Efficient Application of Signal Processing Methods in Textile Science

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Abstract: - At present time a detailed study of textile structure is necessary in new textile applications, as composites, for instance. In composites the longitudinal yarn axis is derived from digital photographs of structure cuts. The discrete Fourier transform appears as the best method for very efficient description of yarn longitudinal axis. If the spectrum leakage is reduced, yarn axis can be approximated by a small number of harmonics. The filtering can be effectively applied to reduce experimental errors. Last but not least, the yarn axis can be considered as a realisation of random signal. Therefore, basic course on signal processing should be a part of textile education.

Key-Words: Signal theory, textile structure, Fourier transform, yarn axis approximation, random signals, correlation,

1 Introduction

Since nineteen years of last century the textiles are not only a subject of clothing, they are used in many technical areas. Sometimes a general term technical textiles is used for such type of application. Two representative groups of technical textiles are well-known: a big group of textile composites and a smaller, but not less important, group of smart or sensor textiles.

Textile composite contains reinforcement surrounded by matrix. Reinforcement usually consists of several layers of fabrics; the matrix is made from suitable resin. The system is pressed and heated in special regime. Thanks to synergic effect, the composite has unusual properties, well suited for special technical applications. On the other hand, the representative of smart textiles is piezoelectric textile. By application of stress or strain a voltage appears between planar opposite surfaces of the textile.

The technical textiles are subjected to many strict and specific requirements. Since the basic parameters of textiles depend on both the material and structure, a detailed knowledge of structure is necessary. At present time the textile structure research is based on the detailed study of structure microphotographs. Very efficient optical microscopy or computer tomography makes possible getting of detailed microphotographs of planar cuts or specific projections of the whole volume structure. They are input for special methods used for structure elements description and 3D visualization.

In this paper we focus to the efficient description of longitudinal axis of the yarns in woven composite. Although a lot of mathematical models for yarn axis were derived, probably the best approach is to consider the real yarn axis as an electric signal and apply suitable methods of signal theory. The paper presents some original results [1, 2].

2 Applied Method

In order the reader understand the method used for the yarn axis description, typical experimental results will be shown in this chapter. Then the task will be outlined and the optimum solution explained. We focus to the description of yarn longitudinal axis, since the methods of signal theory were applied. The perfect description of yarn cross-section is important as well; however modern mathematical approach is used in this case. Virtual reality is used for the 3D structure visualization.

2.1 Experiment

The composite specimen was cut in a suitable plane, polished by a method similar to the metallographic one and the surface was scanned by computer driven microscope. In order to see structure details high magnification is necessary. Due to high magnification partial images, slightly overlapping one another, were scanned. The images were pre-processed by the image analysis system LUCIA, however, more sophisticated image processing was made by our own SW. First of all resulting image of cut surface was composed from partial ones by using own system. No parameters from HW are necessary.

Since the contrast of objects on the image is low, their appearance does not differ significantly and the boundaries are not well-defined, either sophistic methods of image analysis and recognition were not successful. Therefore, the boundary must be marked by different colours by a skilled operator. It is the only hand operation, but the key, hard and time consuming one. Typical result of this step is in Fig. 1. Only a part of image is shown to see details. The boundaries, marked by a white curve, are enhanced to be well visible.

Images with marked boundaries are processed automatically and, as a result, coordinate of yarn boundaries and yarn axis in pixels or physical units are stored in a file. Yarn axis is defined simply as a middle line between boundaries. Yarn axes of eight layers composite are in Fig. 2.

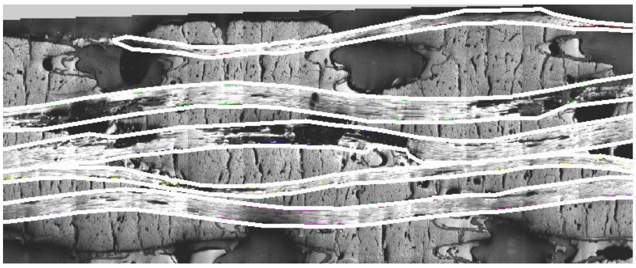

Fig. 1. Yarn boundary after hand processing

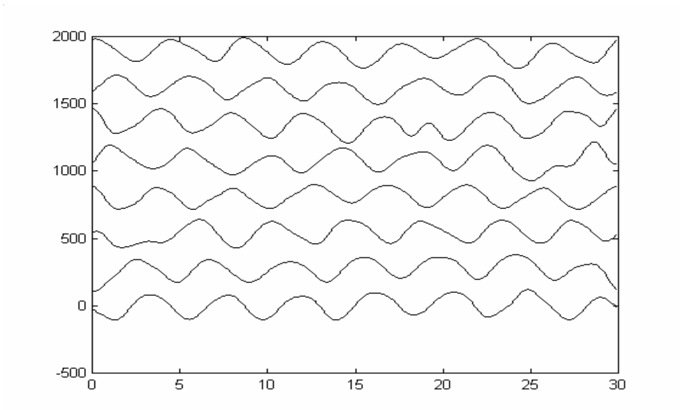

Fig. 2. Yarn axes in real composite prepared by a high pressure technology

The reader can conclude from Fig. 2 that the yarn axes of real composite are quasi-periodic. They contain both the systematic and random components. They can be treated in two ways:

1. If the random component can be neglected, the yarn axis is a periodic signal and the can be described by a Fourier series.
2. If the random component is important and we have a lot of yarns, they can be treated as representation of random signal. In this case there are two possibilities:
    a. Apply a full random signal theory
    b. Apply a statistics to sets of Fourier series coefficients

The Fig. 2 does not show a typical case. The random component of yarn axes in Fig. 2 cannot be neglected; therefore they should be treated as representatives of random process of limited duration, unfortunately. Furthermore, the number of representatives is small. Strong random component was due to the high pressure during composite preparation. More typical are almost periodical yarns. They are usually present in free textiles. Both the cases of negligible and important random component are treated separately bellow.

2.2 Fourier transform

In this chapter we are dealing with one representation of yarn axis and do not consider its random component. Either in this case the perfect analytical description of the y\axis is not possible; its approximation should be made. From the mathematical point of view the yarn axis can be approximated by many means, for instance:

1. Harmonic function
2. Splines
3. Polynom
4. Fourier series
5. Wavelets

From the practical point of view several limitations exist:

1. Approximation coefficients or parameters should have clear physical meaning.
2. The approximation should include the yarn periodicity as its key parameter.
3. The approximation should give meaningful results also out of the interval, at which the function is given.
4. The quality of approximation can be controlled.

Careful comparison of possibilities and limitations reveals that the only method that satisfies all the limitation is the method of Fourier series. It was the reason that we decided to use this approach.

Since the yarn axis is given by discrete coordinates, for example in pixels, the Discrete Fourier Transform (DFT) should be applied [1]. It transforms the information from the spatial domain to the frequency or wave domain that is termed the spectrum. The correct term for the second domain should be the wave-number domain, but the frequency domain is used frequently also as a counterpart to the spatial domain, although it is correct only for the signals in time domain.

The spectrum is, in general, complex: Spectral lines are complex conjugate and, therefore, only half of spectral lines are independent. Since each of them contains independent amplitude and phase, total number of independent frequency domain component is the same as in the spatial domain. Therefore, the same information is in both domains, by the application of DFT no information is lost and no added. However the information in domains has quite different form and it is the power of DFT, allowing many efficient applications, as we will se later.

Two important features that limit or complicate the DFT use are well-known; nevertheless they are briefly mentioned here:

1. Aliasing
2. Leakage

Aliasing in the form of false harmonics, aliases, is due to the small number of samples per period. Because of very large number of pixels and a very small number of waves per yarn, this case cannot happen. Leakage appears, if non-integer number of waves is sampled. It results in a more complicated spectrum than necessary. In contrary to aliasing, the leakage appears almost every time, since the image scanning cannot respect this constraint perfectly. Special caution must be made in order to reduce this effect. Usually the operator’s experience and skill are used.

Analogically to the electric signal processing the information in spectrum can be used by very efficient means. The basic features of yarn can be estimated from the spectral lines in different wave-number ranges. The yarn axis can be approximated by selection of the most important spectral lines. Unwanted features can be removed by a suitable filtering.

2.3 Statistics of spectral lines

As it follows from Fig. 1, yarns differ one another. Also in the case when leakage is reduced, their spectra will differ. In both the domains yarn axis has systematic and random component. In frequency domain the basic statistics (mean value and standard deviation) can be made for the amplitude and phase constant of each spectral line. Mean values allow getting of average yarn. Standard deviation makes possible to predict for given probability the boundary around the average yarn axis into which the real axes will fall with that probability.

If number of independent yarns is high, 500 or more, the type of statistic distribution can be found for every amplitude and phase constant. For amplitudes the normal distribution can be expected. Since the yarn in the image starts randomly, the uniform distribution is expected for phases, at least for phase constant of dominant harmonics.

Detailed statistical knowledge of the most important harmonics allows the construction of virtual composite. If the statistic distribution of important amplitudes and their phase constants is known, the random number generator can be used to generate amplitudes and phases that correspond to possible realizations in real world. One randomly selected value for each important harmonics creates a virtual yarn that can be found in practice, if the number of experimental samples will be very high. Therefore a lot of virtual yarns can be realized and virtual composites can be made from them

2.4 Application of random signal method

The second possibility how to describe the yarn random nature is to use the convolution or correlation [2]. Especially the correlation reveals how the yarns are similar. There are two well-known extreme cases of correlation. If the result of correlation has ideal triangle envelope, the yarns do not differ. If very sharp maximum appears (ideally δ-function), the yarns are very different.

3 Results

Only typical results will be presented here in order to demonstrate the power of DFT for efficient yarn axis description and further effective processing. Several application of the method mentioned above will be the topic of this chapter.

The yarn axis (bottom) and its spectrum (top) are shown in Fig. 3. The spectrum has several important harmonics. Main harmonics corresponds to the basic periodicity. Its neighbours on both sides are responsible for its deviation from the ideal sinusoid. The distortion is not negligible for the yarn in Fig. 3. Low harmonics (1^{st} to 3^{rd} in Fig. 3) are connected with the yarn distortion as a whole. Individual basic periods have a different vertical position in Fig. 3. High harmonics are due to the noise and experimental errors. They are negligible in studied case.

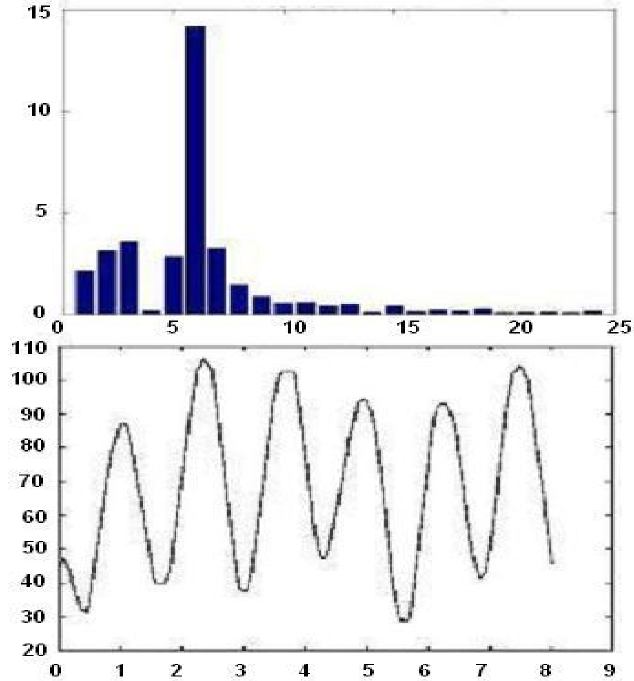

Fig. 3. Yarn axis and its amplitude spectrum

The most important harmonics can be used for yarn axis approximation. The result of approximation by 10 important harmonics is in Fig. 4. The approximation by 20 numbers (10 amplitudes and 10 phase constants) is very close to experiment. Small deviations are only at yarn ends [1].

The effect of leakage was discussed in part 2.2. If integer number of periods is sampled, the spectrum has the simplest form. For the spectrum in Fig. 5, left hand part, this condition is approximately valid, while the spectrum on the right hand side is for the case when a fraction of period is sampled. This spectrum is much more complicated.

Very important spectrum application in signal theory is the filtering operation. This operation can be applied also in the case of yarn axes. The low harmonics of spectrum, like those in Fig. 3, are due to either the production inaccuracy or systematic experimental error. They can be reduced simply by an ideal high pass filter. Fig. 6 shows the spectrum given in Fig. 3 after the filtering. The removal of low harmonics results in straightening of yarn axis; individual periods are almost in the same vertical position.

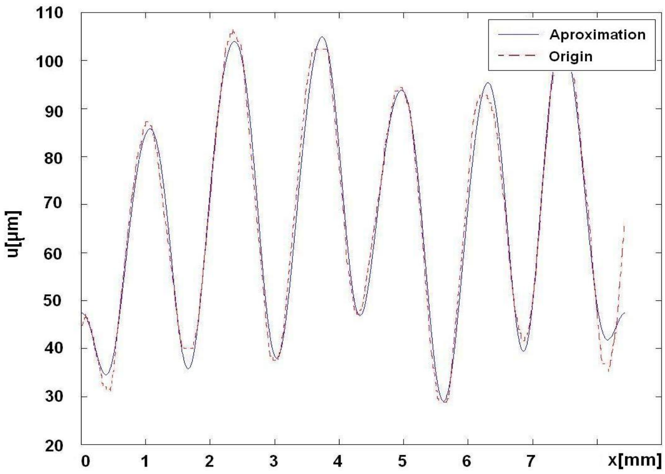

Fig. 4. Yarn axis approximation by 10 harmonics

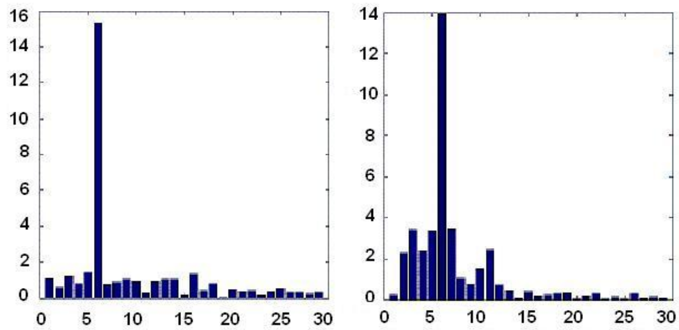

Fig. 5. Spectrum leakage. Left hand part – integer number of period sampled, right hand part – also a quarter of period used.

It was already said in previous chapter and presented in figures of this chapter that the actual yarn axis characteristics contain both the systematic and random components, irrespective of used domain. By the use of a lot of realizations, each component can be determined by statistical methods. A lot of such methods exist; results of only basic ones will be shown here.

At least 500 realisations are necessary for statistics calculations. Since we had only about 80 yarn axes of type shown in Fig. 3, we had to extent the number of realisations by dividing each axis graph into small parts containing only one simple period. The number of realisations increased about 8 times, but the mutual influence of neighbouring periods was destroyed. Therefore some information was lost.

An example of a well defined yarn axis approximation for one period and its spectrum are shown in Fig. 7. The stair wise shape of experimental curve, almost invisible in Fig. 7, is due to the small number of its points. It results also in the small number of harmonics. Since the approximated part has almost harmonically shape, higher harmonics have small values.

In this case of one period the spectrum dominant is the first harmonics. The amplitude and phase angle histograms for the first harmonics are in Fig. 8. We can estimate that the amplitude distribution is normal and the phase angle distribution is uniform.

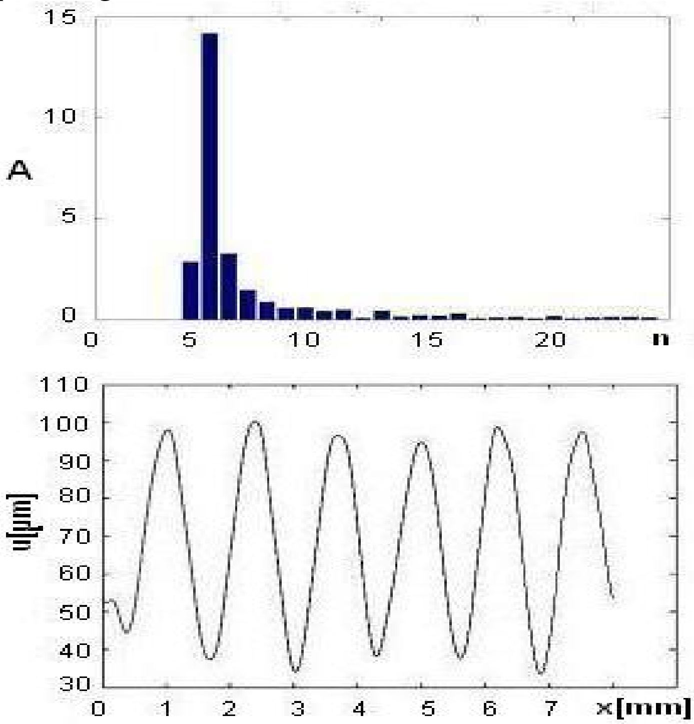

Fig. 6. Application of high pas filter, spectrum after filtration – top, corresponding yarn axis – bottom

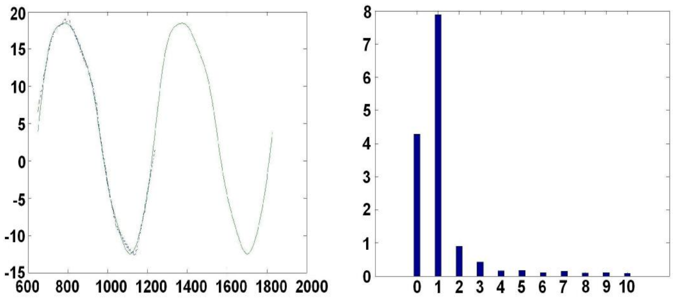

Fig. 7. Approximation of one period (left) and its amplitude spectrum (right).

However the histograms for higher harmonics are quite different. They have a common shape presented in Fig. 9 for the second harmonics. The amplitude histogram has a broad maximum for low values and can be approximated by a log-normal distribution. The phase angle histogram is a two modal one. Maximums of these histograms are for phase shit of 90^o and -90^o, while the minimums are for the same and opposite phase.

Convolution and correlation are basic signal processing operations. The result of correlation of two signals is a measure of their similarity. It is well known that correlation of the same signals (autocorrelation) results in a function of triangle shape, while the output of autocorrelation of ideal noise is the δ-function.

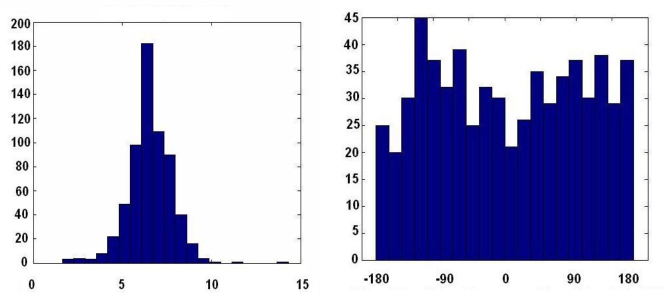

Fig.8. Histogram of amplitude and phase angle of the first harmonics

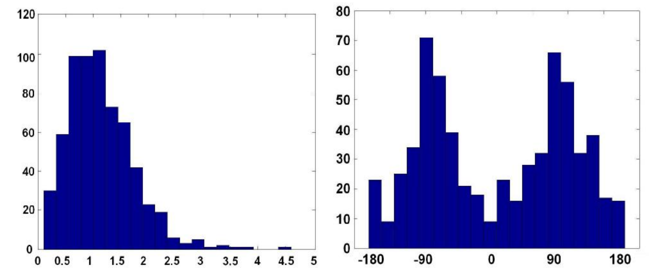

Fig. 9. Histogram of amplitude and phase angle of the second harmonics

The idea can appear that application of cross-correlation to the yarn axes allows getting a suitable measure of their similarity. Typical results are shown in Fig. 10 where the cross-correlation of two yarns is presented [2]. If both the yarns have the same number of periods, the results of correlation is very near to identical yarns, either in the case that the yarn shape is evidently different, see left hand part of fig. 10. However, the case of unequal number of period leads to cross-correlation that differs strongly from the ideal triangle; see the right hand part of Fig. 10. One period is missing in one of yarn axes in this special case.

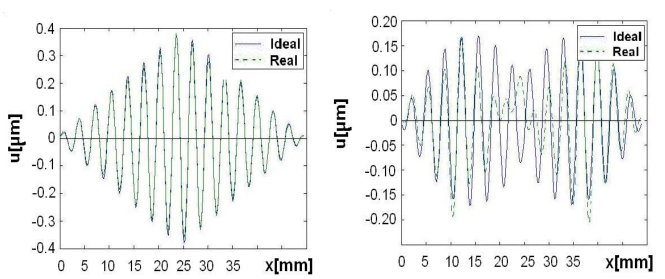

Fig. 10 Cros-correlation of yarns of same number of periods (left) and different number of periods (right)

In theory of random signals we consider a lot of realization of very long signals. In principle, the basic statistical characteristics can be measured either for a given time moment, e.g. across realizations, or for a one realization, e.g. along realization. The key features of random signals are those: they are stationary and ergodic. The signal is stationary, if the characteristics do not depend on the selection of the point at which or from which they are measured. The signal is ergodic, if the results obtained across realizations are the same as those along one realization. In the case of yarns the number of realizations is low, about 80, and their range is short, eight periods. Nevertheless, it follows from preliminary tests that both the features are present [2].

4 Discussion and Conclusions

Well-known digital and random signal processing methods were efficiently applied to textile structure. Some unexpected and surprising results were found when they had been considered as random signals. The statistic distribution of higher harmonics is more complicated than it was expected. The correlation does not reveal either evident difference in the shape of compared yarns. It is probably due to the smoothing effect of integration. However, if the basic periods of compared yarn differ, the correlation triangle changes dramatically.

Although only several results are given, the basic general conclusion follows from them: Suitable methods of signal theory can be very efficiently applied in textile material science. Especially it means that the DFT allows very effective yarn axis description and processing, leakage reduction, efficient approximation, suitable filtering, as typical examples.

Textile science is in its nature interdisciplinary. Interdisciplinary character requires interdisciplinary education. A part of such education should be at least bases of signal theory. Unfortunately the basic course of electrical engineering cannot include such specific and relatively complicated area. Therefore a special course should be provided in the future.

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References:

[1] M. Košek, B. Košková: Analysis of yarn wavy path periodicity of textile composites using discrete Fourier transform. Proc. Sixth International Conference on Composites Engineering, Orlando, Florida, June 27 – July 3, 1999, USA, pp. 427-428.

[2] M. Košek, P. Seják: Analysis of Stochastic Character of Yarn Waviness in Woven Composites, ICCE 11, Proc. of Eleventh International Conference on Composites/Nano Engineering, August 8-14, 2004, Hilton Head Island, USA pp. 377-378