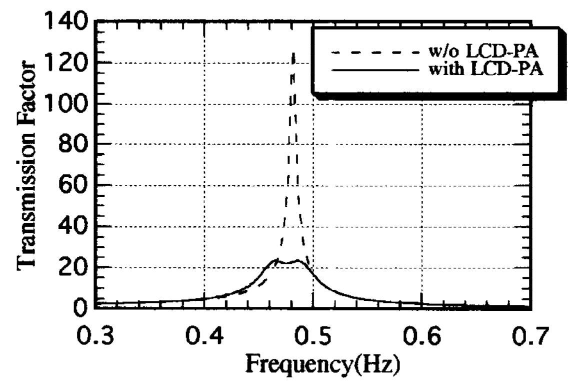


Fig.9 Transmission function under ground vibration

Natural frequency

On the time-displacement measurements of the experiment, a frequency analysis was conducted to obtain the natural frequencies of the building. In the transverse direction (NS-direction), the first natural frequency is 0.48Hz, while the second natural frequency is 1.69Hz. In the longitudinal direction (EW-direction), the first and second natural frequencies are respectively 0.50Hz and 1.69Hz. The period of the displacement is observed to be slightly dependent on the value of displacement and similar periods are found under normally occurring slight motion and under maximum displacement. There is no influence of existence of water in the tank as similar periods are found for a full and empty tank.

Damping ratio

With the measurements obtained from the vibration experiment, the damping ratio for the first natural frequency in the case of free vibration was investigated. If there is no vibration control system, the critical damping ratio is 0.0055 for the transverse NS-direction and 0.0068 for the longitudinal EW-direction. If the vibration control system is employed, the critical damping ratio increases by about a 10 fold to give values of respectively 0.055 and 0. 060 for NS and EW-direction. Fig.8 shows the time-displacement measurement of free vibration experiment for NS-direction.

Transmission function

From the structural movements characteristics the transmission function between the 1st and 26st floor is calculated and the result for NS-direction is shown in Fig.9. If there is no LCD-PA the transmission factor is about 125 for the first natural mode. Employment of the LCD-PA reduces the transmission factor to about 25, about 1/5 of original value for the situation with no LCD-PA.

VIBRATION CONTROL EFFECT BY WIND AND EARTHQUAKE OBSERVATIONS

After completion of the building, wind and earthquake observation has been continued in order to confirm the vibration control effect of the LCD-PA and a number of data was recorded. In the following, some of such data are presented.

Wind Observation Results

On September 16 to 18 in 1995, the typhoon9512 came close to JAPAN and strong wind occurred in Tokyo on 17. At the site of the concerning building, the maximum wind velocity at top of the building was measured as 21.6m/s. The acceleration response of the building with LCD-PA was also measured at roof floor and that without LCD-PA was simulated using the dynamic properties of the building. Fig.10 shows theses time history records. Clearly, LCD-PA was able to reduce the maximum acceleration to about 60% and the r.m.s. acceleration to about 40%, comparing with the case "without LCD-PA".

Earthquake Observation Results

On December 28, 1994, there occurred the earthquake of M=7.5 with the epicenter at Far-off Sanriku and the JMA seismic intensity in Tokyo was Ⅱ. Fig.11 shows the time history records during this earthquake. The accelerations were measured at B3F as an input to the building and at roof floor as a response of the building with LCD-PA. The acceleration response without LCD-PA was also shown in this figure which was obtained by simulation using the dynamic properties of the building. As the results, the maximum values of the acceleration response was reduced to about 60% and the aftershock vibration decreased quickly by using this vibration control system.

CONCLUSIONS

From this series of studies the following conclusions can be drawn:

1. The tuned Liquid Column Damper (LCD) is improved by adding a Period Adjustable equipment (PA), so that the same type of vibration control system can be used for other buildings with different vibration characteristics.
2. The presented LCD-PA uses only one large tank in comparison with conventional liquid damper systems where several smaller tanks are employed.
3. The employment of a LCD-PA reduces the structural response caused by wind or earthquake excitation.

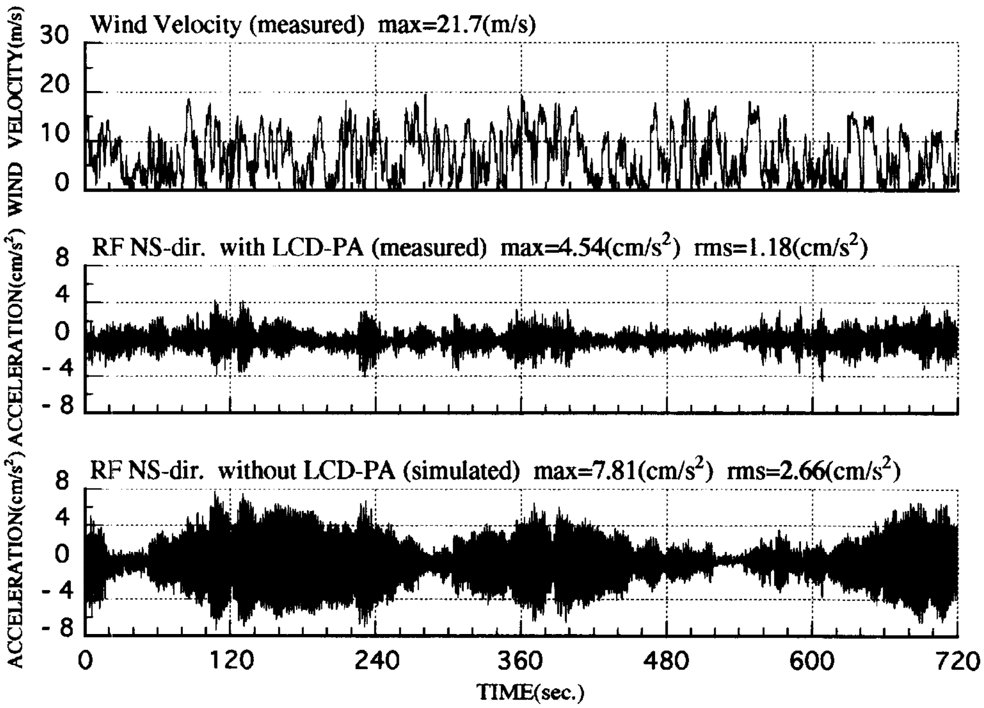


Fig.10 Time history records during typhoon9512
(at 10:07 on September 17, 1995)

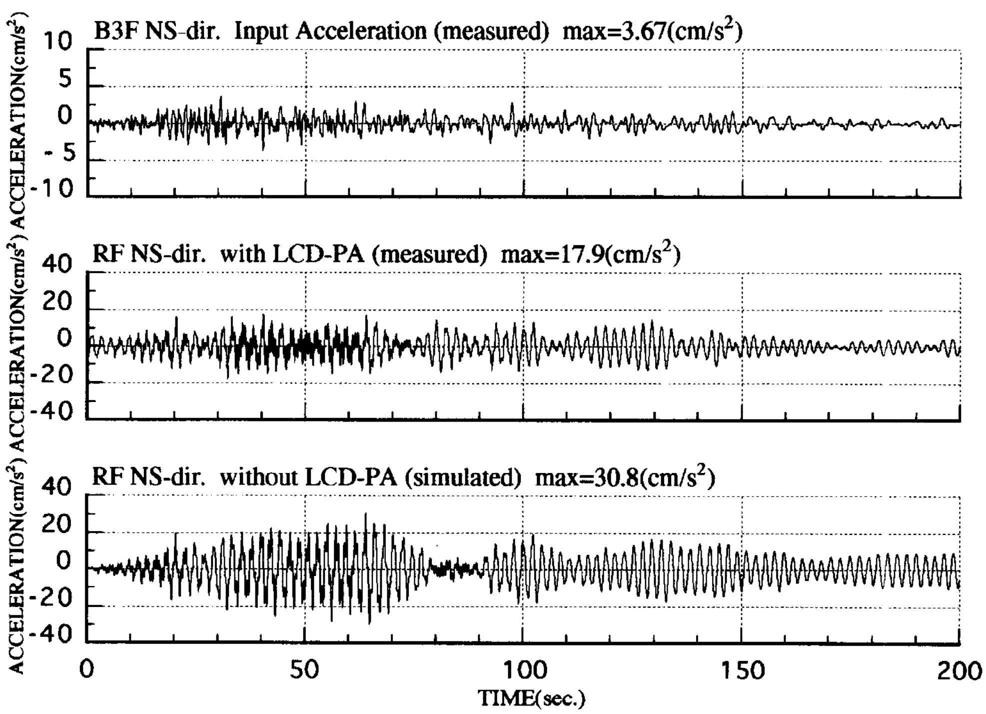


Fig.11 Time history records during Far-off Sanriku Earthquake
(at 21:22 on December 28, 1994)

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