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CONTROL OF HUMAN-INDUCED VIBRATION OF FOOTBRIDGE USING TUNED MASS DAMPERS DESIGNED BY LQR ALGORITHM

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Summary

This paper studied a scenic footbridge which is a long-span steel bridge with low inherit damping and is prompt to human-induced vibration. The dynamic analysis based on the finite element model (FEM) of the bridge show that multi modes of vibration are excited by human loads, and therefore, it is necessary to install Tuned Mass Damper (TMD) for proper vibration control. For single mode of vibration, we can simplify the bridge as a single degree of freedom system for calculation, and obtain the optimally designed parameters of TMD such as mass, stiffness and damping. However, when multi modes of vibration occur, TMD designed for single mode vibration cannot fulfill the control requirement for multi modes s vibration. Thus, it is needed to design additional linear dampers by active control algorithm LQR, so that the comfort requirement of the footbridge can be met under both normal and unfavorable loading conditions.

Keywords: damping; footbridge; tuned mass damper; multi modes vibration; robustness; LQR

1. Dynamics of the footbridge

The fundamental frequency of the footbridge under study is only 1.2988Hz, and a few lower modes also fall into the sensitive frequency range of human-induced vibrations. According to the assessment of human-induced vibrations condition of the bridge, this paper proposes solutions to ensure the footbridge to satisfy the comfort requirement. Accounting for the effect of vibration frequency caused by the population weight, the vertical vibration frequencies of the structure are obtained from ANSYS by different population density.

2. Analysis of pedestrian load excitation

French Highway and Expressway Institute Standard SETRA suggests that the category of pedestrian comfort for outdoor bridge should reach CL1 class, and the maximum vertical acceleration is 0.5 m/s^2.

3. Analysis of human vibration

When the frequency of a certain mode of structure falls near the harmonic frequency of pedestrian load, the structure will be excited to the significant vibration of this mode, so the vibration of pedestrian bridge can be simplified as single-degree-of-freedom resonance which can be expressed in modal coordinate. The equation of motion is:

$$M_n\left(\ddot{Y}_n(t) + 2\xi_n\omega_n\dot{Y}_n(t) + \omega_n^2 Y_n(t)\right) = P_n(t) \quad (1)$$

where $Y_n(t)$ is the generalized mode coordinate of the nth order mode, ω_n is the circular frequency of nth order vibration mode , M_n is the generalized mass, ξ_n is the structural damping ratio taken as 0.01, $P_n(t)$ is the population load. Assuming that the synchronous pace pedestrians are evenly distributed on the bridge, then, $P_n = r_{\phi_s} N_e \alpha G sin\omega t$.

4. Design of TMD

4.1 Design theory of TMD

The working principle of Tuned Mass Damper (TMD), attached to the single-degree-of-freedom structure, is illustrated in Fig. 1.

Thus, for the nth mode, the equation of motion of the system which with TMD installed are:

$$M_n\ddot{Y}_n(t) + (C_n + C_d)\dot{Y}_n(t) + (K_n + K_d)Y_n(t) - C_d \cdot \dot{X}_d(t) - K_d \cdot X_d(t) = P_n(t) \tag{2}$$

$$M_d \cdot \ddot{X}_d(t) + C_d\left[\dot{X}_d(t) - \dot{Y}_n(t)\right] + K_d[X_d(t) - Y_n(t)] = 0 \tag{3}$$

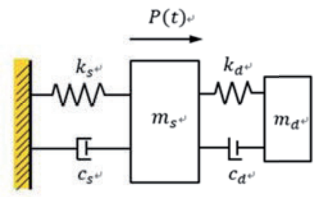

Fig. 1. TMD Schematic

When $P_n(t)$ is a harmonic load, based on the optimally criterion of minimum acceleration of the main structure, the frequency ω_{dopt} and the damping ratio ξ_{dopt} of TMD are as follows[9].

$$\omega_{dopt}/\omega_n = \frac{1}{\sqrt{1+\mu}} + (0.096 + 0.88\mu - 1.8\mu^2)\xi_n + (1.34 - 2.9\mu + 3\mu^2)\xi_n^2 \tag{4}$$

$$\xi_{dopt} = \sqrt{\frac{3\mu(1+0.49\mu-0.2\mu^2)}{8(1+\mu)}} + (0.13 + 0.72\mu + 0.2\mu^2)\xi_n + (0.19 + 1.6\mu - 4\mu^2)\xi_n^2 \tag{5}$$

where, we introduce a parameter:

$\mu = M_d/M_n$;

5. Discussion and Conclusions

This paper studied a scenic footbridge which is a long-span steel bridge with low inherit damping and is prompt to human-induced vibration. The dynamic analysis based on the finite element model (FEM) of the bridge was carried out for both general and extreme pedestrian loading cases. The results showed that it is necessary to install Tuned Mass Damper (TMD) to control the vibration of the bridge induced by human walking. Thus, two TMDs are optimally designed based on the theory of single mode vibration to cater for the case of pedestrian density of d=1.5 person/m^2. However, when the extreme case of pedestrian density of d=3.0 person/m^2 occurs, the TMD designed for single mode vibration cannot fulfill the control requirement. Thus, additional linear dampers were proposed and their parameters were obtained using by active control algorithm LQR, so that the comfort requirement of the footbridge under both normal and unfavorable loading conditions were satisfied.