Active damping of tension truss structures
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Abstract
This paper presents a strategy for active damping of cable structures. The control algorithm has guaranteed stability, including at the parametric resonance. The paper also describes an efficient modelling technique for cable structures; simple and powerful results are established, which allow to predict the closed loop poles with a root locus technique.

1. Introduction
The current design of the space station is largely based on trusses, but it is quite likely that the future large space structures (LSS) will use large trusses connected by tension cables, to increase their global stiffness, in a way similar to that used to stiffen the airplanes in the early days of aeronautics. This concept of tension truss structure has already been used for large mesh antennas (a 10 m deployable mesh antenna was flown by the Russian in 1979); it has the advantages of being deployable, easily reconfigurable by changing the static tension in the cables and lending itself naturally to shape control [1,2].

The active damping of LSS has long been recognized as a major issue, for various reasons such as the interaction of the flexible modes with the attitude control system, the pointing requirements of various instruments mounted on the station, or simply to preserve the micro gravity environment. The active damping of truss structures has received a considerable attention for the past ten years or so, and effective solutions have been proposed [3,4]; active struts including piezoelectric actuators have been developed and control laws with guaranteed stability have been tested successfully [5].
The active damping of cable structures is more difficult, because cables and strings behave in a nonlinear manner and are prone to parametric excitation when the frequency of the supporting structure is close to twice the natural frequency of the cable. J.C. Chen [6] showed that the out-of-plane vibration of a string can be controlled by a positive use of the parametric excitation resulting from the longitudinal motion of the support at a frequency equal to twice the frequency of the transverse vibration of the string (stiffness control).

The damping of cable structures has also become a major issue in civil engineering, because the ever increasing span of the cable-stayed bridges [7] makes them more sensitive to wind and traffic induced vibrations as well as to flutter instability. The distinctive feature here is the presence of some sag in the vertical plane, resulting from the gravity loads (typical value of the sag to length ratio is 0.5%). The active damping of cable stayed bridges with an active tendon has been investigated by Fujino and coworkers [8,9]; the various strategies
investigated for damping the main structure and the in-plane and out of plane vibration of the cable are represented in Fig. 1. They demonstrated that the vertical global mode of the bridge can be damped with a linear feedback of the girder velocity on the active tendon displacement (Fig. 1.a); the in-plane (vertical) local cable vibration can be controlled very efficiently by sag induced forces (Fig. 1.b). Sag induced forces do not affect the out of plane local vibration of the cable, but the stiffness control discussed earlier can be applied (Fig. 1.c); however, experimental results [10] have shown that an instability can occur when the cable structure interaction is large, especially when the structure natural frequency is close to twice that of the cable, causing the time varying tension to resonate with the structure. Note that the following strategies use a non-collocated pair of sensor and actuator and are prone to spillover [11]. In a recent paper [12], the present authors have proposed an alternative control strategy with guaranteed stability; it will be reviewed in section 2. Section 3 will present some experimental results. Section 4 describes briefly an efficient modelling technique for cable-structure; it is applied to a truss with guy cables in section 5. Section 6 presents an approximate linear theory leading to a root locus technique for the closed loop poles prediction.

2. Control strategy

It is widely accepted that active damping of linear structures is much simplified if one uses collocated actuator and sensor pairs [13]; for such configurations, a wide class of controllers with guaranteed stability can be developed using positivity concepts [14].

For nonlinear structure, the use of collocated actuator-sensor pairs is still quite attractive, because there exist control schemes which are guaranteed to be energy absorbing, in the sense that the energy flows from the structure into the control system, at least if we assume perfect actuator and sensor dynamics; such control laws are asymptotically stable. One of them is the well known direct velocity feedback; less known is the dual situation where the actuator controls the relative position $u$ of two points inside the structure (e.g. piezoelectric linear actuator) and the collocated sensor output is the force $T$ in the active member (Fig. 2).

![Figure 2: Force feedback](image-url)
The power flow from the control system is

\[ W = -T \dot{u} \]  

and it is readily verified that the **positive Integral Force Feedback**

\[ u = g \int T \, dt \quad \Rightarrow \quad W = -g T^2 \quad (g > 0) \]  

produces an energy absorbing control. This control law was already applied to the active damping of a truss structure in [5], but it is quite remarkable that it is also applicable to nonlinear structures. All the states which are controllable and observable will be asymptotically stable. In order to appreciate what this means, consider the governing equations of the mass-spring system attached to a cable [8,12] (Fig.3); the governing equations are given by Equ.(3) to (6), where \( y_n \) and \( z_n \) refer to the modal amplitudes of the in-plane (vertical) and out-of-plane modes, respectively, \( u \) is the axial motion of the support and \( g \) that of the structure. The analytical form of the coefficients can be found in [8]; the physical meaning of the various terms is indicated in the equations. The fact that the in-plane natural frequency \( \omega_{in} \) is larger than the corresponding out-of-plane frequency \( \omega_{on} \) is due to the sag. We observe that the additional term in the equation of the spring-mass system is exactly the tension in the cable. In the cable equations, notice that the active sag induced force appears only in Equ.(4) governing the in-plane motion and only for the symmetric modes, because \( \alpha_n = 0 \) if \( n \) is even. On the contrary, the active stiffness variation affects all the modes. In Equ.(6), \( h_u \) is the static stiffness of the cable, we see that all the cable modes affect the tension in the cable with the quadratic term, corresponding to cable stretching, but only the in-plane modes of odd number have a linear influence on \( T \), because \( h_{in} = 0 \) if \( n \) is even.

From the foregoing equations, we can anticipate that the control algorithm will be effective for the global mode of the structure and the local in-plane symmetric modes of the cables which are linearly controllable and observable. For the in-plane non-symmetric modes and the out-of-plane modes of the cables which are observable only through their quadratic contribution to the cable stretching, and controllable only through the active stiffness variation, the control system is likely to be effective only for large amplitudes; its effectiveness will gradually reduce to zero as the vibration amplitude decreases. These observations have been confirmed by the experiment described below.

![Figure 3: Cable structure system](image-url)
Out-of-plane:

\[ m_n (\ddot{y}_n + 2\xi_n \omega_n y_n + \omega_n^2 y_n) + \sum_k \gamma_{nk} y_n (y_k^2 + z_k^2) + \sum_k 2\beta_{nk} y_n z_k - R_n q_n + R_n u_n = F_n \]  

In-plane:

\[ m_n (\ddot{z}_n + 2\xi_n \omega_n \dot{z}_n + \omega_n^2 z_n) + \sum_k \gamma_{nk} z_n (y_k^2 + z_k^2) + \sum_k 2\beta_{nk} z_n z_k - R_n q_n + R_n u_n \]

Structure:

\[ M (\ddot{q} + 2\xi_q \omega_q \dot{q} + \omega_q^2 q) + h_u q - h_u u - \sum_n h_{2n} (y_n^2 + z_n^2) - \sum_n h_n z_n = F_q \]

Cable tension:

\[ T = h_u u - h_u q + \sum_n h_{2n} (y_n^2 + z_n^2) + \sum_n h_n z_n \]
3. Experiment

Figure 4 shows the test structure adopted to represent the ideal situation of Fig.3; the cable is a 2m long stainless steel wire of 0.196 mm² cross section provided with additional lumped masses at regular intervals to achieve a sag to span ratio of 0.5% when the first in-plane natural frequency is $f_{z1} = 5.7$ Hz. The active tendon is materialized by a piezoelectric linear actuator acting on the support point with a lever arm to amplify the actuator displacement by a factor 3.4; this produces a maximum axial displacement of 150 µm for the moving support. A piezoelectric force sensor is colinear with the actuator; because of the high-pass behaviour of this type of sensor, it measures only the dynamic component of the tension in the cable. The controller is implemented digitally on a DSP board. The spring-mass system has an adjustable mass in order to tune its natural frequency; a shaker and an accelerometer are attached to it to evaluate the performances of the control system. In addition to that, a non-contact laser measurement system was developed, to measure the cable displacement.

![Figure 4 : Cable-structure system experimental set-up](image)

Experiments have been conducted with the cable alone and the cable structure system; they are described in more details in [12]. The effect of the control system on the structure is displayed in Fig. 5 and 6 when $f_{cable} = 8$ Hz, $f_{structure} = 12.6$ Hz, and the sag to span ratio $d/l = 0.21\%$. Figure 5 shows the frequency response function between the shaker and the accelerometer mounted on the structure; the free response of the structure from non-zero initial conditions is shown in Fig.6; we see that the control system brings a substantial amount of
damping in the system. As far as the cable modes are concerned, the out-of-plane modes and the anti-symmetric in-plane modes are not affected by the control system, except for large amplitudes where the cable stretching becomes significant; the amount of active damping brought into the symmetric in-plane modes depends very much of the sag to span ratio. The control system behaves nicely even at the parametric resonance, when the natural frequency of the structure is exactly twice that of the cable.

![Graph](image)

**Figure 5**: Experimental frequency response function between the shaker and the accelerometer, with and without control

![Graph](image)

**Figure 6**: Free response of the structure, with and without control
4. Modelling of cable structures

Consider the cable structure of Fig. 7, consisting of a linear structure (here a truss) with a number of nodes interconnected with cables. As an alternative to a general nonlinear finite element approach which would be extremely time consuming, especially for control system design purposes, we have developed a dedicated software which combines a finite element model of the linear structure with an analytical model of the cables in modal coordinates. This model is an extension of that of the cable connected to the spring-mass system of Equ.(3) to (6); the model of each cable is written in a local coordinate system as indicated in Fig. 7; the local x axis is taken along the chord line while the z axis is in the gravity plane (it is arbitrary in a zero-gravity environment).

The governing equations are given in Equ.(7) to (10); their development as well as the analytical expressions of the various constants will be given in a separate report [15]. The tension in the cable is identical to Equ.(6); it can be decomposed into a quasi-static contribution $T_q$ from the axial motion of the supports and a dynamic one resulting from the cable stretching and the sag. If we substitute Equ.(7) into Equ.(8), it becomes identical to Equ.(3), except for the additional term due to the seismic excitation produced by the transverse acceleration of the supports, $\ddot{u}_a$ and $\ddot{u}_b$, which was ignored in Equ.(3). In Equ.(9), there are two additional terms due to the sag: the sag induced stiffness $A_s$. $T_d$ has a linear and a quadratic contribution, the former is responsible for the increase of the natural frequency of the cable in the vertical plane $[\omega_s > \omega_n$ in

![Figure 7: Cable structure model](Image)
Cable $i$

Cable tension

\[ T^i = T^i_q + T^i_d = h^i_u(u_b^i - u_a^i) + \sum h^i_{1n}z_n^i + \sum h^i_{2n}(y_n^i + z_n^i)^2 \]

- $T^i_q$: Quasi-static tension
- $T^i_d$: Dynamic tension

Out-of-plane equation (mode $n$)

\[ m_n\left(\ddot{y}_n^i + 2\xi_n\omega_n\dot{y}_n^i + \omega_n^2 y_n^i\right) + S_n\left(T^i_q + T^i_d\right)y_n^i + \Gamma_n\left(\ddot{y}_a^i + (-1)^{n+1}\ddot{b}_a^i\right) = F_{yn}^i \]

In-plane equation (mode $n$)

\[ m_n\left(\ddot{z}_n^i + 2\xi_n\omega_n\dot{z}_n^i + \omega_n^2 z_n^i\right) + S_n\left(T^i_q + T^i_d\right)z_n^i + \Gamma_n\left(\ddot{z}_a^i + (-1)^{n+1}\ddot{b}_a^i\right) + \Lambda_n T_d^i + \Gamma_{z_n}^i(u_b^i - u_a^i) = F_{zn}^i \]

Structure

\[ M\ddot{x} + C\dot{x} + Kx = \sum_{i}^{\infty} P^i \left\{ T^i_q + T^i_d + \sum_{n} G_{yn}^i\dot{y}_n^i + G_{zn}^i\dot{z}_n^i \right\} + F_{ext} \]
Equ.(4)). The sag is also responsible for the inertia forces induced by the axial acceleration of the supports.

The structure equation (10) is written in the global system of coordinates; the left side is obtained from a standard finite element code; the sum in the right hand side represents the forces applied to the structure by the cables; it consists of the axial loads of the cable tension and the reaction forces due to the transverse vibration of the cable. The rotation matrix $P^i$ transforms the cable loads from the local to the global coordinate systems. The structure equation is further transformed into modal coordinates to reduce the number of degrees of freedom.

In Equ.(7) to (10), an active tendon control placed at one end of a cable (say $a$ in Fig.7) contributes to the quasi-static tension $T_q^i$ for $-h_{ii}^i u_{a}^i$ and also to the inertia forces $-\alpha_n^i \ddot{u}_{a}^i$ which affect only the in-plane modes of the cable. The term $T_q^i$ appears in all the equations and $h_{ii}^i ( u_{b}^i - u_{a}^i )$ is in fact the main contributor to the control of the structure, while $-\alpha_n^i ( \ddot{u}_{b}^i - \ddot{u}_{a}^i )$ is the main source of control for the in-plane modes of the cables.

Equ.(7) to (10) must be supplemented by the control algorithm; assuming that the active tendons are located at extremity $a$ of the cables, the control law for active damping is simply

$$u_{a}^i = \int_{0}^{t} T^i(\tau) d\tau$$

(11)

In order to avoid numerical saturation, it is slightly changed to introduce a forgetting factor and, to account for the finite stroke of the actuator, it is combined with a saturation unit.

Once the equations have been formulated, it is a simple matter to integrate the response of the closed loop system for any external perturbation and arbitrary initial conditions.

5. A truss with guy cables

As an example of application, consider the 12 bar truss with three guy cables of Fig.8; the truss alone was already considered in [5] where its active damping was achieved with two active struts located in the first bay starting from the bottom. Here, we investigate the possibility to control the system with three guy cables of 1 mm diameter attached to the truss as indicated on the figure and provided with an active tendon at their base, at a distance of 1 m from the truss; we assume no gravity, so that the cables behave like strings. Without control, the net effect of the cables is to stiffen the truss, raising its natural frequencies;
the control system affects both the natural frequencies and the damping of the modes. Fig.9 shows the evolution of the resonant peaks of the frequency response between a point force applied along the truss (A in Fig.8) and an accelerometer placed at the top, when the gain $g$ of the control law (11) is changed (the same gain is used for every active tendon). These results have been obtained by simulation, taking into account the physical data of the actuators, including their finite stroke.

We observe that, when the gain increases, the two resonant peaks drop very quickly, then move horizontally towards the lower frequency and then start to rise again at high gains, to become identical to the resonant peaks of the truss without guy cables. This behaviour is the consequence of the well known fact in automatic control that when we increase the gain, the closed loop poles start from the open loop poles and move towards the open loop zeros. Since the zeros are, by definition, the frequencies of the input (the voltage at the piezo) where the output (the cable tension) vanishes, the tension in the cable becomes equal to zero and the guyed truss behaves like the free one.
6. Approximate linear theory

In a situation like the one described in the previous section, the cables are extremely light and behave essentially like strings. If we assume that the interaction between the structure and the cable is restricted to the tension in the cable and if one neglects the cable dynamics, the governing equation is

\[ M \ddot{x} + Kx = -BT \]  \hspace{1cm} \text{(12)}

where \( K \) refers to the structure without guy cables, \( T \) is the vector of tension in the guy cables and \( B \) is the influence matrix. If we neglect the cable dynamics, the tension in the cables is given by,

\[ T = Kc \left( B^T x - \delta \right) \]  \hspace{1cm} \text{(13)}

where \( Kc \) is the stiffness matrix of the cables, \( Kc = \text{diag}(h_a) \), \( B^T x \) is the relative displacement of the extremity of the cables and \( \delta \) the active displacement of the tendons. Combining Equ.(12) and (13), we get

\[ M \ddot{x} + \left( K + BKc B^T \right)x = -BKc \delta \]  \hspace{1cm} \text{(14)}
which indicates that $K+BKcB^T$ is the stiffness matrix of the structure with guy cables. We assume that all the guy cables have the same control law with the same gain,

$$\delta = \frac{g}{s h_u} T$$

Combining with Equ. (13), we have

$$\delta = \frac{g}{s + g} B^T x$$

Substituting in Equ. (14), we obtain the closed loop equation

$$[Ms^2 + (K+BKcB^T) - \frac{g}{g+s} BKcB^T]x = 0$$

From this equation, it is readily observed that as $g \to \infty$, the dynamics of the closed loop system converges toward that of the structure without cables, as we observed in the numerical experiment of the previous section.

Let us project Equ. (17) on the normal modes $x = \Phi z$ of the structure with cables, assumed normalized according to $\Phi^T M \Phi = I$. If we denote $\Omega^2 = \Phi^T (K+BKcB^T) \Phi$, Equ. (17) becomes

$$[s^2 + \Omega^2 - \frac{g}{g+s} \Phi^T BKcB^T \Phi]z = 0$$

To derive a simple and powerful result about the way each mode evolves with $g$, let us assume that we can write

$$\Omega^2 = \Phi^T (K+BKcB^T) \Phi = \Phi^T K \Phi + \Phi^T BKcB^T \Phi$$

where the two matrices $\omega^2$ and $\nu^2$ are also diagonal. This hypothesis amounts to assuming that the mode shapes are little changed by the guy cables. In this case, $\omega^2 = \Phi^T K \Phi$ contains the square of the natural frequencies of the structure without cables. Substituting Equ.(19) into Equ. (18), we obtain a set of decoupled equations; the characteristic equation for mode $i$ is

$$s^2 + \omega_i^2 - \frac{g}{s + g} (\Omega_i^2 - \omega_i^2) = 0$$

or

$$s(s^2 + \Omega_i^2) + g(s^2 + \omega_i^2) = 0$$

(20)
This equation shows that the poles go from $\pm j\Omega_i$ for $g=0$ to $\pm j\omega_i$ for $g\to\infty$ (as we have already seen) and that, in between, they follow the root locus corresponding to the open loop transfer function

$$G(s) = g \frac{s^2 + \omega_i^2}{s(s^2 + \Omega_i^2)}$$

Figure 10: Comparison of the root locus with the numerical simulation

7. Conclusion

The first part of this paper presents a strategy for active damping of cable structures, using an active tendon collocated with a force sensor. The guaranteed stability has been confirmed by experimental results, even at the parametric resonance.

The second part of the paper describes an efficient modelling technique for cable structures; it is applied to a truss with guy cables and the numerical results are compared to linear predictions. Simple and powerful results are established, which allow to predict the closed loop poles with a root locus technique.
References


