Towards applicability of wavelet-based cross-correlation in locating leaks in steel water supply pipes

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Abstract. The paper discussed the application of wavelet-based cross-correlation analysis to the processing of the leak noise signals acquired in the field. Nine recordings produced with the commercial leak noise correlator are considered in this study. All the cases are considered as classified as challenging for signal interpretation. For most of the cases, the basic correlation technique proved to be insufficient to measure the time lag with the required confidence. We implemented a wavelet cross-correlation algorithm for time lag estimation. At least in five cases out of nine, it managed to estimate time lag accurately. In three of the remaining cases, it failed. Unfortunately, due to a lack of information on field studies when records were produced, we are not able to investigate the reason of failures. We concluded that the proposed solution is practical and can be implemented in the software of leak noise correlators.

1. Introduction
The article is devoted to the practical application of wavelet analysis to the problems of identification and location of leaks in metal water supply networks. Determining the position of pipeline leaks is an important practical task for which many methods are used [1, 2] - in-pipe mobile robots [3], acoustic and ultrasonic active and passive methods [4], hydraulic pressure and flow methods [4, 5], and more.

A common non-destructive method of examination of small sections of water pipes is the usage of leak noise correlators. This method has a forty-year history of use in practice [6] and since it has proven itself well both with metal pipes [7] and with polymer and plastic pipes [8]. It should be noted, that the application for plastic pipes is conventionally considered a more complex task [9, 10] and its effective solution normally requires non-trivial approaches to process signals [10-15].

Despite the fact that the problem of detecting leaks in metal pipelines is regarded solved, actually, this is not always the case. In the practice of using leak noise correlators, cases arise when the diagnosis of metal pipelines is difficult and results are hard to be interpreted. This may be due to a variety of factors, such as the impossibility of high-quality installation of sensors, the specific location of the pipe tray, or the presence of extraneous noise at the worksite. In these cases, the basic correlation technique described in [16] is insufficient to correctly estimate the lag time. With these cases, more complex signal processing algorithms are required, as, for example, time-frequency analysis [10, 17]. This article describes the use of wavelet-cross-correlation (WCC) analysis for processing signals acquired in the practical study of water supply networks.
2. Materials and methods

The work is devoted to the use of WCC analysis for processing recordings of vibroacoustic signals acquired in the course of the examination of various water supply pipes using a leak noise correlator. All signal recordings were obtained in the field using the Kaskad-3 commercial correlator [18] described further in this section. For signal processing, the mathematical apparatus of continuous wavelet transform (CWT) was applied. The implementation of CWT to correlation analysis of time series is described in more detail in [19]. The signal processing algorithm is briefly introduced and explained in the final part of this section. The software implementation of the algorithm was carried out mainly in Mathcad Prime 4, however, Matlab 2020b was also used to visualize and interpret the results.

2.1 Leak noise correlator

All signal recordings were obtained in the field using the leak noise correlator Kaskad-3 by RentTechnologies Ltd [18]. The equipment is shown in Figure 1. The device is designed to search for leaks on pipes with diameters varying from 80 mm to 1200 mm and with a longness of the surveyed line higher than 40 m.

![Figure 1. Leak noise correlator Kaskad-3 produced in Moscow (Russia) by RentTechnologies Ltd.](image)

The characteristics of the correlator are available online on the official website of the manufacturer [18]. It should be noted that non-trivial cases are investigated in the work, therefore some recordings were acquired under conditions partially inconsistent with the measurement requirements.

2.2 Wavelet based cross-correlation

The algorithm used for the computation of the WCC function is based on the time-frequency correlation analysis technique described in [20] and on a technique of precomputation of discrete filters banks corresponding to the type of the mother wavelet proposed in [21]. A detailed justification and demonstration of the used algorithm are presented in [19]. This subsection is a brief description of it.

Let us assume that we have stereo recordings of noise-leak signals $s_A(t)$ and $s_B(t)$ captured by the sensors on the opposing sides of the pipe under the examination. We will take that both of these signals are sampled with the constant sampling interval $\Delta$. So we have two time series $s_A(t_i)$ and $s_B(t_i)$ ($t_i = \Delta i$).

The number of ticks in each sound channel of the recording is dependent on both sampling interval $\Delta$ and on the duration of the recording session $T$. For all considered cases $\Delta \approx 1/22000$ sec$^{-1}$ and $T \approx 3$ min so the total number of ticks $U = T \Delta$ is rather big to be processed within the single time window. To deal with this problem we applied the technique of signal segmentation, described in [22]. We divided samples on $Q$

$$Q = \left\lfloor \frac{U}{N} \right\rfloor$$
nonoverlapping segments with \( N \) ticks in each one. In the equation above, floor brackets denote the rounding to the closest smaller integer value.

To compute the WCC we use the formula below for various scale factors \( m = 0, 1, \ldots, M-1 \) [19]

\[
 r_{AB}^{(m)}(\tau) = F^{-1} \left[ \Psi_m \times \sum_{q=0}^{Q-1} F\left(s_{AB}^{(q)}\right) \times F\left(s_{AB}^{(q+1)}\right) \right].
\]

where \( F \) – forward discrete Fourier transform (DFT), \( F^{-1} \) – inverse DFT, \( \ast \) - element-wise complex conjugation, \( \times \) - element-wise product, \( \Psi_m \) – filter response function for scale factor \( m \), and superscript \( q \) denotes the ordinal number of the data segment used. We used a fast Fourier transform algorithm for DFT, so we considered \( N = 2^n \) (\( n \) - integer).

Set of filter response functions \( \Psi \) was computed once for predetermined number of frequency intervals \( M = n \) and for particular mother wavelet \( \psi(x) \) [21]

\[
 \Psi_m = F^{-1}(\psi_m) \times F(\psi_m), \ m = 0, 1, \ldots, n-1
\]

\[
 \psi_m(x_j) = \frac{1}{\sqrt{a_0^m}} \cdot \psi\left( \frac{j \cdot \Delta}{a_0^m}\right), \ j = -\frac{N}{2}, \frac{N}{2} + 1, \ldots, \frac{N}{2} - 1.
\]

It should be noted, that the mother wavelet could be real- or complex-valued. In the latter case, WCC function \( r_{AB} \) will be complex-valued as well. In this study, we used real-valued Difference of Gaussian mother wavelet

\[
 \psi(x) = e^{-x^2} - \frac{1}{2} \cdot e^{-\frac{x^2}{8}}.
\]

3. Results and discussion
We examined nine sets of recordings obtained during the examination of metal pipelines. In each case, after a visual inspection, a leak was detected and its location was pinpointed. Unfortunately, we were not able to get comprehensive data on the parameters of the pipeline and the leak for every case.

All recordings were processed in the similar way described above. The filter bank was computed once prior to the experiment. The size of the data segment and the range of variation of the scale factor were chosen as \( m = n = 16 \) (\( N = 2^{16} \)).

3.1 Leak noise signals
Available information on considered cases is in table 1. The reference diagram is in figure 2.

\[
 D \quad L \quad sensor A \quad sensor B \quad leak
\]

**Figure 2.** Reference diagram of employment of leak noise correlator.
Table 1. Parameters of recordings and corresponding practical cases.

| Case | Recording parameters | Pipe parameters | Leak |
|------|----------------------|-----------------|------|
|      | 1 / Δ, Hz | Duration, min | D, mm | L, m | Material | X, m |
| 1    | 22050     | 1.02           | 500   | 139  | Steel    | 46   |
| 2    | 21362     | 3.00           | 700   | 138  | Steel    | 46   |
| 3    | 21362     | 3.00           | 100   | 75   | Steel    | 51   |
| 4    | 21362     | 3.00           | 100   | 92   | Steel    | 86   |
| 5    | 22050     | 1.01           | 300   | 126  | Steel    | 33   |
| 6    | 21333     | 2.00           | 300   | 89   | Steel    | 23   |
| 7    | 21333     | 2.00           | 90    | 32   | Steel    | 14   |
| 8    | 21333     | 2.00           | 100   | 137  | Steel    | 40   |
| 9    | 21333     | 2.00           | 200   | 49   | Steel    | 23   |

Plots and diagrams of WCC for all listed cases are in figures 3-5.

3.2 Results validation

In the left column in the figures, one can see 3D plots of WCC. Redline connects local maximums for each scale factor m. Values of WCC for each scale factor were normalized by their root mean square. In the right column in the figures are color map diagrams that show exclusively the local maximums.

Considering the clearest local maximums we estimated a time lag \( \bar{\tau}_0 \). Estimations were obtained as the best possible approximation of outlined dots with the vertical straight line. To validate the results, we calculated the empirical sound velocity \( \bar{V}_0 \) and compared it with the expected sound velocity \( V_0 \). We used the formula in [23] to get \( V_0 \) using the diameter and the wall thickness of the water-filled steel pipe. The results are summarized in table 2.

Table 2. Validation of the results.

| Case | \( \bar{\tau}_0 \), msec | \( \bar{V}_0 \), m/sec | \( V_0 \), m/sec | \( |V_0 - \bar{V}_0|/V_0 \), % |
|------|--------------------------|------------------------|-----------------|-----------------------------|
| 1    | 40                       | 1175                   | 1121            | 4.8                         |
| 2    | 123                      | 374                    | 1047            | 64.3                        |
| 3    | -22                      | 1227                   | 1268            | 3.2                         |
| 4    | -64                      | 1250                   | 1268            | 1.4                         |
| 5    | 58                       | 1034                   | 1199            | 13.8                        |
| 6    | 18                       | 2389                   | 1199            | 99.2                        |
| 7    | 3                        | 1333                   | 1273            | 4.7                         |
| 8    | 46                       | 1239                   | 1268            | 2.3                         |
| 9    | 6                        | 500                    | 1225            | 59.2                        |

In cases 1, 3, 4, 7, and 8 the error is relatively low, so we can confirm that the estimated time lag \( \bar{\tau}_0 \) is close to true time delay \( \tau_0 \). Small errors could be explained by insufficient accuracy of distance measurements on the field and by inaccurate a posteriori estimation of pipe walls thickness. Results for case 5 could be affected by the same factors. At the same time, results for cases 2, 6, and 9 are unsatisfying and discussed in the conclusion.
Figure 3. WCC plots and diagrams for cases 1, 2 and 3 correspondingly.
Figure 4. WCC plots and diagrams for cases 4, 5 and 6 correspondingly.
Figure 5. WCC plots and diagrams for cases 7, 8 and 9 correspondingly.
4. Conclusion
As one can see in figures 3-5 and table 2, WCC gives a rather good estimation of lag time in most cases. However, unsatisfying results were obtained for at least three cases. For case 2 presented in figure 3 (in the middle), there is a significant peak corresponding to $\tau_0 = 39$ msec ($V_0 = 1179$ msec) that could be associated with the true time lag. The estimated time lag corresponds to sound velocity in the air and might be a marker of badly installed sensors. In cases 6 (figure 4 on the bottom) and 9 (figure 9 on the bottom) there are no peaks on WCC functions that might correspond to true time delay. Unfortunately, we do not have full and consistent information on the conditions in the field, so we can not make any motivated assumptions about the possible reasons.

In this paper, we studied the practical applicability of the WCC algorithm proposed and described in [19]. The study confirmed that the WCC method can make a useful tool in the leak noise correlator software. Even though the novel method did not show the highest efficiency, that might be due to ill field conditions or mistakes by the correlator’s operator.

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