ACTIVE TENDON CONTROL OF CABLE-STAYED BRIDGES: THEORY AND IMPLEMENTATION

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ABSTRACT

This paper presents a strategy for active damping of cable-stayed bridges, using active tendons. The first part of the paper summarizes the theoretical background: the control law is briefly presented together with the main results of an approximate linear theory, which allows to predict the closed-loop poles with a root locus technique. The second part of the paper reports on experimental results obtained with a 30m long cable-stayed bridge mock-up built on the reaction wall of the ELSA test facility at the JRC Ispra (Italy); this test structure is used to demonstrate the practical implementation of the control strategy with hydraulic actuators. Finally, some potential full-scale applications are identified, concerning temporary active systems for bridges under construction, and permanent systems for suspension bridges.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>u</td>
<td>actuator displacement</td>
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<tr>
<td>g_p</td>
<td>physical controller gain</td>
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<tr>
<td>g</td>
<td>reduced controller gain</td>
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<tr>
<td>T</td>
<td>dynamic tension in the active cable</td>
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<td>W</td>
<td>mechanical power</td>
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<td>K_c</td>
<td>active cable stiffness</td>
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<tr>
<td>s</td>
<td>Laplace variable</td>
</tr>
<tr>
<td>Ω_i</td>
<td>natural frequencies with active cables</td>
</tr>
<tr>
<td>ω_i</td>
<td>natural frequencies without active cables</td>
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<tr>
<td>ξ_i</td>
<td>modal damping ratio</td>
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1. INTRODUCTION

In recent years, cable structures have had spectacular applications in large cable-stayed bridges. However, cable and deck vibrations have become a major design issue, because the ever-increasing span of the bridges makes them more sensitive to flutter instability as well as to wind and traffic induced vibrations. The highly non-linear behaviour of cables with sag and the coupling between the cables and the bridge deck is a prominent feature of the problem; several cases of parametrically excited cable vibrations have been recorded on actual bridges [1]. An overview of the stay cable vibration and control is available in [2]. The difficulty of damping the stay cable vibration justifies the development of active devices for future large bridges. Several strategies have been proposed for the active tendon control of the global modes of a bridge, as well as for the in-plane and out-of-plane cable vibrations [3, 4, 5, 6, 7]; all of them use non-collocated actuator/sensor configurations. These strategies use different control algorithms for the various vibration modes, and they have been found to be prone to instability when the interaction between the cable and the structure is large. An alternative strategy has been proposed by the present authors [8, 9, 10], which is based on a displacement actuator (active tendon) collocated with a force sensor; this approach does not rely on a model of the system and enjoys guaranteed stability properties (assuming perfect actuator and sensor dynamics). This approach will be reviewed below. The active tendon control for flutter suppression was considered analytically in [11, 12] with non-collocated sensors placed on the bridge deck. As mentioned earlier, non-collocated actuator/sensor pairs are prone to spillover instability. The proposed strategy is also applicable to flutter control [13].

2. CONTROL STRATEGY

2.1 Control law

It is widely accepted that the active damping of linear structures is much simplified if one uses collocated actuator-sensor pairs [9, 14]; for nonlinear systems, this configuration is still quite attractive, because there exists control laws that are guaranteed to remove energy from the structure. The direct velocity feedback is an example of such "energy absorbing" control. When using a displacement actuator (active tendon) and a force sensor, the (positive) Integral Force Feedback

\[ u = g_p \int T \, dt \]  

also belongs to this class, because the power flow from the control system is \[ W = -T \dot{u} = -g_p T^2 \]. This control law
applies to nonlinear structures; all the states that are controllable and observable are asymptotically stable for any value of $g_p$ (infinite gain margin). The foregoing theoretical results have been confirmed experimentally with a laboratory-scale cable structure similar to that of Fig. 1(a) [9, 15]. Figure 1(b) shows the frequency response function (FRF) between a disturbance force and the acceleration measured on the structure, with and without control, together with the corresponding free response after an impulsive load.

### 2.2 Prediction of the closed-loop poles

If we assume that the dynamics of the active cables can be neglected and that their interaction with the structure is restricted to the tension in the cables, it is possible to develop an approximate linear theory of the closed-loop system. For a decentralized feedback control law

$$u = \frac{g}{s} K_c^{-1} T$$

(2)

where $T$ is the local force measurement, $u$ is the active tendon displacement, $K_c$ is the stiffness of the active cable ($K_c^{-1}T$ represents the elastic extension of the active cable) and $g$ is the control gain (the same for all control elements; note that for simplification reasons, $g$ is here a reduced gain, different from the physical gain $g_p$ in equation (1); it is normalized by the cable stiffness $K_c$, and has now the unit of a frequency). The following results have been established in earlier studies [9, 15] and are illustrated in Figure 2:

1. If we assume no structural damping, the open-loop zeros are $\pm j \omega_i$ where $\omega_i$ are the natural frequencies of the structure where the active cables have been removed.
2. The open-loop poles are $\pm j \Omega_i$ where $\Omega_i$ are the natural frequencies of the structure including the active cables.
3. As $g$ goes from 0 to $\infty$, the closed-loop poles follow the root locus corresponding to the open-loop transfer function:

$$1 + g \left( \frac{s^2 + \omega_i^2}{s (s^2 + \Omega_i^2)} \right) = 0$$

Figure 2: Root locus of the closed-loop poles
Thus, the closed-loop poles go from the open-loop poles at $\pm j\Omega$ for $g=0$ to the open-loop zeros at $\pm j\omega_i$ for $g \to \infty$.

The depth of the loop in the left half plane depends on the frequency difference $\Omega_i - \omega_i$ and the maximum damping, obtained for $g = \Omega_i \sqrt{\Omega_i / \omega_i}$, is

$$g_{\text{max}} = \frac{\Omega_i - \omega_i}{2\omega_i}$$

Equation (4) is used very conveniently in the design of actively controlled cable structures.

3. LARGE-SCALE EXPERIMENT

This section describes the large-scale cable-stayed bridge mock-up installed at the JRC Ispra, in the frame of the ACE project [16]. Main experimental results are presented hereunder. More details on the experimental campaign can be found in [17,18].

3.1 Hydraulic actuator

For cable-stayed bridges, the active tendon, placed at the anchorage of a stay-cable, must simultaneously sustain the high static load (up to 400t) and produce the dynamic load, which is at least one order of magnitude lower than the static one ($< \pm 10\%$). This has led to an active tendon design consisting of two cylinders working together: one cylinder pressurized by an accumulator compensates the static load, and a smaller double-rod cylinder drives the cable dynamically to achieve the control law. The two functions are integrated in a single cylinder, as illustrated in Fig. 3; the double-rod part of the cylinder is achieved by a rod-in-rod design; this solution saves hydraulic energy and reduces the size of the hydraulic components. The double rod part of the cylinder is position controlled; the long-term changes of the static loads as well as the temperature differences require adaptation of the hydraulic conditions of the accumulator. The actuators used in this project were designed and manufactured by Mannesmann Rexroth (currently Rexroth Bosch) in collaboration with the Technical University of Dresden.
3.2 Mock-up

The mock-up (Fig.4) was designed and manufactured by Bouygues in the framework of the ACE project; it has been installed on the reaction wall of the ELSA facility at the Joint Research Center in Ispra. It consists of a cantilever beam (l=30m) supported by 8 stay-cables (d=13mm); the stay cables are provided with additional masses to achieve a representative sag-to-length ratio (the overall mass per unit length is 15kg/m). An intermediate support can also be placed along the deck to tune the first global mode and the cable frequencies. Because of the actuator dynamics and the presence of static load, the implementation of the control requires some alterations from Eq. (1):

(i) A high-pass filter must be included after the force sensor to eliminate the static load in the active cables.

(ii) In hydraulics, the flow rate is directly related to the valve position which is the control element; it is therefore more natural to control the velocity than the position. On the other hand, the control law (1) involves an integral controller producing the control input, which is the actuator displacement; it is equivalent to use a proportional controller and a velocity input. The actual implementation of the control is shown in Fig.5. The overall controller includes a high-pass filter with a corner frequency at 0.1Hz (to eliminate the static load), an integrator (1/s) and a low-pass filter with corner at 20Hz, to eliminate the internal resonance of the hydraulic actuator. The overall FRF (uÆT) of the active control device is represented in Fig.6. The dotted line refers to the digital controller alone (between 1 and 3 in Fig.4), while the full line includes the actuator dynamics (between 1 and 2 in Fig.5). Notice that (i) the controller behaviour follows closely a pure integrator in the frequency range of interest (0.5Hz - 2Hz) and (ii) the actuator dynamics introduces a significant phase lag above the dominant modes of the bridge.

3.3. Experimental results

Figure 7 shows the open-loop FRF seen from one of the active tendons (T/u; between 2 and 4 in Fig.5); we recognize the alternating poles and zeros, typical of collocated actuator/sensor pairs [14]. The instantaneous frequency of the input signal is also indicated on the time axis, to allow the identification of the main contributions to the response. Figure 9 shows the FRF between the proof-mass absolute velocity and the bridge deck displacement for the same values of the gain. One sees that the active tendon control brings a substantial reduction in the vibration amplitude, especially for the first global bending mode.
of 50s). The figure also displays the time response (on the plane parallel to the time axis) and the Fourier spectrum (on the plane parallel to the frequency axis). The volume under the surface represents the total amount of energy in the signal; one sees that the bursts of vibrational energy which appear as the frequency of the sweep sine is tuned with the natural frequencies of the structure are eliminated by the active damping.

Figure 9: FRF between the proof-mass absolute velocity and the bridge deck displacement, for various values of the gain

Using a band-limited white noise excitation and a specially developed identification technique based on the spectral moments of the power spectral density of the bridge response, M. Auperin [21] succeeded in isolating the first global mode of the bridge. Figure 11 compares the experimental root-locus with the predictions of the linear approximation; the agreement is surprisingly good, especially if one thinks of the simplifying assumptions leading to Eq.(3). The marks on the experimental and theoretical curves indicate the fraction of optimum gain $g/g^*$, where $g^*$ corresponds to the largest modal damping ratio.

4. POTENTIAL APPLICATIONS

Theoretical computations have been carried out on realistic civil engineering structures, in order to demonstrate the efficiency of the system [22]. These predictions are based on Eq.(4).

The first application concerns the cable-stayed bridge over the Tarn Valley in Millau (France). According to the construction procedure, the tall pylons are erected first and the cantilever deck is constructed as shown in Fig. 12 until the various parts are connected together. This configuration is the most critical from the wind response, and it is suggested to use an active control system during the construction stage. It consists of six active cables, each composed of 31 T13 steel strands (d=13mm) (Fig. 12). The table inserted in Fig. 12 gives the damping ratios that could be expected from such a control system.
The second application considers the use of active stay-cables for active damping of a suspended bridge. The one considered in the example has a main span of 850m; the main cable is equivalent to 1000 T13 strands. 8 active stay-cables (each composed of 31 T13 strands) are added to the original design (2 per side and per pylon), as shown in Fig. 13. As indicated in the table inset, this configuration would lead to structural damping between 5 and 14% for the first 5 modes.

Figure 12: Active damping of a tower of the Millau Bridge (France) during the final stage of the construction (artist view)

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Figure 13: Active damping of the Askoy suspension bridge

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\xi$ (%)</th>
</tr>
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<tbody>
<tr>
<td>1 long</td>
<td>11</td>
</tr>
<tr>
<td>1 transv</td>
<td>4</td>
</tr>
<tr>
<td>1 torsion</td>
<td>2.7</td>
</tr>
<tr>
<td>2 transv</td>
<td>0.2</td>
</tr>
<tr>
<td>2 long</td>
<td>1.4</td>
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</table>

Figure 11: Comparison of experimental and analytical root-locus of the first bending mode.

5. CONCLUSION

A strategy for active damping of cable-stayed bridges with active tendons has been developed and tested. The control architecture is decentralized and uses collocated actuator/sensor pairs; the local force feedback has guaranteed stability. An approximate linear theory has been developed to assist in active tendon placement and in predicting the system performances. Large-scale experiments have been performed on a mock-up equipped with hydraulic actuators in the framework of a collaborative research effort sponsored by the European Union; these tests have confirmed the efficacy of the proposed approach and helped to identify technological issues. Potential full-scale civil engineering applications have been identified, where active cables could be very effective to damp the structure.

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