I-334 MODAL INTERACTION IN GALLOPING OF BRIDGE TOWER

Univ. of Tokyo Member Fujino Yozo
Student Kasa Hirofumi
Student P. Phoonsak
Member Ito Manabu
Member Shino Izumi

1. INTRODUCTION

Generally, to consider galloping instability of flexible structures such as bridge towers or cables, structure is assumed to vibrate in the single mode shape whose natural frequency is the lowest one. However, when the onset wind velocity of the lowest mode is nearly equal to that of the higher modes by attaching TMD [1] or when the higher mode frequency is nearly equal to the lowest mode one, the higher modes may participate in galloping oscillation [2]; the "single vibrating mode" assumption is not any more valid. This paper presents the results of wind tunnel experiment using bridge tower model whose natural frequency $f_1 \doteq f_2$ and also attempts to explain experimental observations by nonlinear analysis using the slowly varying method.

2. WIND TUNNEL EXPERIMENT OF BRIDGE TOWER AND DISCUSSIONS

Three dimensional model of bridge tower, as shown in Fig. 1, was used in this experiment. The top portion of this tower is very long then the in-plane second mode frequency (7.75 Hz.) is nearly equal to the in-plane first mode frequency (7.25 Hz.). Their mode shapes and frequencies are shown in Fig. 2. The wind tunnel experiment using this tower was carried out under uniform wind flow whose direction was perpendicular to the tower. There are two interesting observed phenomena to be pointed out in this experiment.

The first one is that self-excited vibration occurred firstly with the second mode at wind velocity above 2.3 m/s while the first mode self-excited vibration was stated at somewhat higher wind velocity about 2.5 m/s. Note that $\beta_1\omega_1/\beta_2\omega_2$ is 1.07 (β : damping ratio ω : circular natural frequency) and this can explain the onset wind velocity of each mode. At high wind velocities, selection of the first mode or of the second mode in steady-state response was found to depend on the disturbances given to the tower.

The other interesting observation is that at high wind velocities, when tower was galloping in first mode steady-state amplitude, sometimes without any exteranl disturbances, the first mode amplitude started to decay while the second mode growed up and finally reached the steady-state motion as shown in Fig.3. This phenomenon can be explained by the effect of coupled aerodynamic force as shown in following section.

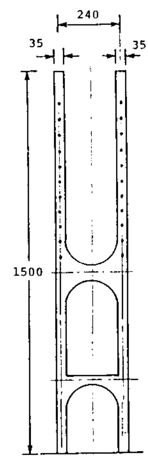

FIG. 1 DIMENSION OF MODEL IN M.M.

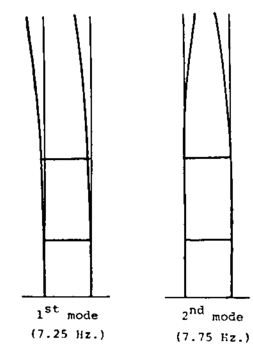

FIG. 2 MODE SHPAE AND FREQUENCY

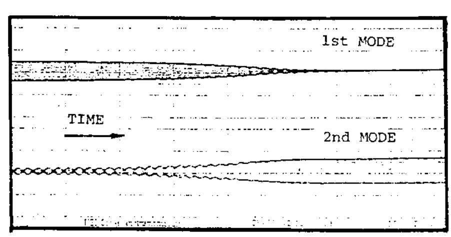

FIG. 3 TIME-HISTORY RESPONSE OF TOWER

3. ASYMPTOTIC ANALYSIS

To consider the effect of coupled aerodynamic force, modal analysis is applied. Using only the first and second modes, tower's response is written as

$$Y(x,t) = \Phi_1(x)\cdot y_t(t) + \Phi_2(x)\cdot y_2(t)$$

$\Phi_1(x)$ and $\Phi_2(x)$ are mode shapes of tower obtained by eigenvalue analysis. Substituting $Y(x,t)$ into the equation of motion with quasi-steady self-excited aerodynamic force yields the following set of equaiton of motion.

$$\ddot{y}_1+\omega_1^2 y_1 = \alpha_1\dot{y}_1+\alpha_2\dot{y}_1^2+\alpha_3\dot{y}_1\dot{y}_2+\alpha_4\dot{y}_2^2+\alpha_5\dot{y}_1^3+\alpha_6\dot{y}_1^2\dot{y}_2+\alpha_7\dot{y}_1\dot{y}_2^2+\alpha_8\dot{y}_2^3$$

$$\ddot{y}_2+\omega_2^2 y_2 = \beta_1\dot{y}_2+\beta_2\dot{y}_1^2+\beta_3\dot{y}_1\dot{y}_2+\beta_4\dot{y}_2^2+\beta_5\dot{y}_1^3+\beta_6\dot{y}_1^2\dot{y}_2+\beta_7\dot{y}_1\dot{y}_2^2+\beta_8\dot{y}_2^3$$

The parameters $\alpha_1-\alpha_8$ and $\beta_1-\beta_8$ are function of mode shape, wind velocity and structural properties. The above equaitons are nonlinear coupled second-order differential equations which can be changed to first-order differential equaitons using the following transformations.

$$y_1 = a_1(t)\cos\phi_1 + \epsilon y_{11}(a_1,a_2,\phi_1,\phi_2)$$

$$y_2 = a_2(t)\cos\phi_2 + \epsilon y_{22}(a_1,a_2,\phi_1,\phi_2)$$

$\Phi_1 = \omega_1(t-\psi_1(t)$, $\Phi_2 = \omega_2(t-\psi_1(t)-\psi_2(t))$, a_1, a_2, ψ_1 and $\psi_2$are slowly varying functions of t. Carrying out some algebrical manupulations with the realtion $\omega_1 = \omega_2$ yields final equations for steady state oscillation as

$$\dot{a}_1 = 0.5\alpha_1 a_1 + 0.375\omega_1^2 a_1^2\alpha_5 + 0.25\omega_2 a_1 a_2^2\alpha_7\ (1 + 0.5\cos 2\omega_2\psi_2)$$

$$\dot{a}_2 = 0.5\beta_1 a_2 + 0.375\omega_2^2 a_2^2\beta_8 + 0.25\omega_1 a_1^2 a_2\beta_6\ (1 + 0.5\cos 2\omega_2\psi_2)$$

$$\dot{\psi}_1 = -0.125\omega_1((\omega_2/\omega_1)^2 a_2^2\alpha_7 + (\omega_1/\omega_2)a_1^2\beta_6)\ \sin 2\omega_2\psi_2$$

Solving these equations, the stability maps for steady-state oscillation at different values of $\omega_2\psi_2$ are obtained. Stability map at $\omega_2\psi_2 = \pi/2$ together with the experiment path is shown in Fig.4. In this figure, at point 1 zero amplitude of both mode are stable. At point 2, self-excited vibration of second mode is stable while zero amplitude of first mode is also stable. However, as shown in Fig. 5 (a_1-a_2 phase plane),when tower is excited with first mode, its amplitude will grow but after sometime it decays while the second mode oscillation becomes stable. This result agrees with the observed phenomena shown in Fig. 3.

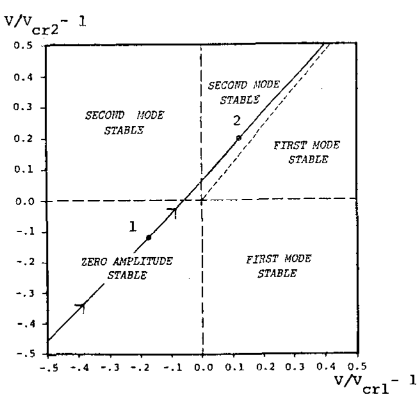

FIG. 4 STABILITY MAP AT $\omega_2\psi_2 = \pi/2$

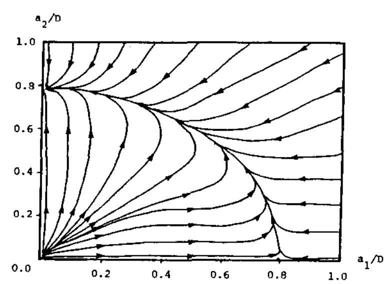

FIG. 5 $a_1 - a_2$ PHASE PLANE AT POINT 2

This analysis qualitiatively explains the observed phenomena. However, there are some observed phenomenon such as multimodal self-excited oscillation which can not be explained by this analysis possibly because of the absence of aerodynamic stiffness terms. The further study is in progress.

REFERRENCES

1. Fujino, Y., Pennung, W., and Ito, M., "Suppression of Galloping of Bridge Tower using Tuned Mass Damper", Jour. of Fac. of Eng., Univ. of Tokyo, Vol. 38, No. 2, pp 49-73, 1985.
2. Kasa, H., " Aeroelastic Behaviours of Cable-stayed Bridge Tower", Graduation Thesis, Univ. of Tokyo, 1985. (In Japanese)