Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 453–458

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Experimental data based cable tension identification via nonlinear static inverse problem

Arnaud Pacitti[a,*], Michaël Peigney[b], Frédéric Bourquin[c], Walter Lacarbonara[d]

[a] CEREMA Sud-Ouest, Département Laboratoire de Bordeaux, Bordeaux 33000, France
[b] Université Paris-Est, Laboratoire Navier (UMR 8205), CNRS, École des Ponts ParisTech, IFSTTAR, F-77455 Marne-la-Vallée, France
[c] Université Paris-Est, COSYS, IFSTTAR, F-77447 Marne-la-Vallée, France
[d] Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Rome 00184, Italy

Abstract

This work proposes a new cable tension identification technique based on a static inverse method that, by coupling a universal cable model with displacement and strain sensors data, exploits the differences between the original cable equilibrium problem and that of the cable loaded by a suitable added mass. The formulated inverse problem thus defines a data misfit functional based on the differences in terms of transverse displacements and elongations between the two equilibrium configurations. The inverse problem is implemented in a two-step identification procedure. First, the axial stiffness and mass per unit length are kept constant and the length of the cable is approximately found via a simple line search algorithm using finite differences to estimate the functional derivatives. Second, the other physical parameters are assessed using an adjoint method for which the direct problem, the adjoint problem and the parameters sensitivities are found as derivatives of a Lagrangian functional with respect to dual variables, primary variables, and parameters, respectively. Due to the ill-conditioning nature of the problem, the proposed method does not allow an exact parameter identification but it does lead to an acceptable tension assessment. An experimental test campaign conducted on a multilayered stranded cable 21 m long and 22 mm in diameter subject to several tension levels confirms the relevance and operational feasibility of the proposed inverse method.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: cable, mixed formulation, inverse problem, tension identification

1 Introduction

Tension identification of cables has been widely studied over the years due to its key role in structural health monitoring. When no permanent monitoring system is installed on a bridge, three main methods exist for tension assessment: the use of jacks, the use of tensiometers and dynamical testing. Using jacks on a job site is costly and more likely to happen during a repair or an important maintenance operation (suspenders or anchorage replacements, suspension tuning operation...) for which an accurate tension assessment is not usually necessary. The tensiometer can be of great use for tension identification of small cables and ropes but is dependent on the cable type and has

* Corresponding author. Tel.: +33 5 56 70 63 15 ; fax: +33 5 56 70 63 33.
E-mail address: arnaud.pacitti@cerema.fr

1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.013

to be carefully calibrated in the laboratory. Last but certainly not least, because of its easy application and low cost, dynamical testing for tension assessment has been extensively treated in the literature and used on sufficiently long cables. Despite the great differences between all the established methods in the way this relationship is found and used, they all rely on the combination of three parts: a cable model, some sensors and a post-treatment to obtain the natural frequencies of the cable. It is possible to embrace the variety of combinations looking at the following well-known references: [1], [2], [3], [4], [5]. A brief overview of dynamical testing for tension assessment is given in [6] where the reliability of the methods for cables longer than 19 m was confirmed. For shorter cables, physical uncertainties due to unknown boundary conditions or cable parameters (e.g., length or flexural stiffness) have set the tension assessment issue in terms of identification and inverse problems using the dynamics of tensed (and straight) beam as in [7], [8], [9].

To the authors knowledge, very few works considered the mass per unit length as an unknown of the problem. In practice, however, its value is likely to be known with an uncertainty around 5 to 10%. In the case of dynamical testing using the string theory, there is a direct consequence of this uncertainty on the tension identification precision.

In the present work, an inverse problem is formulated thanks to a data misfit functional based on the differences in terms of vertical displacements and axial elongations between two equilibrium states of the cable, namely, one loaded and the other free. It allows to find the tension in a cable without knowing precisely and *a priori* its physical parameters, namely its (stress-free) length L, its mass per unit length and its axial stiffness. The tension is expressed in terms of its corresponding safety factor $\gamma = Af_y/\breve{N}_{max}$, where f_y is the yield stress of the cable, A its cross-section area and $\breve{N}_{max}$ is the maximum value of the tension in the cable. All simulations were conducted in a Python environment embedded in the finite element plateform FEniCS [10].

2 Cable model: primal and mixed formulations of the direct problem

We briefly present the cable nonlinear mixed formulation used for tension assessment. More theoretical and implementation details can be found in [11]. The stress-free configuration $\mathbf{B}^0$ and the current configuration $\breve{\mathbf{B}}$ are described in the Newtonian basis $\{\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3\}$ with origin O. $\mathbf{B}^0$ is described by a curve $\mathbf{C}^0 = \{\boldsymbol{r}^0,\ s \in [0, L]\}$ parameterized by its arclength s whose length is L. Similarly, quantities $\breve{\mathbf{C}}$, $\breve{s}$, $\breve{\boldsymbol{r}}$ and $\breve{L}$ are defined for the current configuration $\breve{\mathbf{B}}$.

We define a space of smooth enough displacement fields H^1 over $[0, L]$ and the two spaces $\mathbb{V} = \{\breve{\boldsymbol{r}} \in H^1 |\ \breve{\boldsymbol{r}}(0) = \boldsymbol{o}$ and $\breve{\boldsymbol{r}}(L) = L_1\boldsymbol{e}_1 + L_2\boldsymbol{e}_2 + L_3\boldsymbol{e}_3\}$ and $\mathbb{V}_0 = \{\delta\breve{\boldsymbol{r}} \in H^1 |\ \delta\breve{\boldsymbol{r}}(0) = \boldsymbol{o}$ and $\delta\breve{\boldsymbol{r}}(L) = \boldsymbol{o}\}$. The problem is formulated as follows:

$$\begin{aligned}
&\text{Find } \breve{\boldsymbol{r}} \in \mathbb{V} \text{ such as for every } \delta\breve{\boldsymbol{r}} \in \mathbb{V}_0 \\
&\int_0^L (\breve{\boldsymbol{n}} \cdot \delta\breve{\boldsymbol{r}}_s)\ ds - \int_0^L \left(\breve{\boldsymbol{f}} \cdot \delta\breve{\boldsymbol{r}}\right)\ ds - [\breve{\boldsymbol{n}} \cdot \delta\breve{\boldsymbol{r}}]_0^L = 0, \\
&\breve{\boldsymbol{n}} = EA\breve{\Delta}\ \breve{\boldsymbol{r}}_s \text{ for } s \in [0, L].
\end{aligned}$$

where the subscript s denotes differentiation with respect to s, the strain according to the Green-Lagrange measure is $\breve{\Delta} = \frac{1}{2}\left(\breve{\boldsymbol{r}}_s \cdot \breve{\boldsymbol{r}}_s - 1\right)$ and EA is the axial stiffness of the cable. This problem is a nonlinear minimization problem:

$$\text{Find } \breve{\boldsymbol{r}} \in \mathbb{V} \text{ minimizing } J(\breve{\boldsymbol{r}}) = \int_0^L \left(\tfrac{1}{2}EA\breve{\Delta}^2 - \breve{\boldsymbol{r}} \cdot \breve{\boldsymbol{f}}\right)\ ds \tag{1}$$

It can be completely solved thanks to the displacement only formulation given above. It is however interesting for data assimilation purposes to introduce the strain as an unknown imposing its definition as a constraint and by letting $\breve{T}$ be the associated Lagrange multiplier. Thus, the problem (1) reads:

$$\begin{aligned}
&\text{Find } \breve{\boldsymbol{r}} \in \mathbb{V}, \breve{\Delta} \in \mathbb{P}_\Delta \text{ and } \breve{T} \in \mathbb{P}_T \text{ such as} \\
&J(\breve{\boldsymbol{r}}, \breve{\Delta}, \breve{T}) = \int_0^L \left[\tfrac{1}{2}EA\breve{\Delta}^2 - \breve{\boldsymbol{r}} \cdot \breve{\boldsymbol{f}} - \breve{T}\left(\breve{\Delta} - \breve{\Delta}^e\right)\right]\ ds \qquad (2) \\
&\text{is a saddle point and } \breve{\Delta}^e := \frac{1}{2}\left(\breve{\boldsymbol{r}}_s \cdot \breve{\boldsymbol{r}}_s - 1\right)
\end{aligned}$$