2021 International Seminar on Electron Devices Design and Production (SED)

Features of the Implementation of the Extremal Filtration Method in the Distributed Optic-Fiber Temperature Sensor

Ivan A. Ershov, Oleg V. Stukach, Nina V. Myasnikova

***Abstract*—The signal processing method based on extremal filtration in low signal-to-noise ratio conditions was proposed. The extremal filtration is similar to the empirical mode decomposition (EMD) method, but complex mathematical calculations are absent that is the main advantage. Using it in real measuring devices significantly increases the speed rate. The extremal filtration process is an algorithm that involves sequentially repeating until an optimal result. The disadvantage of this method is decreasing the spatial resolution since every iteration due to a reduction in the number of samples. It is an especially negative fact in areas of sharp signal change. This paper demonstrates how to solve this problem using linear interpolation and to improve the result obtained by simple extremal filtration.**

***Keywords*—fiber optical temperature sensor; DTS; signal processing; spatial resolution; measurement accuracy; EMD data processing; Raman scattering.**

I. INTRODUCTION

The fiber-optic sensors (Fig. 1) are a new generation of measurement instruments that significantly exceed the classical electronic tools. Unlike their predecessors, the fiber-optic sensors are lighter, smaller, immune to electromagnetic interference, and have a high spatial resolution. In monitoring systems for dangerous industrial objects, these sensors reveal their potential completely. The optical fiber is a sensitive element several kilometers long. This allows the distributed measurements using only one sensor. This is physically impossible with classical electronic sensors.

One example of the monitoring system based on the fiber-optic temperature and strain sensors is proposed in the paper [1]. This paper shows clearly how detailed information about the state of an object can be obtained using fiber-optic sensors. The authors fulfilled a two-dimensional distribution of temperature and deformation during the heating and cooling of the object. Only three optical fibers were used for this. Such a high level of detailing is indispensable in the monitoring systems for dangerous production objects.

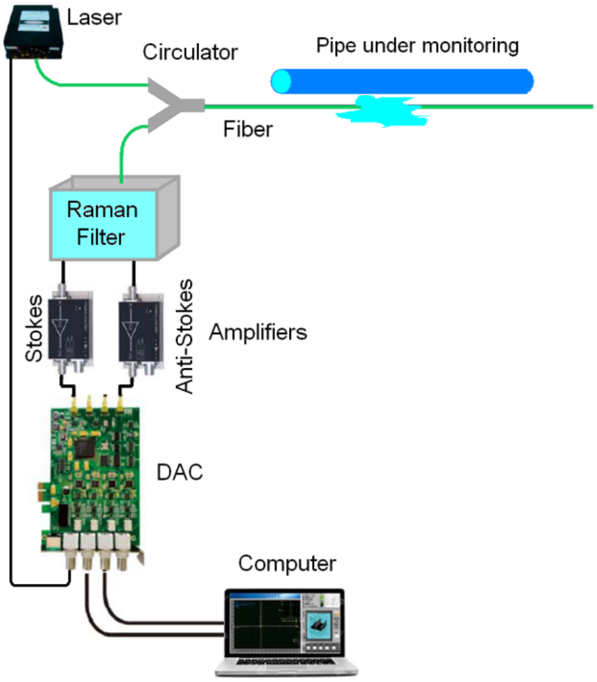

Fig. 1. Structure of the DTS

The authors of the paper [2] have developed monitoring of the behavior of the enclosure of a telecommunication tower. The sensors were installed both inside the building and outside. Thus, detailed data were obtained on the dependence of temperature on deformation. At the same time, the authors noted that measurements from sensors installed outside the building recorded unstable measurements due to the aggressive environment: hail, birds, rain. In this case, some of the measurements can not be considered as reliable. This paper shows one of the problems with fiber optic sensors: the low strength of the optical fiber. The use of the protective covers will be negatively affected by the device sensitivity.

In this paper, we use the experimental data from the fiber-optic temperature sensor based on Raman light scattering. The operation principle is based on receiving and measurement of the spectral components of the back-

---

Ivan Ershov is with Novosibirsk State Technical University, Novosibirsk, Russia, e-mail: ershov@corp.nstu.ru, ORCID: 0000-0003-1524-6508.

Oleg Stukach is with National Research University Higher School of Economics, Moscow, Russia; Novosibirsk State Technical University, Novosibirsk, Russia, e-mail: tomsk@ieee.org, ORCID: 0000-0001-6845-4285.

Nina Myasnikova is with Penza State University, Penza, Russia, e-mail: genok123@mail.ru.

978-1-6654-3941-1 @2021 IEEE

reflected signal called Stokes and Anti-Stokes that depends on temperature [3]. The time difference between the input and target signals is determined by the domain of the fiber to which the signal belongs to. There are a lot of methods for the optic-fiber measurement of temperature. For example, paper [4] presents a fiber-optic sensor based on Bragg gratings fiber (FBG). The authors measure the temperature and deformation of the magnetic core for a contactor. The fiber-optic sensor is ideal for such measurements due to its immunity to electromagnetic hindrances. The operation principle is based on the measurement of the Bragg wavelength displacement. Bragg wavelength shift occurs when the grating is deformed or the temperature is changed. The use of FBG to measure strain, made it possible to identify the electromagnetic force in the magnetic core contactor.

In addition to regular applications in monitoring systems, fiber-optic sensors are used to determine the object form. Paper [5] provides a detailed review of the current state-of-the-art of Fiber Optic Shape Sensors (FOSS). Fiber-optic sensors are ideal for these systems due to their advantages: flexibility, lightweight, small size, resistance to electromagnetic hindrances, corrosion resistance, ability to measure the multiple parameters, intrinsic safety. The authors write about such fields of application as civil engineering, industrial and aerospace engineering, and medicine. Fiber-optic sensors are a good replacement for traditional measurement methods. It may be the case therefore now there are many technical solutions in various fields of science and technology based on fiber-optic measurements.

One of the promising solutions is a new method and corresponding device that allow temperature measurements [6]. The operation principle is based on a distributed loss profile created from the laser beaming to fiber. It is used to adjust the ratio between the amplitudes of the Raman Stokes and anti-Stokes signals. This results in more accurate profiles in the distributed temperature sensors (DTS). Thus, measurement accuracy is achieved by changing the signal amplitude ratio in DTS.

The Dynamic Threshold Identification Method (DTIM) was proposed to use for detecting leaks in pipelines with an accuracy of 1 meter [7]. DTIM can determine the leak location based on the study of the thin structure of the received signal. In [8] the Fuzzy Temperature Difference Threshold Method (FTDTM) was proposed to use for detecting and predicting the efficiency of photovoltaic modules of solar cells. The central idea of the method is related to the formation of fuzzy ratios, the definition of relationship matrix, and the calculation of predicted temperature. There is ample evidence that the improvement of signal processing methods in sensors is required, with the use of dependence measures and possibly with dynamic identification.

II. MODELING

This paper deals with the extremal filtration problem likewise [9]. The challenge is to identify a signal with a low signal-to-noise ratio (SNR). Many engineers use standard signal processing methods [10–12]. However, these methods are frequently ineffective, which requires thousands of realizations for the signal to be used for SNR compensation. There is no general effective method for signal processing with a high noise level. So this article deals with solving this problem.

As in previous work [9], extremal filtration is a key processing step in DTS. This method perfectly processes signals without sharp changes of the mathematical expectation. The disadvantage of this method is connected with decreasing the spatial resolution after series of iterations. Some solving approach for this problem is described in the paper. For amplification of the research, we use 20 series of the signal from a real fiber-optic temperature sensor. The signal is the anti-Stokes component $U(s)$, which is used to calculate the temperature (Fig. 2).

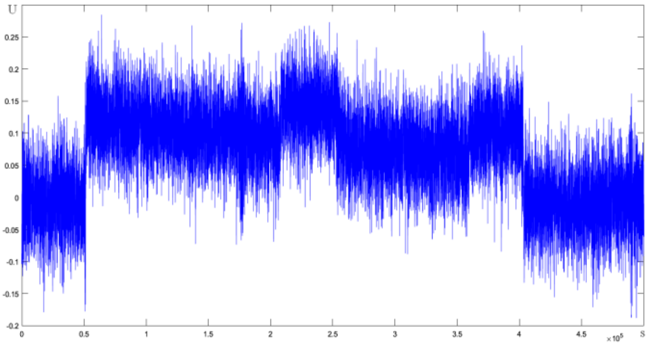

Fig. 2. The original signal

The extremal filtration is analogous to the more well-known Empirical Mode Decomposition (EMD) method. An essential difference between extremal filtration and EMD is the lack of complex mathematical calculations. In practice, using this method instead of EMD, you can significantly increase system performance. This is especially true for remote monitoring. The extremal filtration method is described in detail in [13].

The iterations of the extremal filtration are repeated sequentially many times until an optimal result. Fig. 3 shows the processing results after each iteration.

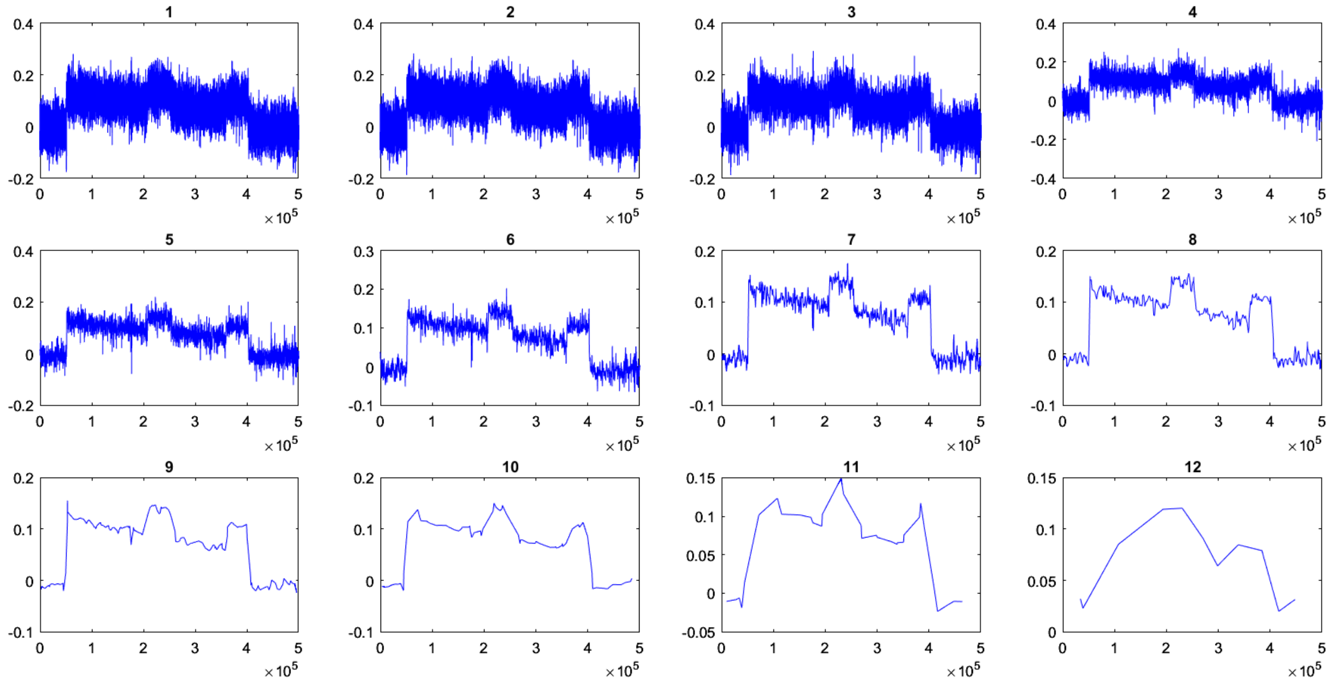

Fig. 3. Iterations of the signal processing

The signal becomes smoother with each new iteration of the program. Nevertheless, the rise time and fall time for the signal become increased, which negatively affects the characteristics of a measurement device. This problem is visible in Fig. 4, which shows the domain of a sharp amplitude change in the signal and the result of filtering in this domain.

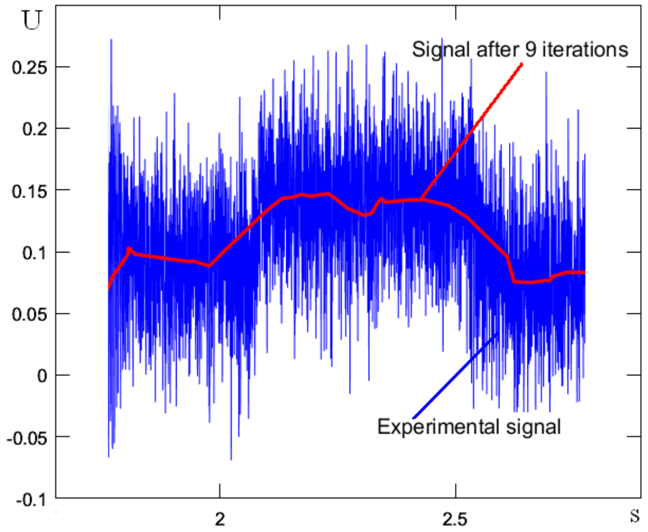

Fig. 4. Part of the signal before and after extremal filtration

The solution is to replace the domain of the rise- and fall time after filtering by field of the signal that has been processed through fewer program iterations. So it is necessary to support an automatic searching for the rise- and fall times. The most logical solution is to use a derivative chart. But if you put the original signal and its derivative to the chart, it will be impossible to detect the domain of the sharp amplitude changes due to the high noise level. Therefore, the signal after nine iterations was used. The rise- and fall time domains are much more marked on it (Fig. 5).

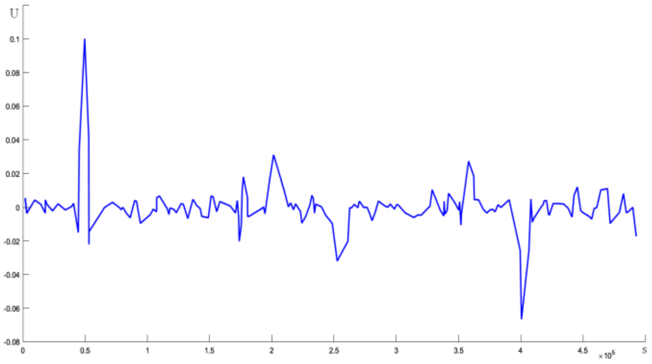

Fig. 5. A derivative of the signal after 9 iterations

Next, using linear interpolation we replace the domains of the rise- and fall times after 10 iterations (Fig. 6).

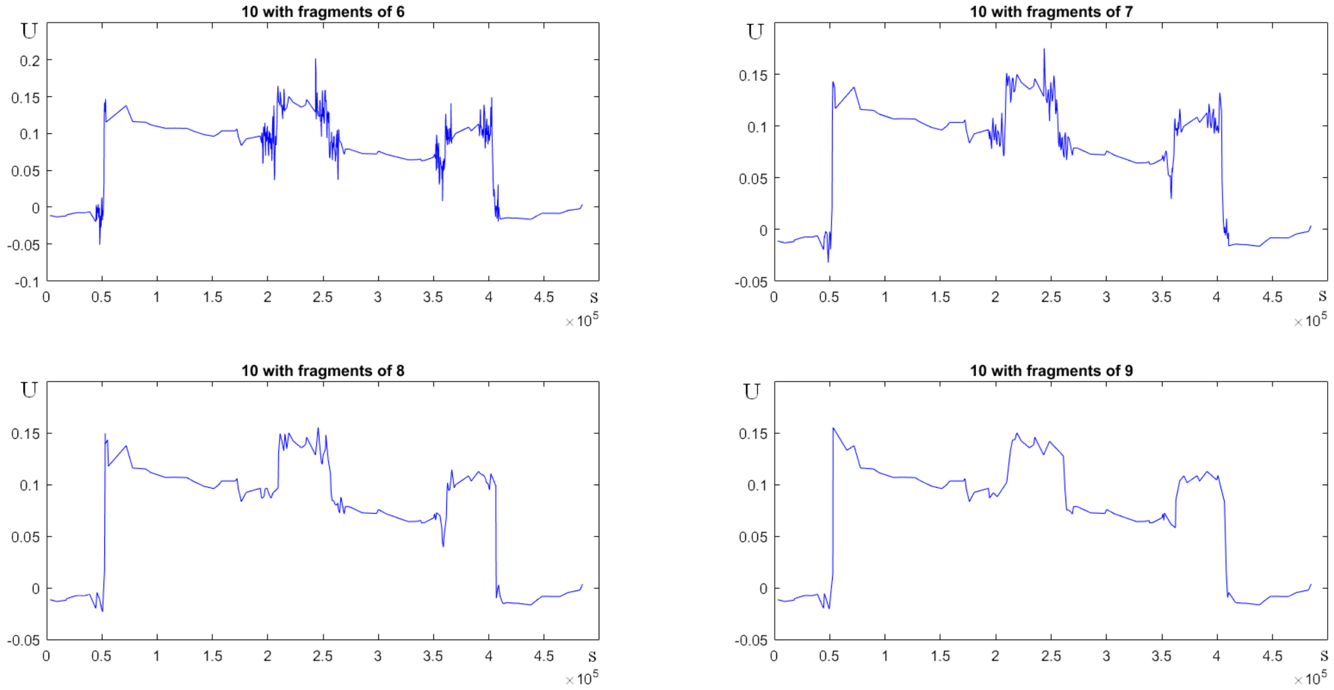

Fig. 6. The filtered signal after linear interpolation

It would be the best option to choose a signal with fragments after seven iterations. The use of signals after larger iterations will lead to a significant spatial resolution decrease (Fig. 7). To reduce the noise in the fields of the rise- and fall time of the signal, we use the averaging of series. The result for averaging of 20 signals after extremal filtration with the replacement of fragments by linear interpolation is shown in Fig. 7.

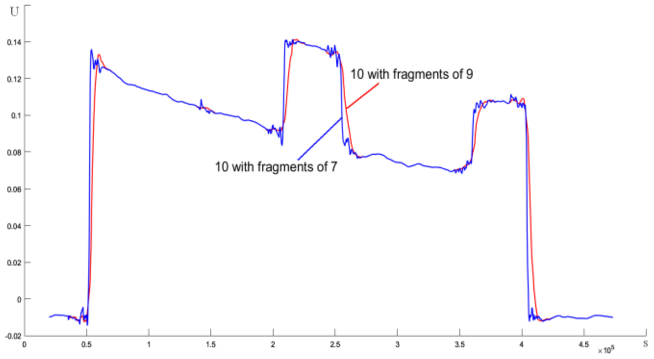

Fig. 7. Averaging of 20 filtered series

A significantly more series are required to achieve a similar result using classical methods. At the same time, extremal filtration does not contain complex mathematical calculations that will significantly reduce the system performance. This is an important factor for choosing the method for implementation in measurement systems.

III. CONCLUSION

The design of the fiber-optic sensors is a promising direction. Year by year there is a growing number of fields where fiber-optic sensor systems are replacing the classic electrical sensors. It is impossible to achieve maximum accuracy only by improving the hardware, especially when measurements involve signal processing with a low SNR. Extremal filtration is one technique that can be used in practice. It allows increasing the operation rate of the system due to a small number of series of the signal without complex mathematical operations. A similar EMD method loses out to extremal filtration in terms of operation rate due to the use of the spline interpolation. Method of averaging a set of signal loses in performance due to measurement thousands of signal sets and the absence of a rigorous mathematical justification for the result reliability.

IV. ACKNOWLEDGMENTS

This study has been funded by Russian Foundation for Basic Research according to the research project N 20-08-00321 “Increasing of the Spatial and Temperature Resolution of the Information Signal in the Distributed Temperature Sensors”.

REFERENCES

[1] Wenyu Liao, Yiyang Zhuang, Chao Zeng, Wen Deng, Jie Huang, Hongyan Ma, “Fiber optic sensors enabled monitoring of thermal curling of concrete pavement slab: Temperature, strain and

inclination," *Measurement*, 2020, Vol. 165, DOI: 10.1016/j.measurement.2020.108203.

[2] R. Unzu, J.A. Nazabal, G. Vargas, R.J. Hernández, C. Fernández-Valdivielso, N. Urriza, M. Galarza, M. Lopez-Amo, "Fiber optic and KNX sensors network for remote monitoring a new building cladding system," *Automation in Construction*, 2013, Vol. 30, DOI: 10.1016/j.autcon.2012.11.005.

[3] O.V. Stukach, I.V. Sychev, "Signal Processing in the Distributed Temperature Sensors by Raman Backscatter: Review of New Outcomes", *Radioengineering*, 2018, no. 3, pp. 86–92. URL: http://www.radiotec.ru/number/1764.

[4] Cesar Caytuiro Tapia, Jorge Luis Roel Ortiz, Uilian José Dreyer, Jean Carlos Cardozo da Silva, Kleiton de Morais Sousa, "Evaluation electromagnetic contactor magnetic core temperature and dynamic strain using fiber Bragg gratings," *Measurement*, 2020, Vol. 166, DOI: 10.1016/j.measurement.2020.108174.

[5] Ignazio Floris, Jose M. Adam, Pedro A. Calderón, Salvador Sales, "Fiber Optic Shape Sensors: A comprehensive review," Optics and Lasers in Engineering, 2021, Vol. 139, DOI: 10.1016/j.optlaseng.2020.106508.

[6] United States Patent No. US 7585107 B2, "Corrected DTS measurements based on Raman-Stokes signals". Inventors: Domino Taverner, Trevor MacDougall. Date Sep. 8, 2009, MPC, GOIK L/6, GOL 5/00.

[7] Yang Xu, Jian Li, Mingjiang Zhang, Tao Yu et al "Pipeline Leak Detection Using Raman Distributed Fiber Sensor With Dynamic Threshold Identification Method", *IEEE Sensors Journal*, July 2020, Vol. 20, Issue 14, P. 7870-7877, DOI: 10.1109/JSEN.2020.2980366, URL: https://ieeexplore.ieee.org/document/9034004.

[8] Tao Yu, Chunguang Ren, Yanbing Jia, Jian Li, et al "Photovoltaic Panel Temperature Monitoring and Prediction by Raman Distributed Temperature Sensor With Fuzzy Temperature Difference Threshold Method", *IEEE Sensors Journal*, January 2021, vol. 21, Issue 1, P. 373–380, DOI: 10.1109/JSEN.2020.3015508, URL: https://ieeexplore.ieee.org/document/9164943.

[9] I.A. Ershov, O.V. Stukach, N.V. Myasnikova, I.B. Tsydenzhapov and I. V. Sychev, "The Resolution Enhancement in the Distributed Temperature Sensor with the Extremal Filtration Method," 2020 Dynamics of Systems, Mechanisms and Machines (Dynamics), Omsk, Russia, 2020, pp. 1-3, doi: 10.1109/Dynamics50954.2020.9306163.

[10] Pingyu Zhu, Xiaobo Xie, Xiaopeng Sun, Soto M.A. "Distributed modular temperature-strain sensor based on optical fiber embedded in laminated composites," *Composites Part B: Engineering*, 2019, Vol. 168, pp. 267-273, URL: https://ieeexplore.ieee.org/document/9306163

[11] Jacob T.A., Matty E.P., Fronk B.M. "Experimental investigation of in-tube condensation of low GWP refrigerant R450A using a fiber optic distributed temperature sensor," *International Journal of Refrigeration*, 2019, Vol. 103, pp. 274-286.

[12] Wang Z.L., Zhang S.S., Chang J., Lv G.P., et al "Adaptive data acquisition algorithm in Raman distributed temperature measurement system," *Optik*, 2014, Vol. 125, Iss. 8, pp. 1821-1824.

[13] N.V. Myasnikova, M.P. Beresten, M.G. Myasnikova, "Development of Decomposition Methods for Empirical Modes Based on Extremal Filtration," *2020 Moscow Workshop on Electronic and Networking Technologies (MWENT)*, Moscow, Russia, 11–13 March, DOI: 10.1109/MWENT47943.2020.9067378. URL: https://ieeexplore.ieee.org/document/9067378.