Estimation of unknown trace spacings and pitch angles for helical fibre DAS data

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Summary

Trace co-ordinates (*x,y,z*) were interpolated for fibre optic data acquired at the Containment and Monitoring Institute's Field Research Station (CaMI.FRS) using straight fibre trace spacing from the interrogator and a helical trace spacing calculated using the nominal pitch angle for the helical cable and all available knowledge of the CaMI.FRS fibre loop (eg. GPS co-ordinates, well depths, fibre indices of refraction, etc.). This process does not tell us which fibre trace should assigned a specific set of co-ordinates. Arbitrary geometry assignment followed by a trace sort proved that the calculated helical fibre trace spacing was incorrect (Figure 1). We theorized that the actual helical pitch angle varied enough from the nominal pitch angle to affect our results. This abstract shows results from a cross-correlation and linear regression method to estimate helical trace spacing and corresponding pitch angle for helical fibre datasets where a co-located dataset (straight fibre, geophone, accelerometer) exists. For the test dataset, helical trace spacing estimated from geophone and accelerometer data is within 3 cm (or less) of those estimated from the finely sampled straight fibre data.

Theory

For two helically wound fibre cables (1 and 2) recorded by the same DAS interrogator we can derive

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

where *D* is distance (or trace spacing), *IR* is an index of refraction, and θ is the pitch angle for each helical fibre cable. For the case where cable1 is not helically wound (straight fibre cable), cos ($\theta 1$) = 1, and solving for the pitch angle of cable 2 gives

$$\theta = \theta 2 = cos^{-1}\left(\frac{Dactual2 * IRactual2}{Dactual11 * IRactual1}\right) \text{ or } \varphi = cos^{-1}\left(\frac{Dactual2}{Dactual1}\right), \qquad (2)$$

where φ is the pseudo-pitch angle obtained if we disregard the indices of refraction.

We can estimate a slope *m = Dactual2/Dactual1* by cross-correlating each trace acquired on cable1 with all the traces from cable2 and using the maximum cross-correlation amplitude at zero lag to determine which trace numbers from cable2 best match trace numbers from cable1. We then use linear regression to obtain the slope and intercept of the best-fit line to the cross-correlation trace number results. This relationship may then be used to register the two datasets in space by fractional trace number. Note that we can generalize usage of Equation 2 by substituting accelerometer or geophone data instead of fibre data. In this case we are still able to calculate pitch angles, but they have no physical meaning.

Method

We gathered accelerometer, geophone, straight fibre, and helical fibre data for twenty-seven Vibe Points from a walk-away/walk-around VSP conducted at the CaMI.FRS in 2018. Accelerometer and geophone source gathers were converted to strain-rate (Hall et al., 2020; Monsegny et al., 2021). All source gathers were corrected for time-zero issues between recorders, bandpass filtered to match frequency content, and trace amplitudes were normalized before cross-correlation. Matlab® functions *xcorr2*() and *fitlm*() were used to determine robust least-squares linear fits to cross-correlation trace number results for each dataset comparison for each Vibe point. As the process 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 before averaging the remaining results.

Results

Table 1 summarizes helical trace spacing predictions using the nominal 30 degree pitch angle for the helical cable with and without index of refraction corrections (top two rows), and as estimated from linear regression slopes (bottom two rows). The estimated pitch angle from borehole fibre is different enough from the trench fibre result that we speculate the borehole helical cable has stretched vertically, affecting the pitch angle. The *Ntraces* column shows the number of traces required to cover an arbitrary 300 m distance, and the range of required traces (502 vs. 520) is more than enough to explain the discrepancies observed in Figure 1. Figure 2 shows the same data as Figure 1, but with traces interleaved using fractional trace numbers calculated using the average slope and intercept from the linear regressions. This is clearly a better result than we initially obtained. Finally, Table 2 shows results from cross-correlating geophone and accelerometer data with straight and helical fibre data. The difference between fibre/fibre trace spacing results and geophone/accelerometer results vary from 1 mm to 3.2 cm depending on the input datasets.

Discussion

We can register datasets and estimate a pseudo-pitch angle for helically wound fibre cable data solely from recorded data in the presence of a co-located dataset by utilizing cross-correlations and linear regressions. This process requires no prior knowledge of trace spacings for the two datasets or knowledge of the software or fibre indices of refraction. If the co-located dataset has a known trace spacing, we can also estimate an unknown trace spacing, for example, the helical fibre cable trace spacing from a known geophone, accelerometer, or straight fibre trace spacing.

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References

Hall, K. W., Innanen, K. A., and Lawton, D. C., 2020, Multi-component accelerometer and geophone comparison to fibre-optic (DAS) data: *GeoConvention, Conference Abstracts*.

Monsegny, J. E., Hall, K. W., Trad, D. O., and Lawton, D. C., 2021, Least Squares DAS to geophone transform: *GeoConvention, Conference Abstracts*.

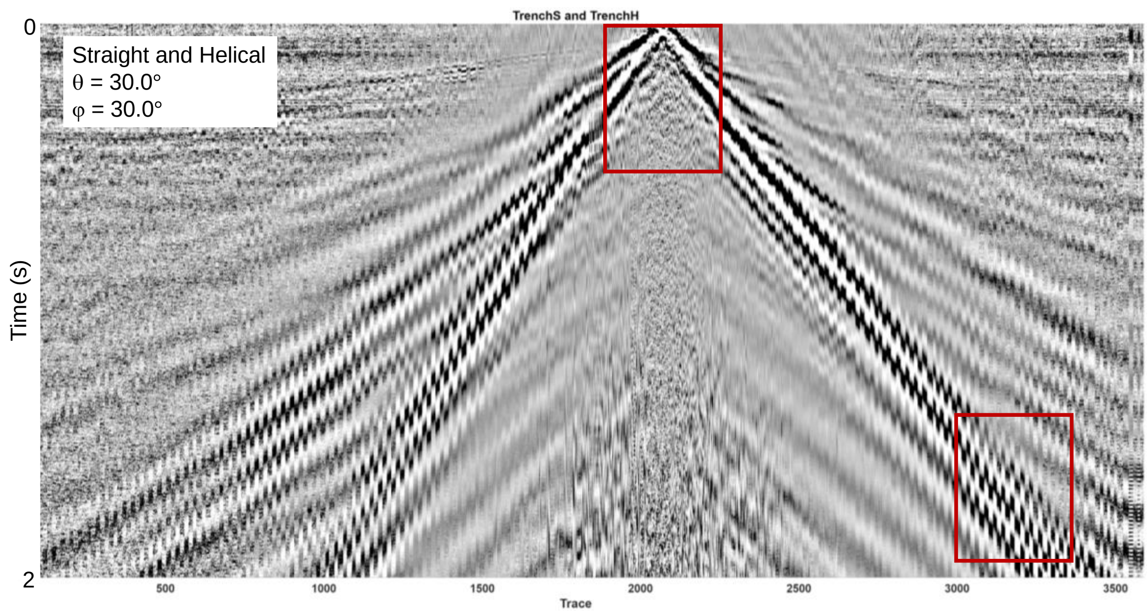

Figure 1. Trenched helical and straight fibre data interleaved using interpolated coordinates plus an arbitrary trace shift to visually match data near the Vibe point. Helical trace spacing was calculated using the nominal pitch angle and no index of refraction corrections. Note that the datasets match less well with increasing distance. Straight fibre trace spacing = 0.667 m and helical fibre trace spacing = 0.577 m (Table 1).

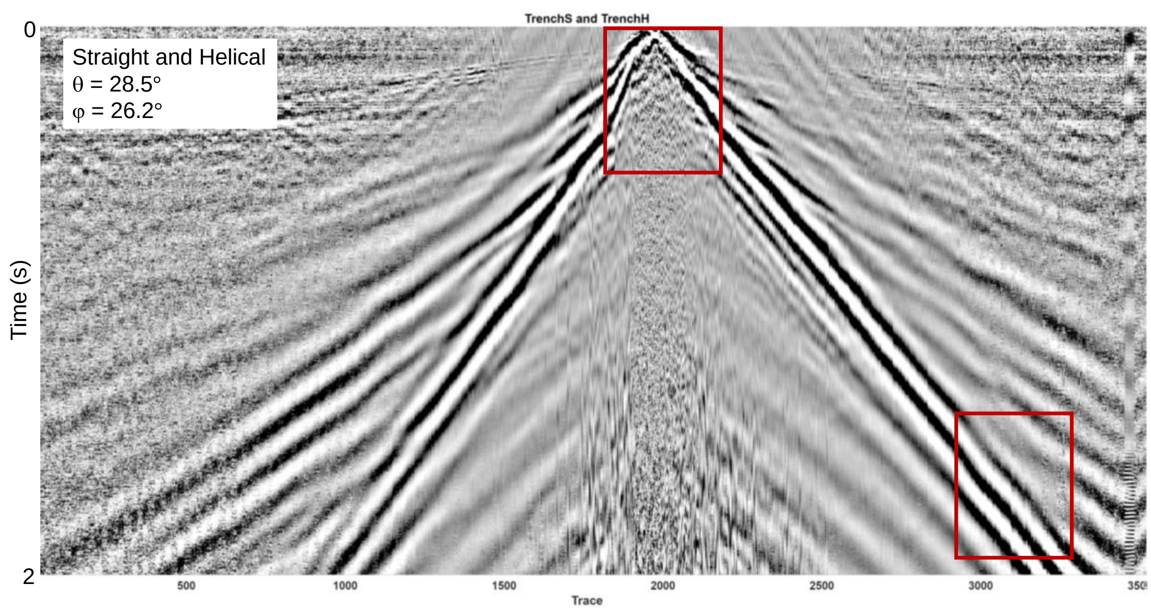

Figure 2. Trenched helical and straight fibre data interleaved using a linear relationship between straight and helical fibre channel numbers derived from cross-correlations and linear regression of trenched fibre data. Straight fibre trace spacing = 0.667 m and helical fibre trace spacing = 0.598 m (Table 1).

Table 1. Summary of results for straight fibre data cross-correlated with helical fibre data. Calculated (top two rows) and estimated (bottom two rows) helical trace spacing *D*. Numbers highlighted in red are the inputs for the trace spacing calculation.

	nVP	*θ (deg)*	*φ (deg)*	*m*	*D (m)*	*TD (m)*	*Ntraces*
Nominal θ	N/A	30.0	30.0	0.866	0.577	300	520
Nominal θ *with IR correction*	N/A	30.0	27.8	0.885	0.590	300	509
Borehole *m* estimate	20	29.6	27.3	0.888	0.592	300	507
Trench *m* estimate	21	28.5	26.2	0.897	0.598	300	502

Table 2. Summary of results for geophone and accelerometer data cross-correlated with helical and straight fibre data. Predicted helical trace spacings (Pred. D2) are from Table 1, Estimated straight and helical trace spacings (Est. D2) are from Equation 2, and the difference between the two are shown in column *ΔD2*

Run Name	*nVP*	*Nom. D1 (m)*	*Nom. m*	*Est. m*	*Nom. φ (deg)*	*Est. φ (deg)*	*Pred. D2 (m)*	*Est. D2 (m)*	*ΔD2 (m)*
Geo Helical Borehole	26	5	0.118	0.122	83.2	83.0	0.592	0.610	0.018
Geo Straight Borehole	22	5	0.133	0.137	82.3	82.1	0.667	0.685	0.018
Acce lHelical Borehole	25	1	0.592	0.596	53.7	53.4	0.592	0.596	0.004
Accel Straight Borehole	24	1	0.667	0.671	48.2	47.9	0.667	0.671	0.004
Geo Helical Trench	19	10	0.060	0.060	86.6	86.6	0.598	0.599	0.001
Geo Straight Trench	21	10	0.067	0.063	86.2	86.4	0.667	0.634	0.032