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Fabien Treyssede

► **To cite this version:**

Fabien Treyssede. Veering of dispersion curves and prestress effects in multi-wire helical waveguides. 9th GDR Conference on Wave Propagation in Complex Media for Quantitative and Non Destructive Evaluation, Dec 2015, AUSSOIS, France. 3p. hal-01346169v2

HAL Id: hal-01346169

<https://hal.science/hal-01346169v2>

Submitted on 10 Feb 2017

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Veering of dispersion curves and prestress effects in multi-wire helical waveguides

Fabien Treyssède

Abstract Guided wave based methods are of potential interest for the non destructive evaluation of cables. However, the understanding of mechanisms governing the propagation of guided waves is particularly complicated owing to the helical and multi-wire structure of strands, the basic elements constituting cables. The complexity of the problem is further increased by the effect of high tensioning forces applied on cables. A typical dispersion curve veering phenomenon, sensitive to the applied loads, occurs in seven-wire strands, a common type of strands in modern constructions. The main goal of this paper is to highlight the origin of this phenomenon.



1 Introduction

Based on a semi-analytical finite element (SAFE) method, recent progress has been made in the modeling of wave propagation in seven-wire strands [1, 2]. Nevertheless, some works are still required. A typical dispersion curve veering phenomenon occurs for the fundamental longitudinal mode. This phenomenon, sometimes referred to as *notch frequency*, has been observed both experimentally [3] and numerically [1] but its origin is still unexplained. Besides, the notch frequency significantly increases with applied loads. This increase turns out to be essentially caused by interwire contact effects, as shown by numerical tests [2]. However, the convergence of numerical results has to be assessed. In particular, further works are needed to quantitatively check the modeling of contact with reference solutions.

IFSTTAR, GERS, GeoEND, F-44340 Bouguenais, France, e-mail: fabien.treysse@ifsttar.fr

2 Numerical method

SAFE modeling of helical waveguides under prestress. The application of a SAFE method consists in assuming an axial harmonic dependence of acoustic fields before finite element discretization, so that only the cross-section needs to be meshed. With this technique, the axial variables must be separable. For helical strands, this separation is possible with a specific curvilinear coordinate system, called twisting coordinate system [1, 4], which has constant non zero torsion but zero curvature. In order to account for prestress effects, one starts from the so-called linearized updated Lagrangian formulation of non-linear mechanics (see for instance Ref. [5]). This formulation is here extended to twisting coordinates and adapted to a SAFE formulation. The SAFE method finally leads to the following kind of eigensystem, characterizing the elastic guided modes in prestressed strands:

$$\{\mathbf{K}_1 - \omega^2 \mathbf{M} + ik(\mathbf{K}_2 - \mathbf{K}_2^T) + k^2 \mathbf{K}_3\} \mathbf{U} = \mathbf{0}, \quad (1)$$

The matrices \mathbf{K}_i ($i=1,2,3$) include geometric stiffness terms related to the Cauchy prestress of the static state. Further details can be found in Refs. [2].

Static contact modeling. The first step of the analysis is to compute the static prestress state. One starts from the homogenization method described in Ref. [6]. In this paper, an iterative procedure is used to properly account for contact, based on a node-to-node procedure together with a direct elimination method [7]. As the axial load is incremented, contact pairs of nodes are formed on both sides of the initial point-to-point interwire contact zone, until the prescribed axial strain ε is reached.

3 Results

Notch frequency phenomenon and interwire contact effects. The cross-section of the seven-wire strand (steel) is meshed with six-node triangles and refined at contact regions. Based on the static model, the contact half-width is computed as a function of the normal contact force up to the prescribed axial strain $\varepsilon=0.6\%$. Good agreement is found with Hertz analytical solution for parallel cylinders (results not shown for paper conciseness). Based on the SAFE model, Figure 1a shows the notch frequency phenomenon of the fundamental longitudinal mode, usually denoted as $L(0,1)$. The notch frequency increases from 0.32 (62Hz) in the unloaded case to 0.42 (82Hz) in the loaded case. These values are in agreement with the experiments of Refs. [3, 8]. The notch frequency corresponds to a curve veering phenomenon between the dispersion curves of two distinct longitudinal-like wave modes [1], labeled as $L(0,1)a$ and $L(0,1)b$. As recalled in Sec. 1, its increase is indeed mainly due to the increase of interwire contact width rather than prestress itself [2]. In order to briefly assess convergence, Fig. 1a also gives results with a refined mesh (46893 dofs): changes are negligible for the loaded case, thus indicating a good accuracy

with the initial mesh. Convergence can yet hardly be achieved for the unloaded case, somehow purely theoretical, because the contact width tends to zero.

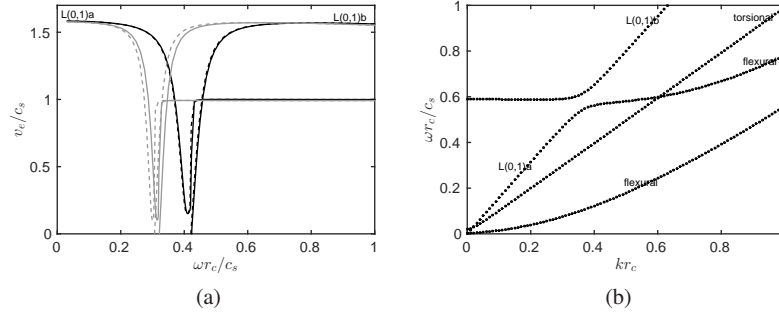


Fig. 1: (a) Curve veering for $\varepsilon=0\%$ (gray) and for $\varepsilon=0.6\%$ (black), continuous lines: initial mesh (12369 dofs), dashed lines: refined mesh (46893 dofs). (b) Dispersion curves in the (k, ω) plane for the uncoupled blocked peripheral wire.

The uncoupled peripheral wire. Following the analysis of Ref. [9], curve veering phenomena usually occur in a weakly coupled system and may be predicted from the uncoupled system. Let us consider an uncoupled peripheral wire, radially blocked along its contact width. Blocking the radial displacement in such a narrow region completely breaks the circular symmetry of the wire and, as opposed to the free cylinder case, the compressional, flexural and torsional motions get fully coupled. A curve veering actually occurs, in a very similar fashion as for the fully coupled strand. This veering is due to the coupling between two modes, one of longitudinal type and the other of flexural type, as shown in the (k, ω) plane by Fig. 1b. It can be inferred that the origin of the notch frequency inside seven-wire strands lies in the radial displacement constraint imposed on peripheral wires by the central one.

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