



Assessing the number of twists of stranded wires using ultrasound

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Abstract – Wiring, of different degrees of complexity, is a dominant part of mechanical support in constructions, electromagnetic and telecommunication signal transmission cables, among other applications. Single and manifold twisted wires are prominent examples of such utilities and are susceptible to mechanical irritations and deterioration. They require ultrasonic non-destructive testing and health monitoring. The objective is to develop an ultrasound-based technique to automatically measure the number of twists per meter in winded wire strands implementable in the industry, to be used during an ultrasonic scan and provide the number of twists per meter during cable production, for instance, to verify that calibration is still in place. Fourier transformation is applied as an expedited non-destructive testing method of twisted wires. Digital signal processing to obtain spatial and time spectral representation recognition due to amplitude variance, induced by the varying distance between the transducer and wire, is developed depending on the number of twists. Two different spatial spectral analyses satisfactorily quantify the number of twists by providing the distance between each twist. The method is robust and applicable when the distance between the transducer and strand is not constant, as the industry requires.

Keywords: Twisted wires, Stranded wires, Ultrasound, Non-destructive evaluation

1 Introduction

Historically, an application of twisted wires was barbed wire. The widespread and most economical twisted wires comprise the essential rigid components of many mechanical structures [1] and are used as actuators to pull heavy objects [2]. They also play a prominent role in communication and data networking among coaxial cables and fiber optics. Most horizontal cables run from communication closets to wall outlets [3]. They are often used in telecommunications, ethernet connections, and digital subscriber lines (DSL) [4], among other applications.

Non-destructive methods for detecting flaws, fatigues, fragility, and mechanical and structural defects of these wires include magnetic imaging with the appropriate digital image processing, which is helpful in the localization of defects in wire ropes [5]. Electromagnetic methods, which depend on the spatial distribution of magnetic flux and enable relating irregularities or discontinuities to defects, are also applicable [2, 6]. The load was measured on seven-wire strands using neutron diffraction [7]. Also, thermovision techniques were reported as an effective way of detecting defects, but they may have some destructive effects due to increased temperatures at the locations of defects [8]. Ultrasonic guided waves were used to detect

defects in seven-wire strands [9], steel wires [10], helical multi-wire armors [11], and for the inspection of elevator steel wires [12, 13]. They were used to measure the load on multiwire strands [14–18] and combined with other optoacoustic methods involving digital image correlation to detect defects by strain accumulations due to simultaneously applied acoustoelastic effects in seven-wire steel strands [19]. Apart from the aforementioned guided wave methods and acoustic emission [20, 21], no other ultrasonic method has been involved, to the authors' best knowledge. A recent review of damage detection methods on wires, including ultrasonic guided wave methods, has recently been proposed [22].

As ultrasound is already extensively used in the industry and even exists on assembly lines, a method is proposed that can be used to evaluate the number of twists per meter, N_{tpm} , directly during fabrication. The method should consider easy-to-implement apparatus as well as the signal processing method. Furthermore, the method should be able to be used in addition to standard ultrasonic defect scanning without any other acquisition needed. Above all, it should be robust even in situations where the distance between the transducer and the wire fluctuates with time. The work evaluates the number of twists per meter N_{tpm} of twisted copper wires. Comparative research is done in the industry from capacitance measurements if the cable is a conductor [23], but there is no reliable method for non-conductive

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wires. In the current study, B-scans of twisted wires samples collected in pulse-echo mode are analyzed using the Fourier transform, which enables extracting information encoded in conventional B-scans. Applied Fourier transforms consider both the temporal and spatial domain, and four different N_{tpm} are studied. The spatial domain approach is adopted after observing limits in the temporal domain analysis. Prior to this analysis, a description of the use of Fourier analysis in the image-processing domain and a quick application is given. An error analysis is done where applicable and the paper ends with an applicability analysis and conclusions.

2 Specimens and experimental setup

In industry, the setup would be a fixed transducer along which a twisted wire passes. Another option could be a continuous line scan of a few cm in the direction of the wires while they are being twisted. Both setups would continuously monitor the twists or, in more advanced analysis, other properties as needed.

In this study, the investigated samples consist of two copper wires, stretched and positioned, as shown in Figure 1. N_{tpm} equal to 5, 14, 19, and 29 is considered. The distance between twists is measured for each case, and the resulting data is specified in Table 1. The scanner has a mechanical movement in the 3-Cartesian axes and 2 angular directions. It is adjusted at a fixed vertical distance of 5 cm and with a fixed inclination to permit a linear scan along the wires. An unfocused transducer with a resonance frequency of 5 MHz was utilized as a transceiver. The input signal is a 5 MHz pulse at 250 V generated by a pulse receiver. The transceiver emits the generated ultrasonic wave, and after interaction with the twisted wire, some of its energy bounces back to the transceiver. The first signal echoes, corresponding to the interaction with the twisted wire, are processed as described in Section 5. The “Winspect” software controls the scanning parameters. They are as follows. The scan length is 40 mm, the scanner speed is 3 mm/s, the resolution is 0.1 mm, the delay is 115 μs , and the threshold is 0.025 V. Acquisition is averaged over 16 assessments to obtain an acceptable signal-to-noise ratio. The same experimental setup is used for wires with different N_{tpm} .

3 Fourier analysis

Fourier analysis, first developed by Jean Baptiste Joseph Fourier (1768–1830), is generally well-known, particularly for time-signals $f(t)$. Practically, measurements occur in a finite time window and at discrete instances (with a fixed sampling rate), whence the transformation involved is the discrete Fourier transform (DFT), often accelerated by built-in fast Fourier transform procedures (FFT). Modern scientists typically assume an FFT in a complex Hilbert space (named after David Hilbert), whence the result of the FFT of a time-signal is a set of numbers, called a vector, of the same length or dimension as the original recorded time signal in which every number is a complex coefficient in a Fourier series consisting of complex

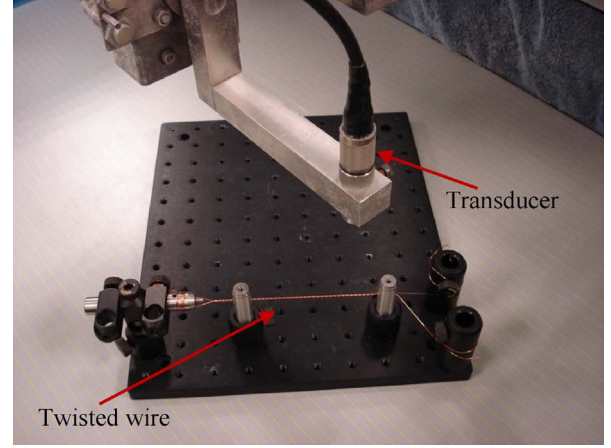


Figure 1. A photograph of the setup: A 5 MHz transducer scans along the horizontal line. Twisting is controlled manually.

Table 1. Distance Δ between twists for the different number of twists per meter N_{tpm} considered.

N_{tpm}	Δ [mm]
5	19.6
14	6.3
19	4.6
29	3.0

harmonic functions. The method can be generalized, such as in the protocol used by Matlab, by representing the recorded time signal and the calculated FFT dimensionless, i.e., only as a function of the index number in the considered series of numbers (vector), as follows:

$$f(k) = \frac{1}{K} \sum_{n=1}^K F_n e^{j \frac{n^2 \pi}{K} k} \quad \text{with } k \in \{1, 2, \dots, K\}, \quad (1)$$

and,

$$F_n = \sum_{k=1}^K f(k) e^{-j \frac{n^2 \pi}{K} k} \quad \text{with } n \in \{1, 2, \dots, K\}, \quad (2)$$

and with the theoretical implications that,

$$f(k) = f(k \pm qK) \quad \text{and} \quad F_n = F_{n \pm qK} \quad \text{with } q \in \mathbb{N}. \quad (3)$$

A function $f(k)$ and its FFT, F_n , can be associated either with a time function to frequency function transform by the following substitution:

$$t_m = (m-1)(t_2 - t_1) \quad \text{and} \quad \omega_n = \frac{(n-1)2\pi}{K(t_2 - t_1)}, \quad (4)$$

or with a spatial function to wave number function transform by this substitution:

$$x_m = (m-1)(x_2 - x_1) \quad \text{and} \quad k_n = \frac{(n-1)2\pi}{K(x_2 - x_1)}, \quad (5)$$

with $\omega_n = 2\pi$ frequency _{n} and $k_n = \frac{2\pi}{\text{wavelength}_n}$.

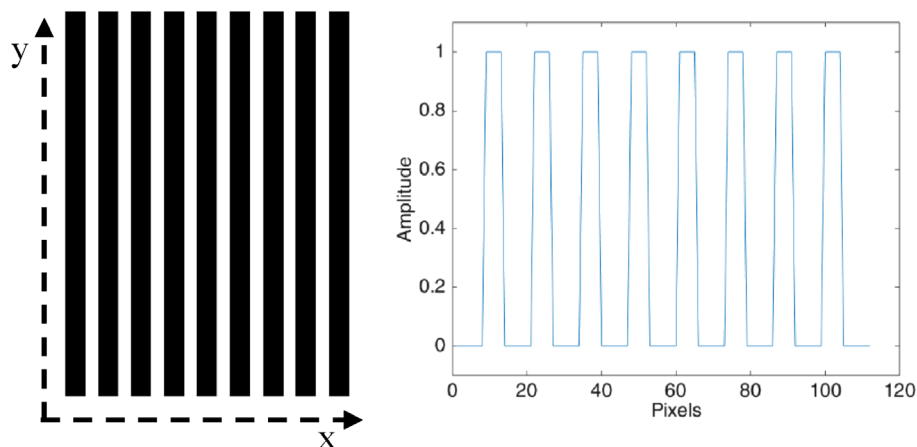


Figure 2. Left: Picture with a repetitive pattern. The spacing between the black lines is 13 pixels and can be determined through Fourier analysis. Right: A slice of the picture along the x -axis, used for 1D Fourier image analysis.

Image analysis occurs in pixel space. One can easily associate appropriate “pseudo-wavenumbers” in an FFT of the image to obtain a form of image transformation in a similar Hilbert space. The pseudo-spectrum indicates the prevalence of certain periodicities or pseudo-wavelengths in the image. If, as in our case, the “image” is a B-scan, then the result to process is similar to an image, and the periodicities in that image can be considered “pseudo-wavelengths” in the framework of an FFT as described above. This technique is applied in this work to extract the twists in strands.

Fourier image analysis to detect repetitive patterns is made as a taster in what’s next to clarify the method better. An image of a repetition of black and white lines is used, as shown on the left side in Figure 2. There are 13 pixels between each black line. The image can be cut into slices along the x -axis that still reveals the pattern on the right side of Figure 2.

Two strategies can be used. The 2D image is used as is, or a 1D slice is considered, as shown on the left and right sides of Figure 2.

First, the image is processed directly with FFT in 2D, resulting in the left side of Figure 3. Several peaks of higher amplitude are visible, but a more prominent one is detected when the wavenumber in the x -direction equals 0.07685 pix^{-1} . This wavenumber indicates the repetition rate of the image pattern, which is, in this case, the period of the black line pattern. The obtained wavenumber gives us a 13.01-pixel spacing which is the sought value, namely 13 ± 0.5 . Then, to compare, one slice is considered on which a 1D FFT is performed, resulting in the right side of Figure 3. A spectrum peak at 0.07685 pix^{-1} is still obtained, leading again to the 13.01-pixel spacing, showing, as expected, that it is adequate to analyze a slice in 1D rather than a 2D FFT on the whole image.

4 Experimental results

A series of B-scans are performed for the four considered N_{tpm} . Excluding the physical properties of the transducer

and the beamforming parameters, the detected signal varies depending on the properties of the scanned area. Examples of measured A-scans are depicted in Figure 4. The first echo corresponds to the interaction of the ultrasonic wave with the twisted wire. This echo is a function of the wires’ diameter, the transceiver’s position with the wire, etc. Only the variation of its amplitude with the scanning position is interesting for this study.

An industrial environment where wires are twisted is not necessarily sophisticated. One must assume that a constant distance between the transducer and wire cannot be maintained to account for poor conditions. Hence, the method must succeed even under distance fluctuations. The temporal B-scans along the horizontal axis of wires with 5 twists are shown in Figure 5. The spatial variations in the time of flight are attributed to the inclination of the sample with respect to the scan axis, as will occur in situ in the industrial environment. As such, the A-scans and B-scans provide limited information about the reflectivity of the wire. The patterns vary along the scan distance due to the twists. Figure 5 shows a repeated pattern of the high and low amplitude of the first echo caused by the periodic reflectivity pattern of the twisted wires and reveals N_{tpm} , when properly analyzed, as was done in an idealized case at the end of Section 4. Although, ideally, the repetition signal should look like the right part of Figure 2, in reality, the amplitude variation in experimentally obtained data is, of course, less pronounced. The eye of an expert may use rough data to extract N_{tpm} . However, in production units, an automated technique is preferred.

The reflected signal is influenced by particular geometrical, and possibly also mechanical, properties of the wire. This variation can be examined acoustically by analyzing the variations of the recorded signals through a spatial Fourier transformation. In addition, some exciting information may also be extracted from the time signals. Hence a time-domain Fourier transformation should also be investigated [24]. The reflectivity of the wire is not only a function of material properties, defects [25], or the number of twists per meter N_{tpm} . However, it is also affected by the

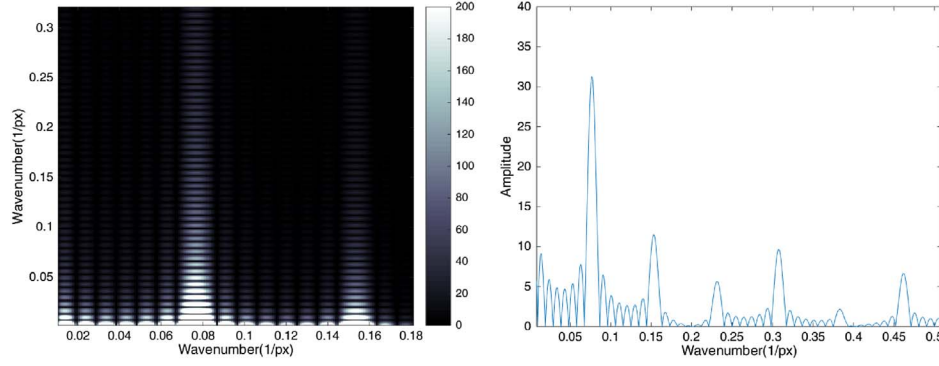


Figure 3. The corresponding FFT results obtained from Figure 2. Left: 2D FFT. Right: 1D FFT. Both results deliver a wavenumber of 0.07685 pix^{-1} in the x direction, i.e., a spacing of 13 pixels.

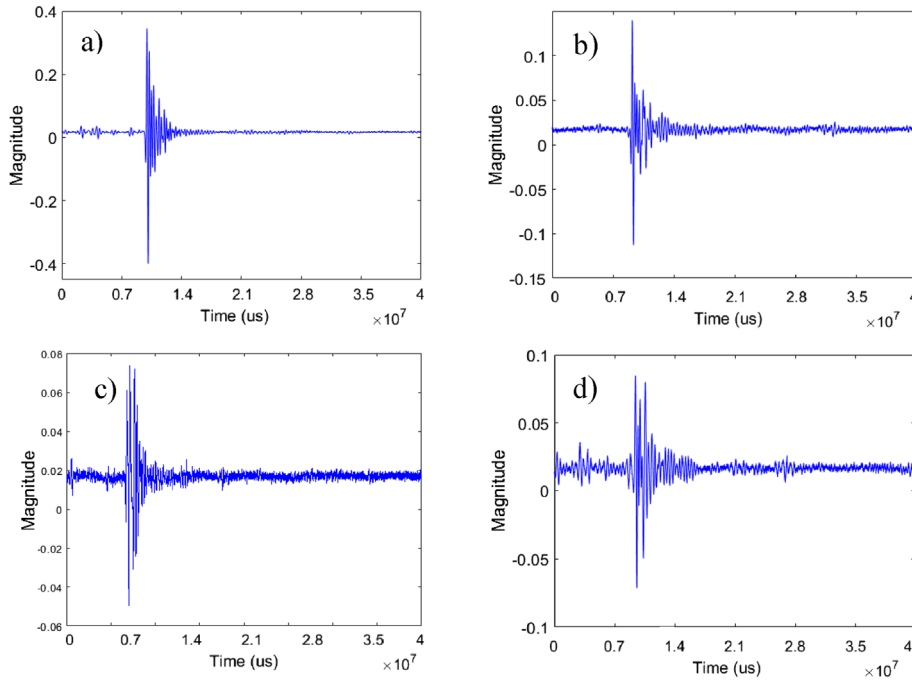


Figure 4. A-scan time signals collected from twisted Cu-wires with variable N_{tpm} , 5 (a), 14 (b), 19 (c), and 29 (d).

3D geometry of the twisted strands. This research is of particular interest because the geometry variations reflect sound in preferential directions that are not always those of the transducer. In other words, received amplitude variations may be valuable tools for quick and reliable measurements of N_{tpm} .

A temporal frequency response analysis is first presented for all the considered N_{tpm} (i.e., 5, 14, 19, and 29). Therefore, the Fourier transformations were calculated for each scan position as B-scans were recorded. An example is given, in Figure 6, for $N_{\text{tpm}} = 5$. From this 2D representation, the maximum magnitude for each frequency is taken, and the representations in Figure 7 are obtained. For each N_{tpm} (i.e., 5, 14, 19, and 29), the spectra are computed, using the procedure just described, by considering different parts of each time signal.

To begin with, the whole signal is used, then the first wave packet of the signal (shown in green in Fig. 7 and referred to as the reflective signal). Finally, the difference between the frequency response of the whole signal, in blue, and the frequency response of the first part of the signal, in green, is also calculated and referred to as the frequency of the “analysis signal.” The spectrum of the “analysis signal” reveals that the number of frequency peaks increases with N_{tpm} . This indicates that N_{tpm} is a characteristic feature upon which the spectra can represent fingerprints. Still, a precise interpretation may be difficult. Therefore, the industry requires a more straightforward approach, described below.

The following method may be more appropriate for an industrial environment where the operator is not necessarily experienced in ultrasound research. As outlined in Section 4,

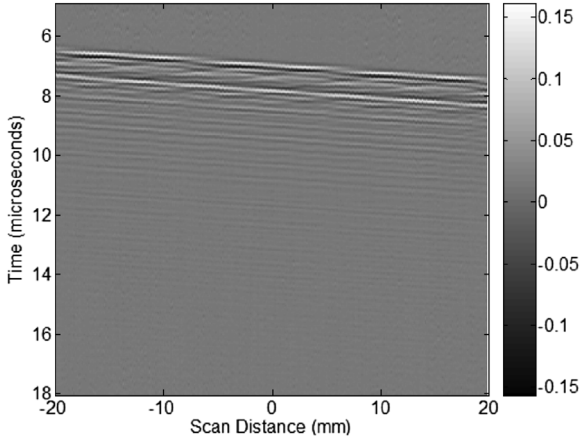


Figure 5. Time of flight of reflections along a B-scan line in a Cu-wire with 5 twists.

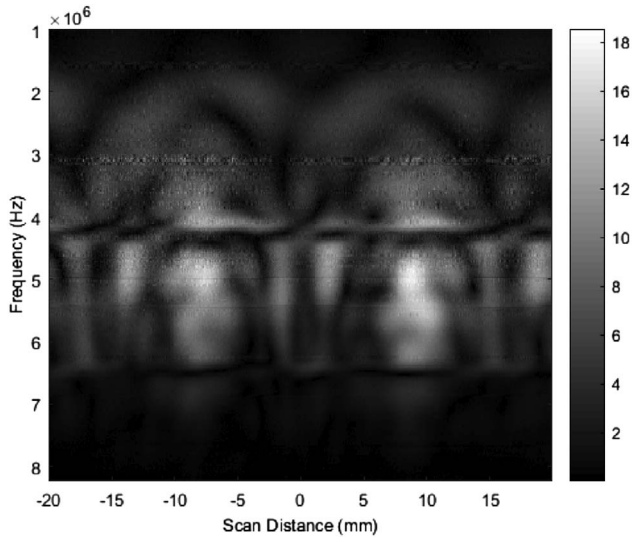


Figure 6. Example of a temporal frequency response, calculated over the whole duration of the signals, function of the position given by the scan distance for $N_{\text{tpm}} = 5$.

it is based on an analysis using “pseudo-wavenumbers.” This method is applied to values of N_{tpm} . A Fourier transform is done from the spatial domain to a pseudo-wavenumber domain for every instant in time. In other words, it is a 1D FFT in space for each recorded time. The result is a pseudo-wavenumber spectrum as a function of time. Similar to the temporal frequency analysis, a 2D representation is obtained. It can also be interpreted as the 1D Fourier transforms along the recorded B-scan data at each time instance. The result for the sample with $N_{\text{tpm}} = 29$ is shown in Figure 8.

From Figure 8, one can see that the main part of the energy is located between 0 mm^{-1} and 0.8 mm^{-1} . The wavenumber is a function of N_{tpm} , so a first estimation of the latter could be made. However, the most significant amount of energy is spread in time and wavenumber dimensions, making the analysis and the evaluation of the number

of twists difficult. Based on the data in Table 1, which relies on a periodicity measurement using a caliper, with an error of 0.1 mm , one expects values between 0.318 mm^{-1} and 0.323 mm^{-1} , 0.981 mm^{-1} and 1.014 mm^{-1} , 1.336 mm^{-1} and 1.397 mm^{-1} , 2.026 mm^{-1} and 2.167 mm^{-1} , for, respectively, N_{tpm} 5, 14, 19 and 29.

A maximum of energy is visible in Figure 8, circled in red, with a peak of energy that can be observed at $0.314 \pm 0.01 \text{ mm}^{-1}$, resulting in a periodicity between 19.38 mm and 20.66 mm . The expected value of 19.6 mm per twist is in this range. Finding confirmation in the obtained results by backward reasoning is comforting. However, an operator should be capable of reading the results in a forward and, above all, straightforward manner.

Therefore, as a second step, a procedure is applied that can be explained by keeping Figure 8 at hand. The procedure runs through all the time-dependent values and stores the maximum for each vertical axis location. In addition to offering clearer results, it also ensures that the results are not sensitive to a distance offset between the transducer and the twister wire. These maxima are plotted as a function of the inverted vertical axis data in Figure 9. In that figure, the maximum amplitude is shown as a function of mm/twist for the wires with 5, 14, 19, and 29 twists. The prominent visible peak gives the distance between twists as $20, 6.6, 4.72, \text{ and } 3.07 \text{ mm/twist}$, respectively. The error depends on the value and is found by considering the 0.1 mm scanning resolution over 40 mm , producing 400 samples per scan. Therefore, the “pseudo-wavenumbers” ranging from 0 to 4 mm^{-1} , have a resolution of 0.01 mm^{-1} . The obtained results for the distance between twists, considering the error range, are, respectively, between 19.38 mm and 20.66 mm , 6.53 mm and 6.67 mm , 4.68 mm and 4.76 mm , and 3.05 mm and 3.09 mm . Given that the relative error in the caliper measurements, shown in Table 1, is more significant for smaller distances, the difference between the ultrasonically obtained results and those obtained with a caliper is more prominent for smaller distances between twists. Therefore, the difference is due to errors in the caliper measurements and not in the ultrasound measurements. The method can be fully automated because an operator requires only minimal operational and interpretational input and offers reliable results.

5 Applicability criteria

Error estimations were performed in the above analysis of the obtained results. Still, an applicability issue arises inherently to the used technique that must also be addressed.

Since the reported work is based on the discrete Fourier transform of measurements taken in a limited space interval L , an applicability criterion can be determined for the applied method. The measurement resolution R is given by:

$$R = \frac{S_R}{N}, \quad (6)$$

S_R being the sample rate, and N , the number of samples. For time signals measured over a time interval T , R is the

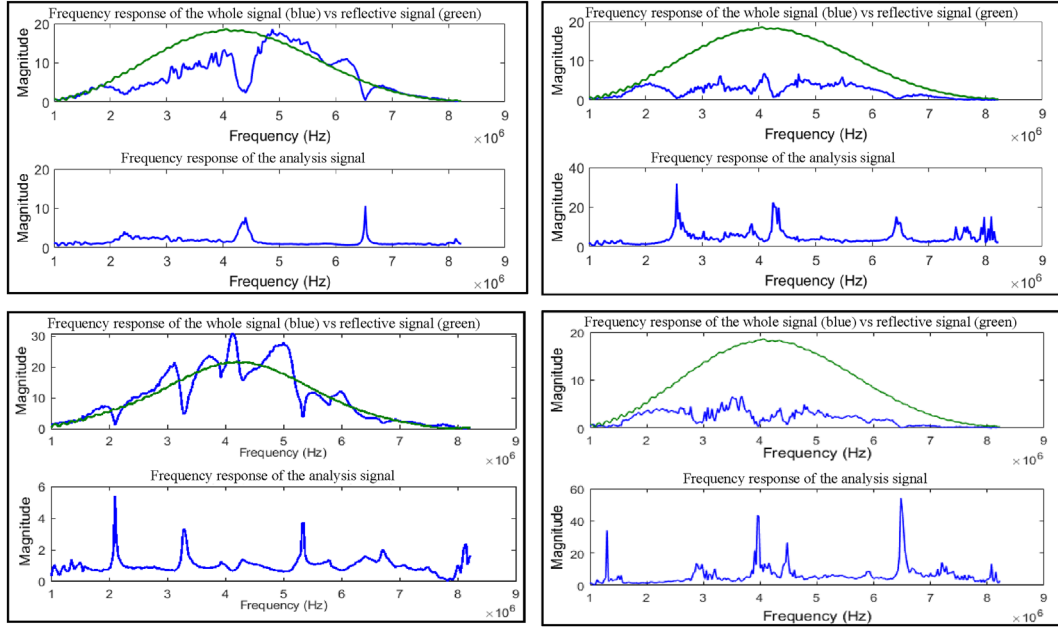


Figure 7. Frequency spectra of the whole signals (blue, top of each frame), the first wave packet of the signals (green), and the difference of the two frequencies (bottom of each frame) are depicted for Cu-wires with a variable number of twists per meter N_{tpm} , 5 (top left), 14 (top right), 19 (bottom left) and 29 (bottom right).

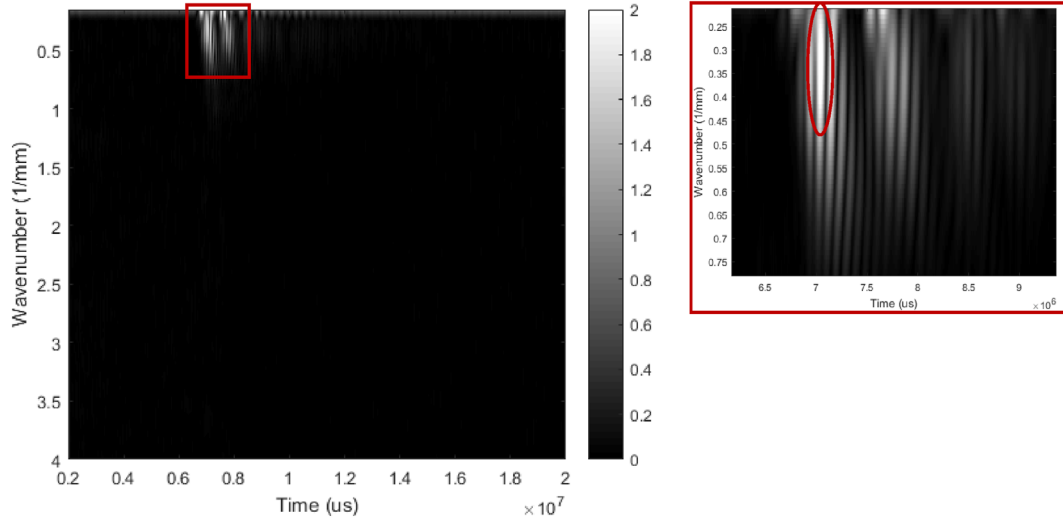


Figure 8. Spectrum in terms of pseudo-wavenumbers obtained by an FFT from the spatial domain at each instant. The example's $N_{\text{tpm}} = 29$. A zoom-in of the boxed area is visible on the right. A maximum of energy can be seen at $0.314 \pm 0.01 \text{ mm}^{-1}$ resulting in a periodicity between 19.38 mm and 20.66 mm, in agreement with the expected 19.6 mm value in Table 1.

step size in the frequency domain, $\Delta f = \frac{1}{T}$, while for space signals measured over a length L , R is the step size in N_{tpm} , $\Delta N_{\text{tpm}} = \frac{1}{L}$. In other words, if one measures over 1 m, the accuracy is one twist per meter. Practically, it means that the uncertainty of the applied technique is always one twist per measured length, or the longer the measurement length, the smaller the error. Additional factors may play a role in possible errors, which cannot be defined in general terms and are due to inaccurate signals obtained with the measurement. Still, there is a possibility to

compare obtained results with particular applicability criteria of the applied method as an additional tool to retain or discard results.

Nyquist's theorem in the current framework means that at least two samples per twist must be taken to determine N_{tpm} accurately. In other words, the first criterion is formulated as,

$$N_{\text{spt}} = \frac{N}{N_{\text{tpm}}L} > 2, \quad (7)$$

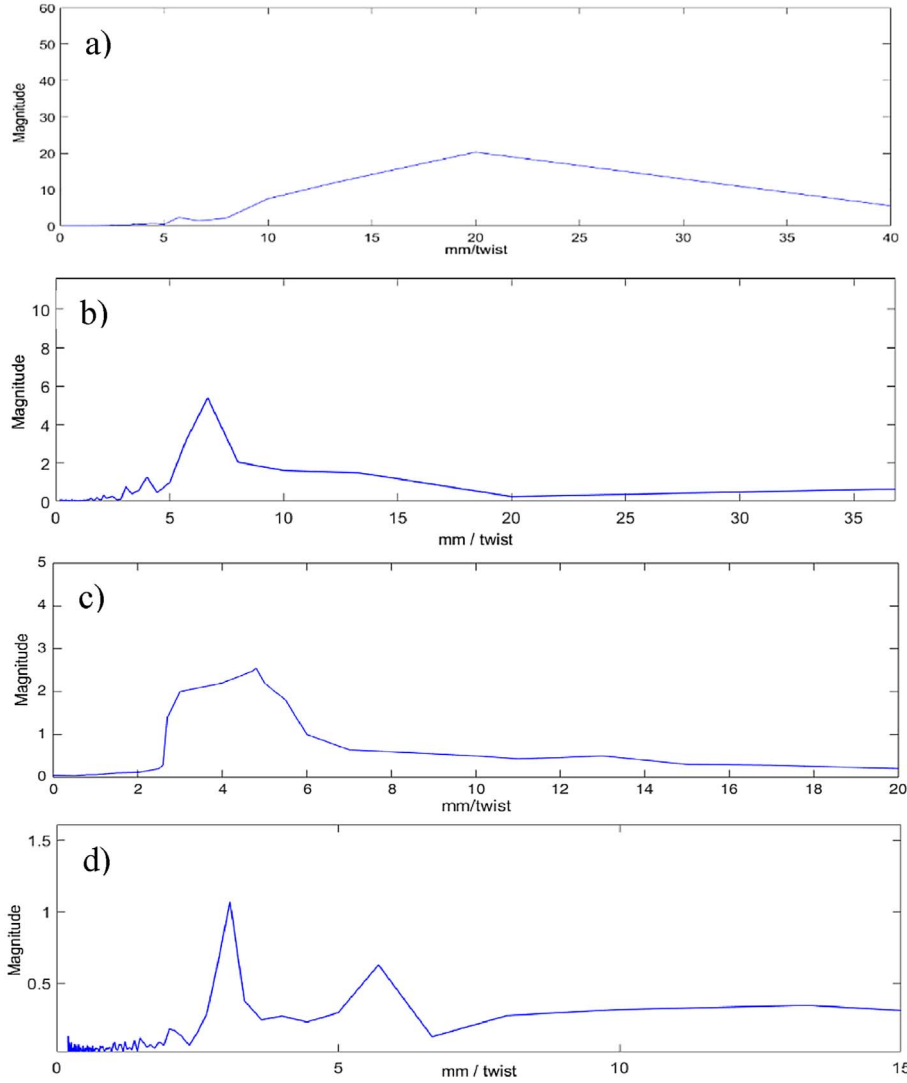


Figure 9. Results for Cu-wires with variable N_{tpm} , 5 (a), 14 (b), 19 (c), and 29 (d). Prominent peaks at respectively 20, 6.6, 4.72, and 3.07 mm/twist are observed.

with N_{spt} the number of samples per twist. The twist length is defined as,

$$T_l = \frac{1}{N_{\text{tpm}}}, \quad (8)$$

and must be larger than the measurement interval L , equivalent to a time window that must be at least the length of the period of the fundamental frequency of a time signal. In other words, there is a second criterion,

$$L > \frac{1}{N_{\text{tpm}}}. \quad (9)$$

Both criteria, (7) and (9) are combined as,

$$\frac{1}{N_{\text{tpm}}} < L < \frac{N}{2N_{\text{tpm}}}. \quad (10)$$

As a result, when the measurement and analysis procedures are applied, one must verify that the combined criterion

(10) is adequate. If the measurement delivers a value $N_{\text{tpm}} = w$, then one must check that $w > \frac{1}{L}$ and also that $w < \frac{N}{2L}$. If either of these criteria is violated, the measurement is false.

6 Conclusion

This paper uses short ultrasonic pulses to study twisted wires, which are omnipresent in the industry. From B-scan-Fourier Transform results, information, such as, in particular, the number of twists or spins per meter, N_{tpm} , was successfully extracted.

The difference between the frequency spectrum of the first reflective part of the signal and the whole signal's frequency spectrum was first considered. This difference is more dependent on the multiple interactions with the several N_{tpm} , while the used normalization accounts for

possible distance variations between wire and transducer. The method, however, is not inviting for less-skilled machine operators.

As a consequence, another method, based on pseudo-wavenumber analysis, was presented. It is done by taking the spatial Fourier transform for every instant. Figure 8 was obtained and provided indications that the twist distance may be extracted. An automated extraction technique was then found to offer reliable results by taking the maximum over time of the entire time range and plotting the result, as in Figure 9, as a function of the inverse of the vertical axis of Figure 8. An adequate estimation of N_{tpm} could be determined from the results. The method is robust and applicable when the distance between the transducer and strand changes with time, as the industry requires.

Ethics declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper and that all the authors consent to the content of the manuscript.

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