I - 577 WAVE CONTROL OF CABLE VIBRATION BY ENERGY PRINCIPLE.

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Introduction: Cables with many qualities such as: light weight, high strength with long span coverage have played a important role in the modern bridge design. However, theses advantages which make cables economically preferable can undermine their dynamic stability and therefore make them more vulnerable to the vibrations induced by external loads. This point can justify the special measure for the vibrations control applied to these very flexible structures. In the practices until now, methods of vibration control applied to the cables are relied on the passive devices such as oil damper, tuned mass damper etc., which might have serious limitations if the cable span and therefore the sag-span ratio increases. The difficulty is due to the increase in vibration modes excitable and their closeness in the frequencies. This shortcoming points to the active control as the logical choice for the suppression of cable vibration. Many active control algorithms have been developed so far are based on the modal decomposition which are very powerful in general structures, may again have difficulties due to the closeness of the mode shapes. Another alternative would be the control based on the wave propagation principle which can avoid the modal decomposition and provides more robustness. However, method of wave control to sagged cable by the wave suppression [3] can lead to the concentration of strain energy in a localized region, which might aggravate the problem of fatigue. In this study, a new principle based on the minimization of energy transported by the wave will be proposed.

Wave control in sagged cable:

In general, the wave control implementation in cable is consisted of actuator and two sensors installed nearby. If only the in-plane motion of cable is interested, these devices should be capable of detecting waves and generating forces in both directions in the plane of motion since the longitudinal and transverse waves are coupled in cable with sag. A on-line computer is used to predicting the wave state at the actuator location and calculating the input signal to the actuator. The problem of measurement and prediction are treated in other references [1][3]. This study is only concerned with the control algorithms, therefore the wave state at the control location is assumed to be completely known.

Wave propagation in cable by energy concepts:

The governing equation of motion in sagged cable can be reduced to the wave form as (Ref [3]):

$$\mathbf{v}_t + \Lambda.\mathbf{v}_s + \mathbf{E}.\mathbf{v} + \mathbf{T}^{-1}.\mathbf{f} = 0 \qquad (1)$$

where **E** is a 4x4 matrix in function of the longitudinal stiffness AE, initial tension T_e, mass density ρ and the static configuration of cable, Λ is a diagonal matrix $[c_1, -c_1, c_2, -c_2]$, with c_1, c_2 are longitudinal and transverse wave propagation velocity, **f** is the external forces and the subscripts t,s denote their partial derivatives. The term **v** here stands for the wave state vector and it is related to the state vibration vector **r** as:

$$\mathbf{r} = \mathbf{T}.\mathbf{v} \quad \text{or} \quad \mathbf{v} = \mathbf{T}^{-1}.\mathbf{r} \quad \text{and} \quad \mathbf{r}^T = \left\{ \frac{\partial u}{\partial s}\ \frac{\partial w}{\partial s}\ \frac{\partial u}{\partial t}\ \frac{\partial w}{\partial t} \right\} \qquad (2a,2b,2c)$$

Matrices **T** and $\mathbf{T}^{-1}$ define the transformation between **v** and **r** and their explicit form can be seen in ref.[3]. The variable u, w are horizontal and vertical displacements meanwhile s,t represent the material and time coordinates respectively. With these definitions, the dynamic energy density, that is, the amount of dynamic energy associated with an infinitesimal portion of cable is expressed as:

$$J = EAv_1^2 + EAv_2^2 + T_e v_3^2 + T_e v_4^2 \qquad (3)$$

It can be observed that J is a sum of individual contributions from 4 single waves v_i. These energy amounts are not stationary and could be considered as transported by their corresponding waves. It can be defined an energy index as:

$$J_i = c_i R_i v_i^2 \qquad \text{for } i = 1,4 \qquad (4)$$

This index is interpreted as the flow of energy carried by the wave v_i through a point at certain instance. The coefficient R_i is equal AE or T_e for the case of longitudinal or transverse wave respectively.

Control implementations based on the energy:

The effect of control force on the cable can be expressed as (ref.[3]):

$$\mathbf{T}^{-1}.\mathbf{p} = \mathbf{v}_{t^+} - \mathbf{v}_{t^-} \quad \text{where} \quad \mathbf{p}^T = \left\{ 0 \quad 0 \quad \frac{p_x}{\rho} \quad \frac{p_y}{\rho} \right\} \qquad (5a,5b)$$

For this case, only the in-going waves v^-_i are known from the observations, then there will be 6 unknowns v^+_i and p_x, p_y with 4 equations to be solved. It can be defined a performance index as the total amount of out-going flow of energy according to (4)

$$G = \sum_{i=1}^{4} J_i = \sum_{i=1}^{4} c_i R_i v_i^2 \qquad \text{for } t=t^+ \qquad (6)$$

By substituting v^{+}_{i} from (5a) the expression (6) can be reduced to a quadratic function in p_x, p_y which can be minimized to determined the control forces. If the local coordinate is chosen, expressions of control law will be further simplified, and the control forces is explicitly calculated as:

$$p_x = \rho c_1 (v_1 - v_2) \quad , \quad p_y = \rho c_2 (v_3 - v_4) \qquad (7a,7b)$$

Control performances and discussions

To study the performance of this control, numerical simulations are conducted in three models of cable with different sag-span ratios (0.8%,4%, 8%) under two conditions: free vibration and forced vibration. For each case, the total dynamic energy and the magnitudes of control forces both longitudinal and transverse are computed in the normalized time and are used to evaluate the control performances.

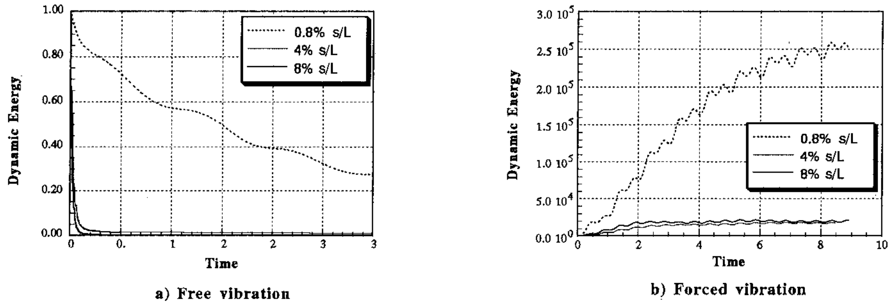

Figure 1 Total energy of vibration in cable.

Figures 1a and 1b show the level of dynamic energy in cable for the free and forced vibrations respectively. It can be observed that in case of free vibration, the total vibrational energy is monotonously decreased. This point suggests that the control designed based on the energy associated to the wave is effectively reducing the localized strain. The performance of control for larger sag-span ratios is much better as shown in both figures. The time for free vibration to be notoriously decreased and the eventual level of forced vibration are significantly smaller in cable with large sag. This may be attributed to effect of longitudinal forces which is more effective when the longitudinal wave becomes of importance.

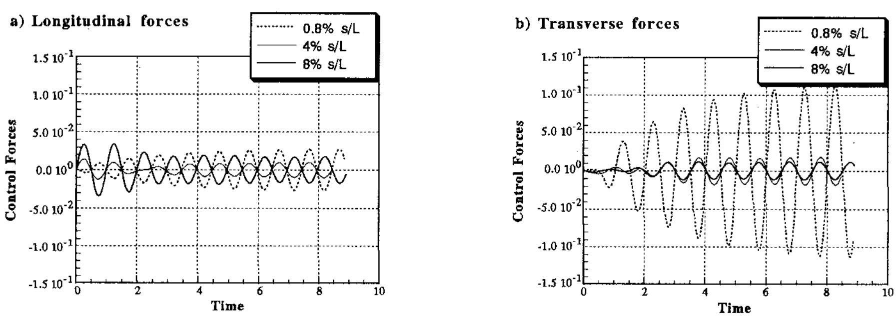

Figure 2. Control forces in forced vibrations.

Figures 2a and 2b show the values of control forces in forced vibrations. It can be observed that both longitudinal and transverse forces required in shallow cable are larger, which implies that the level of vibrations in this cable is higher. In cases of large sag cable, there is an initial decrease in longitudinal forces with a corresponding increase in transverse forces. This might indicates that there is a shift in the vibration shape from the initial odd mode to the even mode.

Conclusion:

The wave control by the energy approach has shown advantages in comparison with the wave suppression scheme, where the localized concentration of strain energy can be avoided. In general, the control is more effective for the cable with large sag-span ratio.

References:

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