

Introduction

DAS-seismic technology has received careful scrutiny in recent years (Mestayer et al., 2011; Mateeva et al., 2014), driven by its promise for enabling a range of cost-effective applications such as deep water 4D VSP monitoring (Mateeva et al., 2013). Reports on applications in walkaway VSP configurations for monitoring of CO₂ injection and storage (Daley et al., 2013) and in the context of sensitive processing such as ambient noise correlation and interferometry (Ajo-Franklin et al., 2015) have been largely positive, though reduced sensitivity and signal-to-noise ratios relative to clamped geophones appear to have been a key limiting issue. Parker et al. (2014) reports laboratory results in which responses from fibre correlate closely with the acoustic field illuminating the fibre (Parker et al., 2014), and the most recent field tests on deep water DAS monitoring remain positive, suggesting that driving the costs even lower is the main current challenge (Chalenski et al., 2016). Perhaps the main technical challenge is that DAS fibre exhibits strong directionality arising from its insensitivity to strain which is not tangential to the fibre; this is referred to as the *broadside (in)sensitivity* issue. Alteration of fibre geometry exposes it to a greater cross-section of seismic strains (Mateeva et al., 2014; Kuvshinov, 2016), and is a natural way to mitigate the insensitivity issue. To further progress this line of research, we introduce a geometrical parameterization of a helical-wound fibre encased in a cable whose axis itself may also be arbitrarily curved, e.g., itself a helix. Within this model a range of applications are straightforward, two of which are: (1) generalization of the directionality rules for a broadside elastic wave (e.g., the $\cos^2 \theta$ strain rule for an incident P-wave), and (2) robust estimation of multicomponent elastic signals along the fibre, i.e., the full strain tensor in the inline-crossline-depth (ICD) coordinate system. In this paper we focus on application (1); application (2) will be reported on in a separate communication.

Geometry of a fibre wound helically about an arbitrarily-curved cable axis

Let the position vector $\mathbf{f}$ represent a point on a DAS fibre. Further, let

$$\mathbf{f} = \mathbf{c} + \mathbf{h}, \quad (1)$$

where $\mathbf{c}$ is the point nearest to $\mathbf{f}$ on the axis of the cable and $\mathbf{h}$ is a vector in the plane perpendicular to the axis (see Figure 1a). Let us express this vector in a field/lab coordinate system involving inline (x_1), crossline (x_2), and depth (x_3) axes (which we will refer to as ICD), with the set of unit vectors $\{\hat{\mathbf{1}}, \hat{\mathbf{2}}, \hat{\mathbf{3}}\}$. We will parameterize the curve representing the cable axis in two ways:

$$\mathbf{c} = \begin{bmatrix} c_1(s') \\ c_2(s') \\ c_3(s') \end{bmatrix} = \begin{bmatrix} x \\ c_2(x) \\ c_3(x) \end{bmatrix}, \quad (2)$$

where the first parameterization involves s' , the arc-length along the axis, and the second involves letting the inline coordinate act as the independent variable $x = c_1$. To transform back and forth between them we use the formula

$$s'(x) = \int_0^x dx' \left[\frac{d\mathbf{c}}{dx'} \cdot \frac{d\mathbf{c}}{dx'} \right]^{1/2} = \int_0^x dx' \left[1 + \left(\frac{dc_2}{dx'} \right)^2 + \left(\frac{dc_3}{dx'} \right)^2 \right]^{1/2}. \quad (3)$$

In the arc-length parameterization we next define an s' -dependent coordinate system defined by the cable axis tangent $\hat{\mathbf{t}}(s')$, and the associated principle normal $\hat{\mathbf{n}}(s')$, and binormal $\hat{\mathbf{b}}(s')$:

$$\hat{\mathbf{t}}(s') = \frac{d\mathbf{c}}{ds'}, \quad \hat{\mathbf{n}}(s') = \frac{\mathbf{n}(s')}{|\mathbf{n}(s')|}, \quad \text{where } \mathbf{n}(s') = \frac{d\hat{\mathbf{t}}(s')}{ds'}, \quad \text{and } \hat{\mathbf{b}}(s') = \hat{\mathbf{t}}(s') \times \hat{\mathbf{n}}(s'). \quad (4)$$

Using these cable axis quantities we may next parameterize the helix component. If the cable axis is set to coincide with the inline axis $s' = c_1$, a helix of radius r and lead angle γ winding about this axis can be written

$$\begin{bmatrix} s' \\ r \cos s'/v \\ r \sin s'/v \end{bmatrix} = \begin{bmatrix} s' \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ r \cos s'/v \\ r \sin s'/v \end{bmatrix} = \mathbf{c} + \mathbf{h}, \quad (5)$$

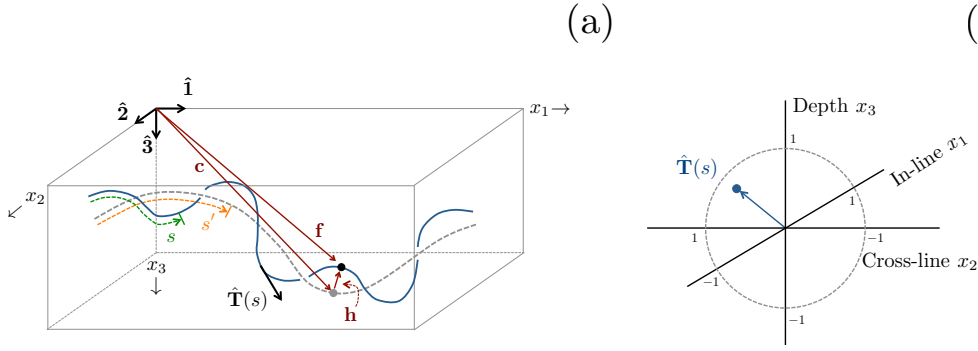


Figure 1 (a) Helical fibre/curved cable axis geometry. (b) Tangents plotted as points in the ICD system.

where $v(\gamma) = r \tan \gamma$. On the right hand side of equation (5) the curve has been decomposed into its **c** and **h** parts. Replacing **c** with the general cable axis in (2), and using the fact that this special form for **h** is maintained at any given s' in the coordinate system in (4), in the ICD system we have

$$\begin{bmatrix} f_1(s') \\ f_2(s') \\ f_3(s') \end{bmatrix} = \begin{bmatrix} c_1(s') \\ c_2(s') \\ c_3(s') \end{bmatrix} + \begin{bmatrix} \hat{\mathbf{1}} \cdot \hat{\mathbf{t}}(s') & \hat{\mathbf{1}} \cdot \hat{\mathbf{n}}(s') & \hat{\mathbf{1}} \cdot \hat{\mathbf{b}}(s') \\ \hat{\mathbf{2}} \cdot \hat{\mathbf{t}}(s') & \hat{\mathbf{2}} \cdot \hat{\mathbf{n}}(s') & \hat{\mathbf{2}} \cdot \hat{\mathbf{b}}(s') \\ \hat{\mathbf{3}} \cdot \hat{\mathbf{t}}(s') & \hat{\mathbf{3}} \cdot \hat{\mathbf{n}}(s') & \hat{\mathbf{3}} \cdot \hat{\mathbf{b}}(s') \end{bmatrix} \begin{bmatrix} 0 \\ r \cos s'/v(\gamma) \\ r \sin s'/v(\gamma) \end{bmatrix}. \quad (6)$$

Finally, the arc-length s along the fibre itself, and the tangent to the fibre, can be computed using

$$s'(s) = \left[1 + \frac{r^2}{v^2} \right]^{1/2} s, \quad \text{and} \quad \hat{\mathbf{T}}(s) = \frac{d\mathbf{f}}{ds} \quad (7)$$

respectively. The quantities s and $\hat{\mathbf{T}}(s)$ are the most important outputs of the model: the signal returning to the DAS interrogator is sensitive to the $\hat{\mathbf{T}}(s)$ component of normal strain a distance s along the arc of the fibre. The previous quantities permit this distance to be connected to position in the ICD system.

***n*-helices and tangents**

Given as input the cable geometry in equation (2) and r and γ , equations (6)–(7) characterize a general helical-wound fibre. Many different possible types of cable axis curvature may be useful, but we will now focus on a special type, an “ n -helix”, which has the a priori positive features of being highly regular, and realizable with existing hardware. Let us define an n -helix in the following way. A 0-helix is a straight line. If a helix is wrapped around this straight line, i.e., if the 0-helix is used as the axis of a new helix, the result is a 1-helix. If we follow the curve of the 1-helix along, and everywhere treat it as the axis of a new helix (or, equivalently, wrap a 1-helix around a new axis), a 2-helix results. If this is continued n times, an n -helix results. (A standard helical-wound fibre would therefore be an example of a 1-helix, and by wrapping such a cable around a cylinder, a 2-helix would result.) The model above can be applied iteratively to create any n -helix desired.

The possible benefit of a 2-helix fibre system is illustrated in Figure 2. In the top row are exaggerated examples of fibres wrapped into 0-, 1- and 2-helix configurations, which are input into the model in the previous section so that their tangents may be tabulated. In Figure 1 we illustrate a tangent point by drawing a dot on the unit sphere in the ICD system. The tangents “explored” by a curved fibre can be plotted on this sphere; the more of the surface of the sphere occupied by dots, the better, because this is indicative of a greater range of strain components that will be sensed by the fibre. The tangents belonging to the 0-, 1- and 2-helices are plotted in the bottom row. The single point produce by the straight fibre is significantly improved upon by the helical wound fibre, which explores a circle on the unit sphere. The jump to a 2-helix produces a striking increase in the tangent coverage, describing the unit sphere almost entirely.

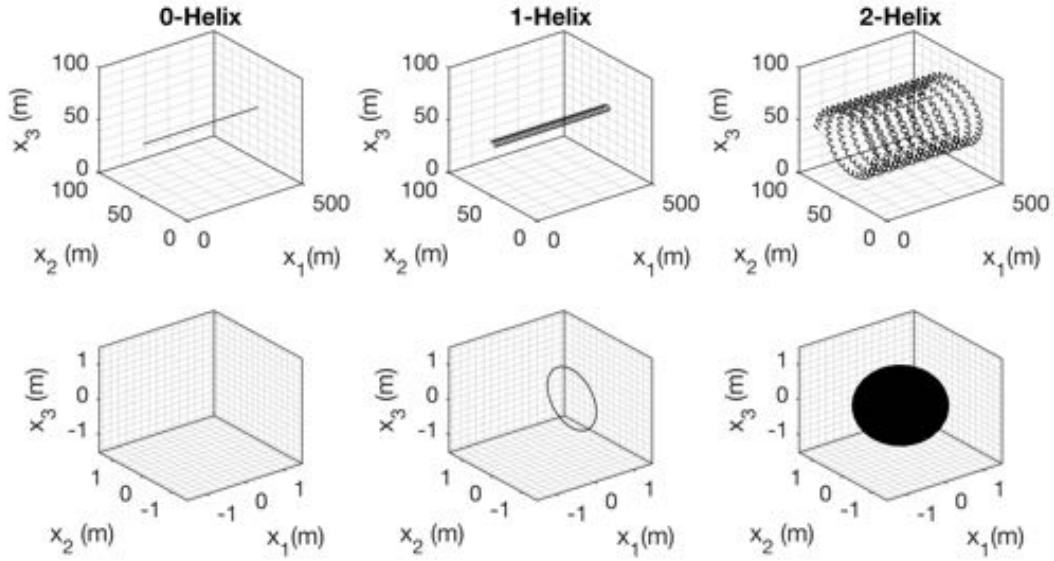


Figure 2 Tangents explored by fibres wrapped into 0-, 1-, and 2-helices.

Broadside P-wave sensitivity of 0-helix, 1-helix and 2-helix fibres

In a separate communication, the use of longitudinal strain measurements, from a fibre wrapped into a 2-helix, to compute local estimates of the tensor strain will be discussed. Here let us examine consequences to the $\cos^2 \theta$ broadside sensitivity rule for straight fibres (Mateeva et al., 2014; Kuvshinov, 2016) when the fibres are wrapped into n -helices. If a P-wave propagating in the direction $\hat{\mathbf{r}}(s)$ impinges onto a fibre a distance s along its length, the projection of the strain of the wave onto the fibre is

$$[\text{fibre strain}] = (\hat{\mathbf{T}}(s) \cdot \hat{\mathbf{r}}(s)) [\text{P-wave strain}] (\hat{\mathbf{T}}(s) \cdot \hat{\mathbf{r}}(s)), \quad (8)$$

which produces the $\cos^2 \theta$ rule for a fixed tangent and a P-wave source placed broadside. In the case of an n -helix, or any curved fibre, for which the model produces an s dependent tangent, the generalization is immediate. In Figure 3 the broadside P-wave response is plotted for examples of 0-helix, 1-helix and 2-helix fibres similar to those in Figure 2. The fibres are plotted in the top row, with a red circle representing the P-wave source point. The second row contains plots of the normalized P-wave strain as a function of incident angle θ . The standard $\cos^2 \theta$ rule is in evidence in all three examples, because the geometry of the fibre has been contained in $\theta(s)$, which obeys $\cos \theta(s) = \hat{\mathbf{T}}(s) \cdot \hat{\mathbf{r}}(s)$. The complexity of the fibre is visible in the irregular manner in which $\theta(s)$ is sampled. More importantly, the bottom row contains plots of the normalized strain as a function of the inline (broadside) coordinate x_1 . In the case of a straight fibre (the 0-helix on the left) the standard broadside insensitivity for low values of x_1 is visible. The 1-helix in the centre panels (i.e., the standard helical wound fibre) significantly increases broadside sensitivity, and a further significant up-tick occurs in the 2-helix case. In the latter example, a periodic, high-sensitivity sampling of the P-wave strain is seen to stably cross the broadside positions (remembering however that these are exaggerated curve shapes).

Conclusions

Optimizing the curvature of DAS fibre systems as they are arrayed in the field, in order to increase signal to noise ratios, and enable estimation of complete multicomponent elastic information, appears to be a ripe area for acquisition research. The greater the complexity of curvature employed the higher the bar is for accounting for the position and orientation of all fibre intervals, but with some care in parameterization, and especially if the curve is highly regular this should not prove insurmountable. The curves we refer to as n -helices have sufficient regularity, broad sampling of tangents, and consistency with available hardware seem particularly promising. In particular, going from a 1-helix configuration (i.e., a standard helical-wound fibre) to a 2-helix (the standard helical-wound fibre wrapped around a

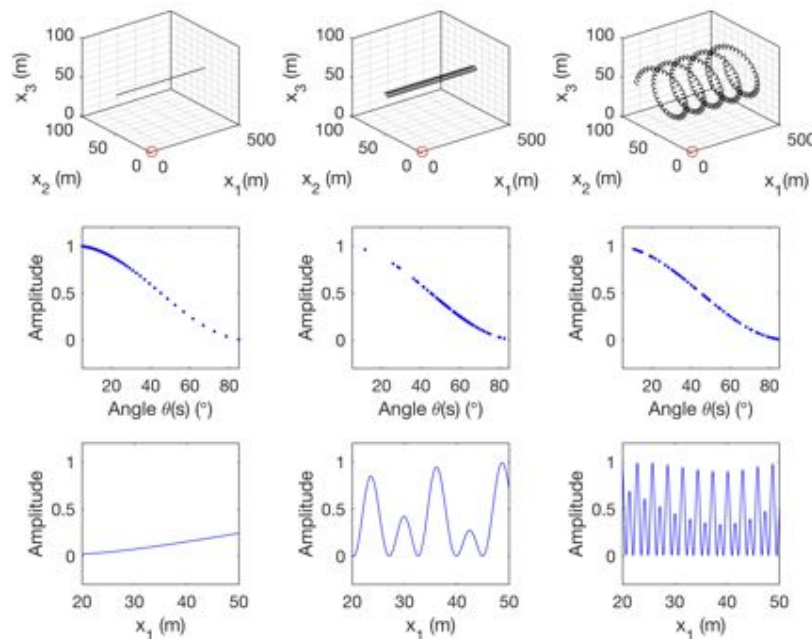


Figure 3 Broadside sensitivities of fibres wrapped into 0-, 1-, and 2-helices.

further cylinder, e.g., a pipe or well bore) appears from a geometrical viewpoint to be capable of greatly enriching the components of strain visible to the system.

Acknowledgements

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