Estimation of helical fiber pitch angle and trace spacing from co-located DAS, accelerometer, and geophone datasets

Kevin W. Hall[,1], Don C. Lawton[1,2], and Kristopher A. Innanen[1]*
[1]CREWES (Consortium for Research in Elastic Wave Exploration Seismology), University of Calgary
[2]CaMI (Containment and Monitoring Institute), Carbon Management Canada

Summary

Distributed acoustic sensing (DAS) data recorded on a fiber loop containing straight and helically wound fiber cables with different indices of refraction poses challenges for determining the trace spacing to use for geometry assignment and dataset registration. Assuming the actual helical pitch angle may be different than the nominal pitch angle, we propose a method to estimate pitch angle and helical trace spacing by cross-correlation with co-located datasets. For a cable with a nominal pitch angle of 30.0 degrees (520 traces per 300 m), cross-correlation with straight fiber data gives estimated pitch angles of 29.6 degrees for helical fiber in a vertical well (507 traces per 300 m) and 28.5 degrees for the same helical fiber in a horizontal trench (502 traces per 300 m). Substituting accelerometer and geophone datasets for straight fiber data does not yield valid estimates of pitch angle, but the estimated trace spacings for helical fiber data are within 3 cm (or less) of those obtained from the straight fiber data.

Introduction

The Containment and Monitoring Institutes Field Research Station (CaMI.FRS) contains an approximately 4.9 km long optical fiber loop comprised of straight fiber cables and helically wound fiber cables that are spliced together end-to-end. The fiber loop traverses two wells, observation well 1 (OBS1) and observation well 2 (OBS2), and a 1 km horizontal trench. We have, in the past, interpolated fiber trace co-ordinates (*x,y,z*) for a 2018 walk-away/walk-around VSP (Hall et al., 2019) using GPS surface locations, downhole gyroscope surveys, software and fiber indices of refraction, and the nominal helical pitch angle, but, it was clear we were not using the correct helical fiber output trace spacing. In addition, it was impossible to know precisely which interpolated coordinates should be assigned to any particular DAS trace. Proper calibration of fibre is critical for all subsequent data analysis, including FWI (Eaid et al., 2020), and multicomponent strain estimations (Hall et al., 2021).

We used a cross-correlation and linear regression method on co-located seismic datasets to estimate the helical pitch angle and trace spacing. This method requires knowledge of the fiber trace spacing used by the DAS interrogator but can be successful in the absence of any knowledge of interrogator or fiber indices of refraction.

Theory

Distance along a helically wound fiber cable can be represented by the hypotenuse of a right-angled triangle. It can easily be shown that distances reported by the interrogator software ($D_{software}$) can be corrected to actual distances (D_{actual}) along a helical cable using

$$D_{actual} = D_{software} \cdot cos(\theta), \qquad (1)$$

where θ is the helical pitch angle.

We may now consider the case where the interrogator software was run using an index of refraction ($IRsoftware$) that is different than the fiber index of refraction ($IRactual$). Using the equations for velocity and index of refraction:

$$v = \frac{D}{t}, and\ IR = \frac{c}{v}, \therefore t = \frac{D \cdot IR}{c}, \qquad (2)$$

where *v* is speed of light in a fiber, *D* is the distance along the fiber, *t* is the observed travel time, *IR* is the index of refraction, and *c* is the speed of light in a vacuum. We may now create two equations for two different indices of refraction and set them equal when the observed travel time is known to be the same for both cases:

$$t_{observed} = \frac{D_{actual} \cdot IR_{actual}}{c} = \frac{D_{software} \cdot IR_{software}}{c}, \qquad (3)$$

which, when combined with Equation (1) leads to

$$Dactual = Dsoftware \cdot \frac{IRsoftware}{IRactual} \cdot cos(\theta). \qquad (4)$$

For two co-located helical cables where cable1 has pitch angle $\theta 1$ and cable2 has pitch angle $\theta 2$

$$Dsoftware = \frac{Dactual1}{\cos(\theta 1)} \cdot \frac{IRactual1}{IRsoftware} = \frac{Dactual2}{\cos(\theta 2)} \cdot \frac{IRactual2}{IRsoftware} \qquad (5)$$

and

$$Dactual2 = \frac{Dactual1}{\cos(\theta 1)} \cdot \frac{IRactual1}{IRactual2} \cdot \cos(\theta 2). \qquad (6)$$

Generalizing for the case where cable 1 is a straight fiber cable, $\theta 1 = 0$ and $\cos(\theta 1) = 1$. If *Dactual1* is the trace spacing reported by the interrogator, we are now able to calculate helical fiber trace spacing (*Dactual2).*

Solving for pitch angle gives

$$\theta 2 = cos^{-1}\left(\frac{Dactual2 \cdot IRactual2}{Dactual1 \cdot IRactual1}\right). \qquad (7)$$

Further, if we disregard the indices of refraction we obtain a pseudo-pitch angle

$$\varphi 2 = cos^{-1}\left(\frac{Dactual2}{Dactual1}\right), \qquad (8)$$

which will give us a reasonable answer if $Dactual2 \leq Dactual1$. If $\frac{Dactual2}{Dactual1} > 1$, $\varphi 2$ becomes an imaginary number.

We may use Equation (8) to calculate a pseudo-pitch angle for two co-located datasets which can be used to register those datasets if we are able to estimate the ratio *Dactual2/Dactual1*. We propose to do this by cross-correlating each channel from a subset of dataset1 with all the channels in dataset2 and using the cross-correlation maximum amplitude at zero lag to find which channel numbers in dataset 2 best match channel numbers in dataset1. We may now use linear regression to obtain the slope (*m*) and intercept (*b*) of the best-fit line to those channel numbers. We expect the linear regression step to provide some robustness in the case of noisy input data.

We may relate dataset1 and dataset2 channel numbers to a common distance by

$$\Delta chan1 * \mathrm{Dactual1} = \Delta chan2 * \mathrm{Dactual2}, \qquad (9)$$

and

$$m = \frac{\Delta chan1}{\Delta chan2} = \frac{\mathrm{Dactual2}}{\mathrm{Dactual1}}. \qquad (10)$$

Substituting Equation 11 into Equations 7 and 8 gives us,

$$\theta 2 = cos^{-1}\left(m \cdot \frac{IRactual2}{IRactual1}\right). \qquad (11)$$

and

$$\varphi 2 = cos^{-1}(m). \qquad (12)$$

Now that we have an estimated slope and intercept relating channel numbers between the two datasets, we may use the equation of a line to register co-located datasets by calculating fractional channel numbers (*chan2*) for dataset2, given integer channel numbers (*chan1*) from dataset1,

$$chan2 = m * chan1 + b. \qquad (13)$$

We are also able to determine which *chan2* is located at the boundary (e.g., where the fiber loop turns 180 degrees at the bottom of the wells and at the ends of the trench) between dataset1 and dataset2 by assuming the boundary is located at *chan1 = chan2*:

$$chan2 = \frac{b}{(1-m)}. \qquad (14)$$

Method

We gathered accelerometer (Scorpion recorder), geophone (Geode and Aries recorders), and DAS data (Fotech interrogator) for common Vibe Points (VP)s from a 2018 VSP conducted at the CaMI.FRS, using VP arbitrarily restricted to being within 65 m of observation well 2 (OBS2), more than 20 m away from above ground junction boxes with fiber splices, and 20 m away from the corners of the trailer that contained the DAS interrogator. This was to exclude source gathers with high-amplitude horizontal bands of noise due to either internal coupling in the DAS interrogator, or source shaking of the wooden posts holding fiber junction boxes above ground level.

Accelerometer and geophone data were converted to strain-rate (Monsegney et al., 2021), time-zero differences were reconciled, and all data were bandpass filtered to a common frequency band before proceeding. We used the *Matlab*® functions *xcorr2*() and *fitlm*() to determine a robust least-squares linear fit to cross-correlation channel number results for each dataset comparison at each source location after normalizing all input trace amplitudes. As the linear regression is sensitive to input trace window selections and noise, we arbitrarily ·discarded any slope estimates that were more than +/- one standard deviation from the median value.

Results

Figure 1a shows an example of pseudo-pitch angle estimation in the OBS2 well for a single VP, and Figure 1b shows the same for the northern half of the trench. Table 1 presents a summary of pseudo-pitch angle (φ) and pitch angle (θ) estimates for the helically wound fiber cable at the CaMI.FRS for multiple VPs. The average estimated pitch angles are different enough for the trench and well data that we speculate the helical cable has stretched vertically in the approximately 300 m deep well.

Table 2 summarizes calculated helical trace spacing for nominal the nominal 30-degree pitch angle with and without index of refraction corrections, and pitch angle estimates for helically wound fiber in OBS2 and in the trench. It also shows the predicted number of traces that will result for each of these trace spacings for an arbitrary fixed distance of 300 m. The 9-trace difference between the trench estimate from the data and calculated from the nominal pitch angle may well explain earlier difficulties interleaving helical and straight fiber data by co-ordinates.

Moving beyond matching channel numbers to better assigning x, y, and z coordinates to DAS traces depends on the availability of co-located dataset with a known geometry. For the survey used in these examples, we had multi-component geophones and straight and helical fiber cables cemented in on the outside of the OBS2 well casing, and a string of temporary multicomponent accelerometers inside the casing. In addition, geophones were planted along the trench on the surface. Table 3 shows the results of cross-correlating geophone and accelerometer data converted to strain-rate (Monsegney et al, 2020) with straight and helical fiber data, and compares the results to OBS2 and trench *Dactual* estimates from Table 2.

Table 1. Summary of pitch angle estimates.

Run Name	nVP	*m*	*φ (deg)*	*θ (deg)*
HelDwn StrDwn	22	0.888	27.4	29.6
HelDwn StrUp	21	0.889	27.3	29.5
HelUp StrDwn	18	0.891	27.0	29.3
HelUp StrUp	21	0.891	27.0	29.3
StrDwn HelDwn	18	0.886	27.6	29.9
StrDwn HelUp	20	0.889	27.3	29.6
StrUp HelDwn	18	0.884	27.8	30.1
StrUp HelUp	23	0.889	27.3	29.6
AVERAGE:	**20**	**0.888**	**27.3**	**29.6**
HelNorth StrNorth	20	0.897	26.2	28.6
HelSouth StrSouthx	20	0.896	26.3	28.7
StrNorth HelNorth	18	0.898	26.1	28.5
StrSouth HelSouth	26	0.898	26.1	28.5
AVERAGE:	**21**	**0.897**	**26.2**	**28.5**

Table 2. Summary of calculated and estimated helical trace spacing.

Run Name	nVP	*Nom. D1 (m)*	*Nom. D2 (m)*	*Est. D2 (m)*	*ΔD2 (m)*
Geo HelDwn	26	5	0.592	0.610	0.018
Geo StrDwn	22	5	0.667	0.685	0.018
Accel HelDwn	25	1	0.592	0.596	0.004
Accel StrDwn	24	1	0.667	0.671	0.004
Geo HelNorth	19	10	0.598	0.599	0.001
Geo StrNorth	21	10	0.667	0.634	0.032

We only had 8 geophones south of OBS 2 along the trench, which turns out to not be enough data to estimate helical trace spacing. For the other geophone and accelerometer data cross-correlated with straight and helical fiber data, the maximum difference between fiber trace spacing calculated from pseudo-pitch angles estimated solely from fiber data is on the order of 3 cm or less (Table 3).

Table 3. Summary of results for geophone and accelerometer strain-rate data cross-correlated with helical and straight fiber data.

	θ (deg)	*φ (deg)*	*m*	*Dactual (m)*	*Ntrace)*
Nominal *θ*	30.0	30.0	0.866	0.577	520
Nominal *θ* with IR	30.0	27.8	0.885	0.590	509
OBS2 *m* estimate	29.6	27.3	0.888	0.592	507
Trench *m* estimate	28.5	26.2	0.897	0.598	502

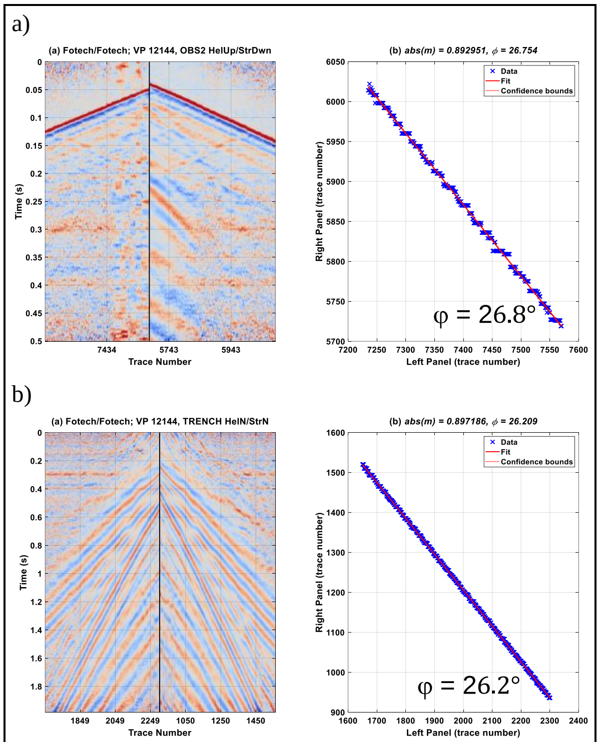

Figure 1: Helical and straight fiber data from observation well 2 (a) and the northern half of the trench (b) for a single VP. The left column shows the data to be cross correlated with helical fiber data on the left and straight data on the right. The graphs in the right column show cross-correlation results (blue dots), the linear-regression results (red lines) and the estimated helical pseudo-pitch angle φ.

Helical fiber pitch angle and trace spacing estimation

Discussion

We may estimate a pseudo-pitch angle for helically wound fiber cables solely from the recorded data in the presence of a co-located dataset using cross-correlations and linear regression. This process requires no prior knowledge of trace spacings for the two datasets, or, in the DAS case, knowledge of the indices of refraction of the fiber or the index of refraction used in the DAS interrogator software. The pseudo-pitch angle is robust in the sense that we obtain similar answers for unfiltered and bandpass filtered input data and matching the domains of the input data (acceleration, velocity, strain-rate) does not seem to change the pseudo-pitch angle estimate significantly.

If the co-located dataset has a known trace spacing, we can also predict an unknown trace spacing, for example, the helical fiber cable trace spacing from a known geophone, accelerometer, or straight fiber trace spacing (e.g., Figures 2a and 2c). Note the improvement gained by using an estimated pitch angle (Figure 2b) rather than the nominal pitch angle (Figure 2a). These figures required an interpreted alignment between the straight and helical fiber data. We may also use the slope and intercept from the linear regression step to register datasets by fractional dataset channel number (Figure 2c). Here, we find that a domain mismatch for the input datasets gives us a bad estimate of the intercept, as will a time-zero mismatch between the two datasets. Bandpass filtering the datasets does not significantly affect result if both input datasets are in the same domain.

It is necessary to estimate pseudo-pitch angles for multiple source gathers and combine the results statistically. Tables 1 and 2 in this report have a column labelled 'nVP,' whose values are always less, sometime significantly less that the total number of input gathers (27). We arbitrarily removed any slopes that were not in the range (median(slope)-stdev <= slope <= median(slope)+stdev). This is because the cross-correlation results, and hence the linear regression slope and intercept results are sensitive to the trace range chosen for the input data. The distance range for one dataset must be entirely contained within the distance range for the second dataset, or the slope will be changed by large numbers of non-unique matches at the ends of the trace range. Large numbers of noisy traces also affect the quality of the results.

Future work

We need to complete dataset registration (Figure 2c) by relating fractional fiber channel numbers to accelerometer and geophone channel numbers and interpolating trace co-ordinates for the fiber data.

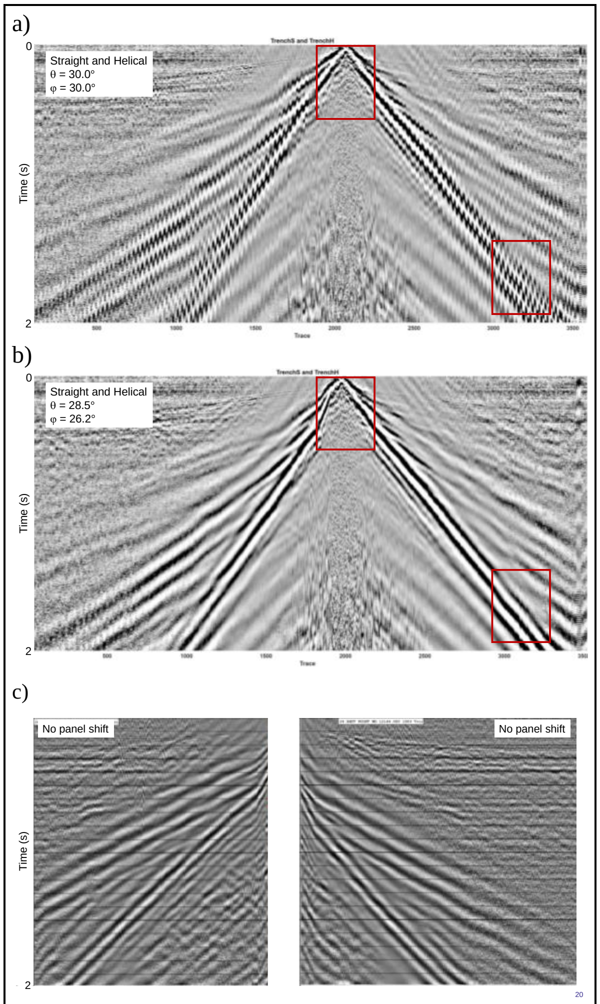

Figure 2: Helical and straight fiber data from the northern trench interleaved with helical trace spacing calculated using the nominal pitch angle and no index of refraction corrections (a), using the estimated pseudo-pitch angle (b), and using the linear relationship between straight and helical channel numbers (c).

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