Nuclear Engineering and Technology 53 (2021) 3122–3125

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

Signal processing method of bubble detection in sodium flow based on inverse Fourier transform to calculate energy ratio

Wei Xu [a], Ke-Jun Xu [a, b, *], Xin-Long Yu [a], Ya Huang [a], Wen-Kai Wu [a]

[a] School of Electrical and Automation Engineering, Hefei University of Technology, Hefei, 230009, PR China
[b] Engineering Technology Research Center of Industrial Automation, Anhui Province, Hefei, 230009, PR China

ARTICLE INFO

Article history:
Received 15 July 2020
Received in revised form
18 March 2021
Accepted 26 March 2021
Available online 6 April 2021

Keywords:
Sodium-cooled fast reactor
Steam generator
Leak detection
Electromagnetic vortex flowmeter
Signal processing method

ABSTRACT

Electromagnetic vortex flowmeter is a new type of instrument for detecting leakage of steam generator, and the signal processing method based on the envelope to calculate energy ratio can effectively detect bubbles in sodium flow. The signal processing method is not affected by changes in the amplitude of the sensor output signal, which is caused by changes in magnetic field strength and other factors. However, the detection sensitivity of the electromagnetic vortex flowmeter is reduced. To this end, a signal processing method based on inverse Fourier transform to calculate energy ratio is proposed. According to the difference between the frequency band of the bubble noise signal and the flow signal, only the amplitude in the frequency band of the flow signal is retained in the frequency domain, and then the flow signal is obtained by the inverse Fourier transform method, thereby calculating the energy ratio. Using this method to process the experimental data, the results show that it can detect 0.1 g/s leak rate of water in the steam generator, and its performance is significantly better than that of the signal processing method based on the envelope to calculate energy ratio.

1. Introduction

In a sodium-cooled nuclear reactor, the steam generator is a heat exchange device between sodium and water [1]. It may occur a leakage to cause a sodium-water reaction accident [2,3]. The product of sodium-water reaction is very corrosive, which will accelerate the leakage of steam generator and cause serious safety accidents [4,5]. Therefore, it is necessary to detect whether the steam generator has leaked in time [6].

The electromagnetic vortex flowmeter is composed of two parts: a sensor and a transmitter (a signal excitation and processing system). It is used to detect whether the sodium flow contains hydrogen bubbles generated by the sodium-water reaction, so as to determine whether the steam generator in the fast reactor has leaked. The electromagnetic vortex flowmeter is installed on a pipe 1–2 m away from the steam generator, and the sodium flow rate in the pipe is greater than 1 m/s. The bubbles will flow with the liquid sodium, so it can be considered that the speed of the bubble is close to the speed of the liquid sodium. Therefore, the time delay caused by bubble transport is not more than 2 s. The sensor signal formation time and the signal processing time add up to less than 2 s. So, when the electromagnetic vortex flowmeter is used to detect bubbles, the response time is only a few seconds. The signal processing method plays a vital role when the electromagnetic vortex flowmeter is used to detect leakage. In Ref. [7], the signal processing method based on the envelope to calculate energy ratio (ER) is proposed, that is, (1) It is regarded that the sensor output signal is composed of flow signal and bubble noise signal. (2) According to its envelope, first the bubble noise signal is extracted, and then the flow signal is calculated. (3) The energy of the signal is regarded as the numerator, and the energy of the sensor output signal is regarded as the denominator, and then the ER of the sensor output signal is obtained. However, this signal processing method sacrifices the sensitivity of the electromagnetic vortex flowmeter when detecting bubbles in sodium flow. This is because the bubble noise signal also introduces local maximum and local minimum points. When searching for the local maximum and local minimum points of the sensor output signal, there is no guarantee that all the local maximum and local minimum points are generated by the flow signal, so that the flow signal calculated by the envelope has a

* Corresponding author. School of Electrical and Automation Engineering, Hefei University of Technology, 193 Tunxi Road, Hefei, 230009, PR China.
E-mail addresses: xwhfut@163.com (W. Xu), dsplab@hfut.edu.cn (K.-J. Xu), 377512419@qq.com (X.-L. Yu), 15556960878@163.com (Y. Huang), wenkai_wu@qq.com (W.-K. Wu).

https://doi.org/10.1016/j.net.2021.03.025

certain deviation from the actual flow signal.

To this end, a new kind of signal processing method is proposed to calculate the ER for improving the sensitivity of electromagnetic vortex flowmeter in detecting bubbles in sodium flow.

2. Research on signal processing method

The characteristics of the sensor output signal is compared and analyzed when there are no bubbles in the sodium flow and when there are bubbles in the sodium flow. The collection conditions of the experimental data used in this short paper are exactly the same as the collection conditions of the experimental data used in Ref. [7]. The frequency bands between the flow signal and the bubble noise signal in the sensor output signal are different, so the inverse Fourier transform method is used to calculate the flow signal in the sensor output signal, and then the ER corresponding to the sensor output signal is calculated, thereby improving the sensitivity of judging the bubbles in the sodium flow according to the ER.

2.1. Signal characteristics

By comparing the difference of the sensor output signal in the frequency domain, the influence of bubbles on the composition of the sensor output signal is determined. To this end, the sensor output signals are compared for different gas injection flow rates at the same sodium flow rate. The signals with a time length of 10s are randomly selected from the sensor output signal when the gas injection flow rate is 0 L/min and 0.8L/min, respectively, and the corresponding amplitude spectra are calculated, as shown in Fig. 1 and Fig. 2. It can be seen that the influence of bubbles on the sensor output signal is mainly reflected in the low frequency band, and regardless of whether the sodium flow contains bubbles, the frequency band of the flow signal is concentrated in a relatively narrow frequency band, such as the frequency band between the red dotted lines in Figs. 1 and 2.

2.2. Signal processing method based on inverse Fourier transform to calculate energy ratio

Due to the characteristics of the sensor output signal in the frequency domain, the frequency band where the flow signal is located is almost not affected by bubbles, so extracting the flow signal in the frequency domain can be closer to the actual flow signal. The flow signal is extracted in the frequency domain by the inverse Fourier transform method. The specific method of extracting the flow signal is: convert the sensor output signal from the time domain to the frequency domain, and only retain the amplitude in the frequency band of the flow signal in the frequency domain, then, the inverse Fourier transform is used to convert the amplitude in the frequency domain to the time domain, and the recovered time domain signal is the flow signal.

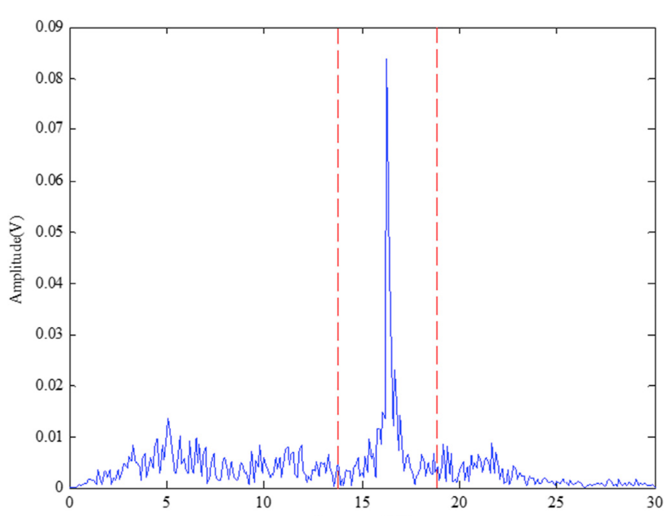

Fig. 1. The amplitude spectrum of the sensor output signal when the gas injection flow rate is 0 L/min.

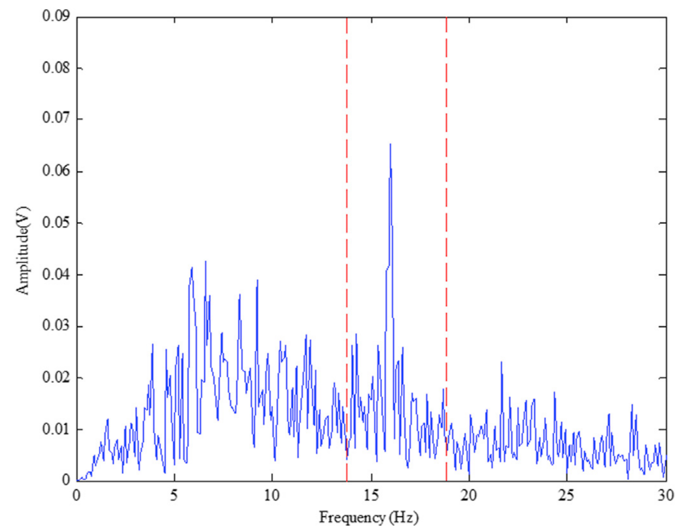

Fig. 2. The amplitude spectrum of the sensor output signal when the gas injection flow rate is 0.8 L/min.

Assume that the sensor output signal is $x(0), x(1), x(2), \ldots, x(N-1)$, where N is the number of points in the sensor output signal sequence. A fast Fourier transform (FFT) algorithm is used to convert the sensor output signal from the time domain to the frequency domain.

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j\frac{2\pi}{N}kn}, \quad k = 0, 1, \ldots, N-1 \tag{1}$$

where $X(k)$ represents the frequency domain sequence.

A number m such that $|X(m)|(\ m = 0, 1, \ldots, N/2-1)$ is maximal is found.

According to the frequency width Δf of the flow signal in the frequency domain, only values in the number interval $[m-a, m+a]$ and the number interval $[N-\ m-\ a, N-\ m+a]$ of $X(k)(\ k = 0, 1, \ldots, N-1)$ is reserved, and the values in other number intervals are all set to 0, where a is equal to the integer part of $\frac{m}{N} f_s$, and f_s is the sampling frequency of the sensor output signal. Denote the modified frequency domain sequence as $X_{\mathrm{mod}}(k)(\ k = 0, 1, \ldots, N-1)$. In this way, only the amplitude within the frequency band where the flow signal is located is retained in the frequency domain.

Then the inverse Fourier transform of $X_{\mathrm{mod}}(k)(\ k = 0, 1, \ldots, N-1)$ is calculated, and the frequency-domain sequence is converted to the time-domain sequence to obtain the flow signal, which are respectively recorded as $x'(0), x'(1), x'(2), \ldots, x'(N-1)$,

The ER of the sensor output signal is

$$ER = \frac{\sum_{n=0}^{N-1} x'(n)^2}{\sum_{n=0}^{N-1} x(n)^2} \quad (2)$$

The steps of the signal processing method for bubble detection in sodium flow based on the inverse Fourier transform to calculate the ER are:

(1) Starting from the first point in the collected sensor output signal, 2,048 data points are continuously selected.
(2) According to the above calculation process, the ER corresponding to the selected 2,048 point signal is calculated.
(3) Perform sliding update on the selected 2,048 data points. Each time the data of 100 points is updated, that is, the first 100 points of the 2,048 data points are discarded, and 100 points of new data are added at the end to reconstruct 2,048 points, and the corresponding ER is calculated again.
(4) Repeat step (3) until all values of ER are calculated.
(5) Perform a moving average filter on all values of ER. Starting from the first value of ER, 10 values of ER are selected consecutively and sorted, and the middle 4 values of ER are selected for averaging as the final result.
(6) Perform sliding update on the selected 10 values of ER. Each time the value of ER is updated 1 point, the first of the 10 values of ER is discarded, and a new value of ER is added at the end to reconstruct the 10 values of ER to calculate the filter result.
(7) Repeat step (6) until all values of ER are updated.

3. Experimental data verification results

According to the above steps, the signals collected under different sodium flow rates are processed, and the calculated values of ER are drawn in the same figure, as shown in Fig. 3. In the figure, QL represents the gas injection flow rate. It can be seen that the values of ER of the sensor output signal calculated by the inverse Fourier transform method are greater than 0.7 when the sodium flow does not contain bubbles and are almost all less than 0.7 when the gas is injected into the sodium flow at the flow rate of 0.8 L/min. It can also be seen from Fig. 3 that when gas is injected into the sodium pipe, the processing result of the sensor output signal fluctuates significantly. This is because the density of hydrogen is much lower than that of liquid sodium, so when hydrogen and liquid sodium are in the same pipe, stratification will occur. The vortex generator in the sensor is used to fully mix the hydrogen bubbles and the liquid sodium. However, it cannot achieve uniform mixing. As a result, the sensor output signal is sometimes greatly affected by bubbles and sometimes less affected by bubbles. Therefore, when the liquid sodium contains bubbles, the fluctuation range of the processing results of the signal processing method will be larger, which can also reflect the reliability of the signal processing method when it is used to distinguish the sensor output signal not affected by bubbles and the sensor output signal affected by bubbles.

This shows that the values of ER of the sensor output signal calculated based on the inverse Fourier transform method can effectively identify the gas injection flow rate of 0.8 L/min, that is, the leak rate of water in the steam generator can be detected as 0.1 g/s.

For comparison, the same set of data is processed according to the steps of the signal processing method for detecting bubbles in sodium flow based on the envelope to calculate ER given in Ref. [7], and the calculated values of ER are also plotted in the same figure, as shown in Fig. 4. It can be seen that when the sodium flow rate is large, no matter whether the sodium flow contains bubbles, the sensor output signal cannot be reliably distinguished according to the ER, so the ER calculated according to the method given in Ref. [7] cannot identify the situation when the gas injection flow rate is 0.8 L/min.

4. Conclusion

From the perspective of frequency domain, it is found that the influence of bubbles on the sensor output signal is mainly reflected in the low frequency band, and the bubbles hardly affect the frequency band where the flow signal is located. Therefore, the flow signal is extracted in the frequency domain. A signal processing method for bubble detection in sodium flow based on the inverse Fourier transform to calculate the ER is proposed. The sensor output signal is first converted from the time domain to the frequency domain. In the frequency domain, only the amplitude within the frequency band of the flow signal is retained, and then the inverse Fourier transform is used to convert the amplitude in the frequency domain to the time domain to obtain the flow signal. Using the energy of the flow signal as the numerator and the energy of the

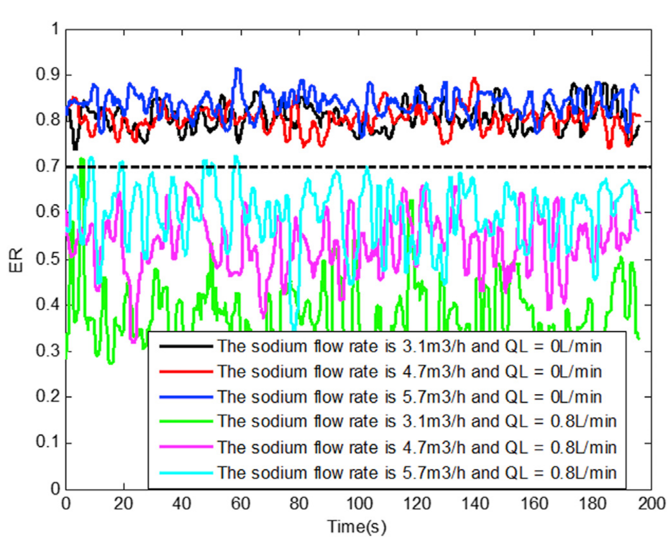

Fig. 3. The values of ER calculated by inverse Fourier transform.

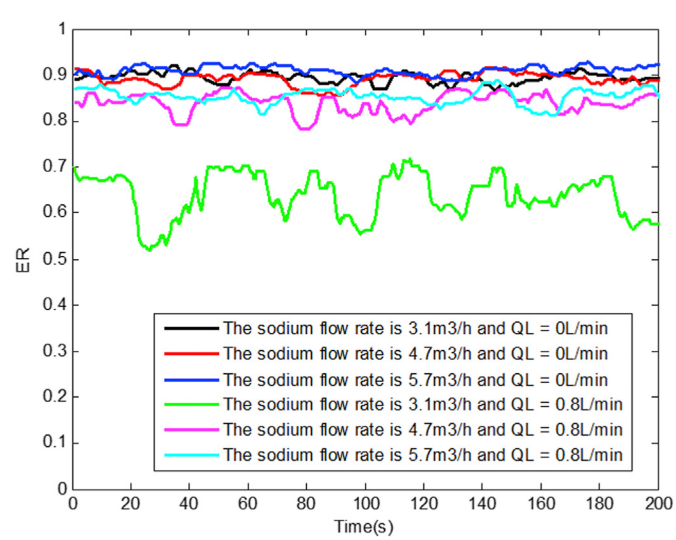

Fig. 4. The values of ER calculated by the envelope calculation.

sensor output signal as the denominator, the ER of the sensor output signal is calculated. The experimental data are used to verify the signal processing method of bubble detection in sodium flow based on the inverse Fourier transform to calculate the ER and the signal processing method of bubble detection in sodium flow based on envelope to calculate the ER, respectively. The verification results show that the signal processing method of bubble detection in sodium flow based on envelope to calculate the ER can detect the leak rate of water in the steam generator is 0.2 g/s and the signal processing method of bubble detection in sodium flow based on the inverse Fourier transform to calculate the ER can detect the leak rate of water in the steam generator is 0.1 g/s.

Declaration of competing interest

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.

Acknowledgements

This work was supported by the National Key Research and Development Plan of China (No. 2018YFB2003900). Thanks to Chongqing Chuanyi Automation Co., Ltd. in Chongqing city, China for providing the EVFM sensors and experimental conditions.

References

[1] S. Kishore, A.A. Kumar, S. Chandramouli, B.K. Nashine, K.K. Rajan, P. Kalyanasundaram, S.C. Chetal, An experimental study on impingement wastage of Mod 9Cr 1Mo steel due to sodium water reaction, Nucl. Eng. Des. 243 (2012) 49–55. https://10.1016/j.nucengdes.2011.11.008.
[2] D.J. Hayes, Water leaks in sodium-heated fast reactor boilers, Phys. Technol. 9 (3) (1978) 96, https://doi.org/10.1088/0305-4624/9/3/I04.
[3] B. Raj, S.L. Mannan, P.R.V. Rao, M.D. Mathew, Development of fuels and structural materials for fast breeder reactors, Sadhana 27 (5) (2002) 527–558, https://doi.org/10.1007/bf02703293.
[4] J.Y. Jeong, T.J. Kim, J.M. Kim, B.H. Kim, N.C. Park, Analysis of micro-leak sodium-water reaction phenomena in a sodium-cooled fast reactor steam generator, Kor. J. Chem. Eng. 26 (4) (2009) 1004–1008, https://doi.org/10.1007/s11814-009-0167-x.
[5] V. Sumathi, S. Jalaldeen, P. Selvaraj, S. Murugan, Vibration of core subassemblies due to large sodium–water reaction in the steam generator of a Liquid Metal Fast Breeder Reactor, Prog. Nucl. Energy 106 (2018) 231–239. https://10.1016/j.pnucene.2018.03.005.
[6] R. Hans, K. Dumm, Leak detection of steam or water into sodium in steam generators of liquid-metal fast breeder reactors, Atom. Energy Rev. 15 (4) (1977) 611–699, https://doi.org/10.1016/0378-4487(77)80006-X.
[7] W. Xu, K.J. Xu, J.P. Wu, et al., Signal processing method based on energy ratio for detecting leakage of SG using EVFM, Nuclear Eng Technol (2020). https://10.1016/j.net.2020.01.023.