Active Control of Cable and Cable-Structure System*

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The governing equation of nonlinear dynamics for cable-structure systems with internal actuators which move in the cable axial direction, is formulated using a global/local mode approach. Many possible internal resonances are clarified. Active control schemes for both local and global modes, using these actuators, are investigated. They are verified by experiments and numerical simulations.

Key Words: Global/Local Mode Approach, Slightly-Sagged Cable, Internal Resonance, Active Control, Cable-Stayed Bridges

1. Introduction

There are many types of cable-structure systems; cable-stayed bridges, transmission lines and cable-supported roofs are the typical ones. They usually possess low inherent damping and are therefore prone to many vibration problems. Interaction between cable and structure vibrations was shown to be significant [for example, Ref. (1)] but is usually ignored in most dynamic modelling or treated separately. In the present paper, a dynamic model which allows cable-structure nonlinear interaction is formulated by using a global/local mode approach. Actuators providing motions in the cable axial direction are included in the model. It is shown that by feeding proper signals to these actuators, cable and/or structural vibrations can be suppressed by many control schemes, i.e., active stiffness control and active sag-induced force for the local cable motions, and active tendon force and active cable inertia force for the global motions. These control schemes are verified by experiments and numerical simulations.

2. Formulation of Nonlinear Dynamics for Cable-Structure System with Internal Actuators

In this paper, the global/local mode approach is employed to obtain the governing equations of cable-structure system: total motions of the system can be expressed in terms of global and local motions. The global motions are 3-D motions of the structure, including quasistatic motions of the cables due to their support movements, while the local motions are the rest of the motions and practically a combination of all cable modal motions (Fig. 1).

Actuator motions in the cable axial direction which are induced by internal actuators are also included in the cable-structure model (Fig. 2). It is shown later that these motions can be used for suppressing the cable and/or structural motions effectively.
Separation of cable motions: 3-D dynamic motions of cable \((u_c, v_c\) and \(w_c\)) are expressed in local Cartesian coordinates (Fig. 3). They can be separated into two parts, quasistatic motions (denoted by superscript \((q)\)) and purely dynamic motions.

The quasistatic motions are displacements of the cable which moves as an elastic tendon due to support movements. They satisfy the time-dependent boundary conditions statically. The boundary conditions at the cable supports \((a\) and \(b)\) are

\[
\begin{align*}
  u_c(x_c=0, t) &= u_a(t) + u_{ca}(t), \\
  u_c(L, t) &= u_b(t) \\
  u_c(x_c=0, t) &= v_a(t) + u_{ca}(t), \\
  u_c(L, t) &= v_b(t) \\
  u_c(x_c=0, t) &= w_a(t), \\
  u_c(L, t) &= w_b(t)
\end{align*}
\]

(1)

where \(u_a, v_a, w_a, u_b, v_b\) and \(w_b\) are the displacements at the cable anchorages due to the structural movements, and \(u_{ca}\) and \(u_{co}\) are displacements due to the actuators installed at the cable anchorages.

Since the cable considered here has small sag, the purely dynamic displacement of the cable in the axial direction can be neglected. The purely dynamic transverse motions of cables can be treated by a conventional procedure for cable with fixed ends. Using the separation-of-variables method, the dynamical cable motions can be expressed as

\[
u_c(x, t) = \psi_c^{(q)}(x, t) + \sum \phi_c(x) g_n(t)
\]

(2)

where \(u_c^{(q)}\) and \(\psi_c^{(q)}\) are quasistatic motion, and \(g_n\) and \(\phi_c\) are generalized coordinates for out-of-plane and in-plane purely dynamic motions, respectively. Out-of-plane and in-plane linear undamped mode shapes of cable with fixed ends can be employed for the spatial functions, \(\phi_c\) and \(\psi_c\).

Global and local modes: Global motions \((u_c, v_c\) and \(w_c)\) are expressed in global Cartesian coordinates. 'Global' motions refer practically to structural motions; in a strict sense they consist of structural motions and quasistatic motions of cables. Using the separation-of-variables method, the global motions can be expressed in terms of the global generalized coordinates \((q)\) and the global modes \((\Phi^x, \Phi^y \text{ and } \Phi^z)\). The global modes may be the eigenmodes computed by the conventional 3-dimensional FEM where cables are treated as tendons in the formulation.

Analytical model: The model is based on the metallic slightly sagged cable normally used in engineering practice. Finite cable motions are included. Small motions at the cable supports are considered. Proportional damping and orthogonality of the global modes are assumed.

The linear undamped mode of cable is used as the local modes \(\varphi_n\) and \(\varphi_n^{(q)}\). The quasistatic motions are expressed in terms of the motions at cable

\[
v_c(x, t) = \psi_c^{(q)}(x, t) + \sum \phi_c(x) g_n(t)
\]

(3)

\[
w_c(x, t) = w_c^{(q)}(x, t) + \sum \phi_c(x) z_n(t)
\]

(4)

where \(\psi_c, \psi_c^{(q)\text{ and } w_c^{(q)\text{ are quasistatic motion, and } g_n\text{ and } z_n\text{ are generalized coordinates for out-of-plane and in-plane purely dynamic motions, respectively.} \text{Out-of-plane and in-plane linear undamped mode shapes of cable with fixed ends can be employed for the spatial functions, } \phi_c\text{ and } \psi_c.\}

Fig. 1 Schematic drawing of (a) global vibration; and (b) local vibration using a cable-stayed bridge

Fig. 2 Cable-structure system with internal actuators

Fig. 3 Local and global Cartesian coordinate system
anchorages. Then, Lagrange formulation is employed and the governing equations are obtained as Eq. (3):

For $k$th global mode

$$
M_0 \ddot{q}_k + 2 \alpha_0 \phi_k \dot{q}_k + \omega_0^2 q_k + \sum_j \left[ R_{ks} q_j + S_{ks} \dot{z}_k \right], \quad (3)
$$

$$
+ \sum_j \left[ \Phi_{ks} (y_j^2 + \dot{z}_j^2) \right] = \sum_j \left[ P_{ks} (u_j - u_{ca}) \right]
$$

$$
+ P_{bs} (u_{cb} - u_{ca}) + P_{cs} (u_{cb} + u_{ca}) \right] = F_{ek}
$$

For $n$th out-of-plane local mode of $j$th cable:

$$
m_\text{c}(\ddot{y}_n + 2 \xi_\text{c} \omega_\text{c} \dot{y}_n + \omega_\text{c}^2 y_n)
$$

$$
+ \sum \nu_\text{c} m_\text{c} \dot{y}_n \dot{y}_n \dot{z}_n + \sum \beta_\text{c} y_n \dot{z}_n = F_{\text{y}n}
$$

(7)

For $n$th in-plane local mode of $j$th cable:

$$
m_\text{in}(\ddot{x}_n + 2 \xi_\text{in} \omega_\text{in} \dot{x}_n + \omega_\text{in}^2 x_n)
$$

$$
+ \sum \nu_\text{in} m_\text{in} \dot{x}_n \dot{z}_n + \sum \beta_\text{in} x_n \dot{z}_n = F_{\text{z}n}
$$

(8)

where $M_0$, $m_\text{c}$, and $m_\text{in}$ are generalized modal masses; $\xi_\text{c}$, $\xi_\text{in}$ are modal damping ratios; $\omega_\text{c}$, $\omega_\text{in}$ are modal frequencies; $q_k$, $\dot{q}_k$ and $z_k$ are generalized coordinates; $R_{ks}$, $S_{ks}$ and $\Phi_{ks}$ are coefficients of coupling between global and local modes; $\beta_{ks}$ and $\nu_{ks}$ are coefficients of coupling between local modes; $F_{ek}$, $F_{\text{y}n}$ and $F_{\text{z}n}$ are generalized forces; $P_{ks}$, $P_{bs}$, $P_{cs}$, $\eta_\text{c}$ and $\eta_\text{in}$ are coefficients of control effects. These coefficients are explicitly shown in Ref. (3).

**Internal resonance**: Governing equations of local and global modes show that internal resonance can occur. Interaction between local modes is possible through quadratic and cubic couplings. Interaction between local and global modes appears as linear and quadratic couplings. Topology of all possible couplings is shown in Fig. 4. By investigating the frequency ratios, the modes whose frequencies are coupled linearly and nonlinearly can be identified and are included in the dynamic analysis of the cable-structure system. Thus, the number of degrees of freedom in the model can be made small. Fujino et al. conducted a dynamic experiment on interaction of local/global motions, using a small cable-stayed beam model. In their experiment, not only linear internal resonance, but also nonlinear auto-parametric resonance in the model was identified.

**Active control**: It can be seen from Eqs. (6) – (8) that many active control schemes can be applied to the local and/or global modes.

For the local modes, two control schemes can be employed. One is a positive use of parametric excitation through variable stiffness terms, $2 \eta_\text{c}(u_{cb} - u_{ca}) y_n$ and $2 \eta_\text{in}(u_{cb} - u_{ca}) z_n$. Therefore, it was termed “active stiffness control”. This can be used for any local mode. The sag-induced force term, $a_n(u_{cb} - u_{ca})$ can be utilized as well. This can be called “active sag-induced force” and used for suppressing vibrations of in-plane symmetric modes. Note that $a_n$ is zero in the asymmetric modes.

For the global modes, two control schemes can be employed through tendon force, $P_{bs} (u_{cb} - u_{ca})$ and cable inertia forces, $P_{bs} (u_{cb} - u_{ca})$ and $P_{cs} (u_{cb} + u_{ca})$. A linear control algorithm can be employed in both schemes.

### 3. Active Control of Cable Vibration

As stated before, there are two methods of active control for local cable modes. Active stiffness control can be employed for any local mode and active sag-induced force for in-plane symmetric modes only. The following part shows the effectiveness of active control of cables. Energy analysis is conducted to clarify the control mechanism and to estimate additional damping and can find the optimal condition for control. Experimentation and numerical simulation are later used to verify the control algorithm.

The model employed is a slightly sagged cable with fixed boundary at one end and longitudinally time-varying at the other (Fig. 5). The movement of the boundary, $u$, is driven by an actuator and is very small. The transverse vibration is confined to one

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**Fig. 4** Topology of global-local and local-local couplings in arbitrary chosen modes

**Fig. 5** Model for analysis, experiment and numerical simulation
plane, and thus the problem is reduced to planar motions. Properties of the cable used in this model are carefully selected to simulate a real cable normally employed in engineering practice. The cable in the model is a stainless steel wire (SUS 304 JIS) of 2.08-meter length. Its cross-sectional area, \( A \), is 2.055 \( \times 10^{-4} \) m\(^2\) and rope modulus of elasticity \( E \) is 1.707 \( \times 10^{11} \) N/m\(^2\). Initial tension is set at 83 N, and masses at regular intervals are added so that mass per unit length is 0.07 kg/m. The cable anchorages are wrapped with rubber in order to obtain realistic inherent damping (\( \xi \) and \( \xi_{\xi} \approx 1.60 \times 10^{-9} \)).

**Planar motions of small-sag cable**

For a cable to be obtained from Eqs. (7) and (8) by setting all global generalized coordinates \( q_r \) to zero. Couplings between in-plane and out-of-plane motions are omitted because the motion is planar. The other modal couplings are also neglected to obtain a simple and interpretable system. Therefore nondimensionalized equations for out-of-plane and in-plane motions can be written as:

For out-of-plane motions

\[
\frac{d^2 \tilde{y}_n}{dt^2} + 2 \tilde{\xi}_{\xi y} \frac{dy_n}{dt} + (1 + \tilde{\alpha}) \tilde{y}_n + \tilde{\beta}_{\xi y} \tilde{y}_n \tilde{y}_{nn} \tilde{y}_n^2 = \tilde{F}_{\.y_n} \tag{9}
\]

where

\[
\tilde{y}_n = \frac{y_n}{u_0}, \quad \tilde{\alpha}_n = (\frac{L}{u_0} \tilde{\alpha}), \quad \tilde{\beta}_{\xi y} = \frac{\nu u_0}{u_0}, \quad \tilde{\xi}_{\xi y} = \frac{\nu u_0^2}{u_0^2} = \frac{(n \pi)^2}{4}.
\]

For in-plane motions

\[
\frac{d^2 \tilde{\beta}_n}{dt^2} + 2 \tilde{\xi}_{\beta n} \frac{d\tilde{\beta}_n}{dt} + (1 + \tilde{\alpha}) \tilde{\beta}_n + \tilde{\nu}_{\xi n} \tilde{\beta}_n^2 \tilde{\beta}_n = \tilde{F}_{\.\tilde{\beta}_n} \tag{11}
\]

where

\[
\tilde{\beta}_n = \frac{\beta_n}{u_0}, \quad \tilde{\alpha}_n = (\frac{L}{u_0} \tilde{\alpha}), \quad \tilde{\nu}_{\xi n} = \frac{\nu u_0}{u_0}, \quad \tilde{\xi}_{\beta n} = \frac{\nu u_0^2}{u_0^2} = \frac{(n \pi)^2}{4}.
\]

Planar motions of small-sag cable: Equations for a cable can be obtained from Eqs. (7) and (8) by setting all global generalized coordinates \( q_r \) to zero. Couplings between in-plane and out-of-plane motions are omitted because the motion is planar. The other modal couplings are also neglected to obtain a simple and interpretable system. Therefore nondimensionalized equations for out-of-plane and in-plane motions can be written as:

\[
\frac{d^2 \tilde{y}_n}{dt^2} + 2 \tilde{\xi}_{\xi y} \frac{dy_n}{dt} + (1 + \tilde{\alpha}) \tilde{y}_n + \tilde{\beta}_{\xi y} \tilde{y}_n \tilde{y}_{nn} \tilde{y}_n^2 = \tilde{F}_{\.y_n} \tag{9}
\]

where

\[
\tilde{y}_n = \frac{y_n}{u_0}, \quad \tilde{\alpha}_n = (\frac{L}{u_0} \tilde{\alpha}), \quad \tilde{\beta}_{\xi y} = \frac{\nu u_0}{u_0}, \quad \tilde{\xi}_{\xi y} = \frac{\nu u_0^2}{u_0^2} = \frac{(n \pi)^2}{4}.
\]

For in-plane motions

\[
\frac{d^2 \tilde{\beta}_n}{dt^2} + 2 \tilde{\xi}_{\beta n} \frac{d\tilde{\beta}_n}{dt} + (1 + \tilde{\alpha}) \tilde{\beta}_n + \tilde{\nu}_{\xi n} \tilde{\beta}_n^2 \tilde{\beta}_n = \tilde{F}_{\.\tilde{\beta}_n} \tag{11}
\]

where

\[
\tilde{\beta}_n = \frac{\beta_n}{u_0}, \quad \tilde{\alpha}_n = (\frac{L}{u_0} \tilde{\alpha}), \quad \tilde{\nu}_{\xi n} = \frac{\nu u_0}{u_0}, \quad \tilde{\xi}_{\beta n} = \frac{\nu u_0^2}{u_0^2} = \frac{(n \pi)^2}{4}.
\]

**Energy analysis**

Energy production, \( E_p \), is defined here as the integral over one steady-state oscillation cycle of \( y_n \), of the product of generalized velocity and generalized force (any term in Eq. (9)). The energy production due to the generalized force associated with \( \tilde{\nu} \), assuming \( s = 2 \), and due to the inherent damping can be written, respectively, as:

\[
E_p(\tilde{\nu} y_n) = -\frac{1}{2} \pi \tilde{\alpha} \tilde{\beta} \tilde{y}_n^2 \sin(\gamma_{\nu n}) \tag{15}
\]

\[
E_p(\tilde{\xi}_{\beta n} \frac{d\tilde{\beta}_n}{dt}) = -2 n \pi \tilde{\xi}_{\beta n} \tilde{\beta}_n^2 \tag{16}
\]

Equating the two expressions for \( E_p \) in Eqs.(15) and (16), the damping effect that is produced by stiffness variation can be evaluated in the form of equivalent additional damping ratio \( \tilde{\xi}_{\beta n} \):

\[
\tilde{\xi}_{\beta n} = \frac{1}{4 n \pi} \tilde{\beta} \sin(\gamma_{\nu n}) \approx \frac{1}{4 \tilde{\beta}} \tilde{\beta} \sin(\gamma_{\nu n}) \tag{17}
\]

This equation implies that optimum damping can be obtained when \( \gamma_{\nu n} \) is equal to 90°.

**Experiment on the first out-of-plane mode**

The performance of active stiffness control is investigated for the first out-of-plane mode. Experimental setup is shown in Fig. 5. The motion of the cable is confined to one plane. Excitation is harmonic. If \( \tilde{\nu} = 0 \), Eq. (9) is reduced to a well-known Duffing equation whose steady-state solutions can be analytically predicted(10). Analytical prediction for the system with control can also be made by using the energy analysis. An equivalent additional damping is employed to represent the control effects, and the solutions to the Duffing equation can be utilized by replacing \( \tilde{\xi}_{\beta n} \) by \( \tilde{\xi}_{\beta n} + \tilde{\xi}_{\beta n}^* \).

The frequency sweep test is conducted by keeping
the forcing amplitude $\bar{a}_f$ constant while the excitation
frequency $\Omega$ is varied in the neighborhood of the
natural frequency. The steady-state responses with
and without active stiffness control are shown in Fig.
6. Active stiffness control is applied by setting $\bar{a}_s$ and
$\gamma_{sw}$ at 2.27% of initial elongation and 90°, respectively.
The experimental results (dots) are well predicted by the
analytical solutions (lines). Large reduction in
response amplitude even with small $\bar{a}_s$ confirms the
effectiveness of active stiffness control.

3.2 Active sag-induced force control

Since the sag-induced force term is a linear function of
the acceleration of the support motion, a linear
velocity feedback control algorithm can be readily
used.

Energy analysis: The same process as for active
stiffness control is employed, and the transverse vabra-
tion $\bar{z}_s$ and the control motion $\bar{u}$ can be written as

$$\bar{z}_s = \bar{a}_w \cos (\Omega t); \quad \bar{u} = \bar{a}_w \cos (\Omega t + \gamma_{sw})$$

(18), (19)

The parameters of the control algorithm are $\bar{a}_w$ and
$\gamma_{sw}$. The additional damping ratio $\xi_{sw}$ is obtained as

$$\xi_{sw} = \frac{\gamma_{sw}}{2} \left(\frac{\bar{a}_s}{\bar{a}_w}\right) \sin (\gamma_{sw}) \approx \frac{\bar{a}_s}{2} \left(\frac{\bar{a}_s}{\bar{a}_w}\right) \sin (\gamma_{sw})$$

(20)

The optimum damping will be obtained when $\gamma_{sw}$ is
90°.

Experiment on the first in-plane mode: The performance
of active sag-induced force is investigated experimen-
tally for the first in-plane mode. The same
model of the cable is employed. Harmonic excitation
with the same amplitude of excitation as in the pre-
vious case is provided.

When $\bar{u} = 0$, the same steady-state response curve
as in the previous case is obtained. A frequency sweep
test with active sag-induced force is conducted by
setting $\gamma_{sw}$ at 90°. The control amplitude is varied in
order to obtain the same additional damping ratio ($\xi_{sw}$ = 5.675 × 10^{-3}) as that of the previous case. The
prediction (lines) and experimental results (dots) are

in good agreement (Fig. 7). The amplitude of control
motion at the steady state can be obtained from Eq.
(20) and it can be shown to be smaller than that in the
previous case by about one order of magnitude. This
implies that active sag-induced force is more efficient
than active stiffness control. However, active sag-
duced force can be applied to in-plane symmetric
modes only.

3.3 Control of nonplanar multimodal motions

It is well known for a small-sag cable that frequen-
cies of the in-plane and out-of-plane modes are
closely spaced. A problem arises when active stiffness
control is applied to a mode. The other uncontrolled
mode which has nearly the same frequency can be
parametrically excited by the control motion. How-
ever, parametric excitation occurs in a narrow range
in the neighborhood of the natural frequency. A
global asymptotic scheme to control in-plane as well
as out-of-plane multimodal cable vibration[11] was
recently developed on the basis of bilinear control
theory. This control scheme utilizes the active
stiffness control and the sag-induced force control
simultaneously.

4. Active Control of Cable-Structure System

Control of global modes is investigated in this
section with emphasis on the effects of internal reso-
nance on the control (due to the presence of cable
vibration). The model used in the previous section is
modified by attaching the previously fixed end of the
cable to a girder (Fig. 8). Strain gages are attached at
the center of the girder to observe its motions. A
phase shifter is employed to produce a control signal
from the observed girder strain. An experiment is

\[ a_{\Omega} \] (mm)

![Fig. 6 Amplitude of steady-state response with and without active stiffness control](image)

![Fig. 7 Steady-state response of the first in-plane mode of cable with and without control (sag-to-span ratio = 0.33%)](image)
conducted to verify the control scheme. Analytical predictions are obtained through a perturbation technique. Since active cable inertia forces are usually small compared with active tendon forces\(^{10}\), only the latter is considered in the following part.

**Analytical predictions**: By varying the initial cable tension, many important global-local coupling patterns can be investigated, i.e., no coupling (pure global mode), linear coupling and quadratic coupling. Only linear coupling between the second global vertical mode \(f_2=19.82\) Hz and the second local vertical mode \(f_2=19.37\) Hz is investigated in the following section.

In this case, other couplings are not significant and are neglected in Eqs. (6) - (8). Only the effect of active tendon control is considered, which can be written in terms of an equivalent additional damping ratio, \(\xi_g = P_m (\omega_c - \omega_g)/2 \omega_g m_g\), where subscript \(g\) indicates the values related to the global vertical mode. The governing equations for both modes are:

for the 2nd global vertical mode
\[
m_g (\ddot{x}_g + 2(\xi_g + \xi_2)\omega_g \dot{x}_g + \omega_g^2 x_g) + S_{g2} \dot{x}_2 = a_{eg} \cos (\Omega_d t)
\]

for the 2nd local vertical mode
\[
m_{sl} (\ddot{x}_2 + 2(\xi_2 + \xi_{2s})\omega_{2s} \dot{x}_2 + \omega_{2s}^2 x_2) + v_{2s} \dot{x}_2 = 0
\]

Excitation is induced in the global mode only. A perturbation technique was applied to Eqs. (21) and (22) to obtain the steady-state responses\(^{12}\).

**Experimental results**: The frequency response of the system without control exhibits a classical pair of principal modes that can be termed local-dominated (around 17.25 Hz) and global-dominated (around 19.8 Hz) when considering the kinetic energy distribution between the girder and the cable. The analytical model agrees satisfactorily. When the control scheme is applied, although the global-dominated peak is significantly reduced, in accordance with the predictions, the local-dominated peak is scarcely affected (see Fig. 9). To investigate this discrepancy, separate tests at the local-dominated frequency for several gain levels are conducted; the results are given in Table 1, showing that some modal properties of the model are modified. Tip motion (Table 1) is the girder tip actual displacement divided by that computed from the mid-span strain signal. This ratio is assumed to be unity if the real mode assumption is verified. This is not exactly the case. Nevertheless, it seems that, amplitude-wise, the girder modal properties are not affected. 'Cable/girder' (Table 1) is the amplitude ratio between the cable and the girder motions. It seems that the control action induces higher stored energy in the cable. 'Phase' (Table 1) is the phase lag between the cable motion and the mid-span strain. It is a good indicator of the phase lag between the girder tip and middle as the cable is excited relatively far from its natural frequency, hence maintaining almost the same phase lag with the

<table>
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<tr>
<th>Gain level</th>
<th>Tip motion</th>
<th>Cable/girder</th>
<th>Phase</th>
</tr>
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<td>34.0</td>
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(1) * assumption (1) prediction

![Fig. 8 Cable-structure model](image)

![Fig. 9(a) Frequency response of girder vertical motion](image)

![Fig. 9(b) Frequency response of cable vertical motion](image)
girdertip where the excitation force acts. Therefore, we have here some clear evidence that the girder mode becomes a complex (nonclassical) model.

5. Conclusions

A simple model which takes into account linear and nonlinear interactions of cable-structure systems has been proposed. The model also includes effects of actuators which move along the cable axial directions at the cable anchorages. Many possible control schemes are shown on the basis of the proposed model, and their effectiveness has been experimentally demonstrated. It has been found that agreement between the experiments and numerical predictions is good in the control schemes.

References

(2) Irvine, H.M., Cable Structures, (1981), MIT Press.