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11. FILTERING TECHNIQUES TO IMPROVE EFFICIENCY OF LEAK LOCALIZATION IN PIPELINES

This chapter deals with issues connected to the detection of leaks in liquid transmission pipelines. Such pipelines are especially exposed to the risk of leakages. The occurrence of a leakage usually leads to huge economical, environmental and social effects. Therefore, leak detection systems (LDS) are installed in transmission pipelines. LDS allows 24 h monitoring of the integrity of the pipeline, where its overall scope of the operational tasks includes detection, localization and estimation of leak intensity.

There are a number of ways to implement LDS [1, 12]. Of fundamental significance appear to be the methods based on measurements of flow parameters in the pipeline, such as mass/ volume flow, pressure and temperature. These methods are called *analytical (indirect, internal or software based) methods*. Their reviews are available in [1, 12].

Pipeline operators are interested in such LDS solutions that would enable leak detection of less than 1% nominal flow intensity. It is important to achieve such aim, when the occurrence of a leak is in both steady as well as in transient state, i.e. related to an operating point change, valve's aperture and closure, pump's start-up or stoppage. The transient state cases still pose a significant issue to solve.

Apart from the system's ability to detect any kind of leakage, another important issue is the precise localization of a leak point. In both the tasks, the response time also plays a significant role.

In order to determine where a leak has occurred, various localization procedures are used. Among them, there are procedures based on the calculation of pressure gradients [9, 10]. Gradient based localization procedures are used both in simplified as well as very advanced solutions of analytical methods.

On the whole, simplified methods have proved to be efficient when the pipeline operates in steady state. The author, in cooperation with other researchers, conducted experimental studies of selected standard and improved proprietary solutions of such methods. The results of the studies are presented in [5, 6, 7]. The proposed solutions were specifically

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aimed at detecting leaks. An essential element of their assessment was the estimation of the performance indexes, such as possible leakage detection level and response time [7] as well as resistance to interference simulated by noises added to acquired measured signals [6]. After detecting a leak, leak localization procedures were carried out and their results were also presented. Another experimental research, conducted with participation, involved changing around 10% of the nominal flow rate in conjunction with a simultaneous simulation of a single leakage in the transient state. It has been proved that for such a large change of the pipe's operating point, simplified methods can also be successfully used for leakage diagnosis in transient states, i.e. for specific operational conditions [8].

As an example of advanced analytical methods, the so-called automatic control approach methods [2, 4] can be mentioned here. Such solutions use a mathematical model of liquid flow dynamics described in the state-space. Common solution for further analysis is an implementation of state observers [3, 4]. These methods are very complex and costly. One of many problems is also building the pipeline's mathematical model and developing its solutions.

Gradient based localization procedures are not as fast as the localization procedures based on negative pressure wave detection [6, 8]. However, compared to those procedures, they are more reliable, i.e. offer lesser risk of missing a leak.

The basic requirement that determines the precision of the leakage localization is an accurate estimation of nominal pressure values. Such an estimate applies to individual measurement points that are included in the calculations. In practice, this means the need to use high accuracy pressure sensors. Next, using the acquired data samples, nominal values are calculated. Most often, averaging of a given set of data samples is applied here, i.e. an average value is calculated.

In the case of transmission pipelines, accurate pressure measurements are not an easy task. Pressure sensors are mounted on the inlet and outlet and along the pipeline. Considering a typical section of a transmission pipeline of 30–100 km in length, this means long distances of individual pressure sensors from a place where the control room of LDS is located. Apart from sensors, numerous additional devices are also used, including A/D converters, communication modules for wire or no-wire data transmission. The measurement system with such extensive and complex structure is difficult to protect from the impact of interference.

Errors and noises generated by measurement devices, in combination with disturbances that occur in the flow, generally result in the quality deterioration of measurement data. It is evident that bad quality of the data will influence LDS and generate false results of diagnosis, as observed in [12].

Consequently, the localization of a leak may not be very accurate, with errors in real pipelines ranging from a few hundred meters up to several kilometres. The errors can be even worse for small leakages, including the ones that have less than 1% nominal flow intensity.

In this work, the attention is focused on a widely used gradient based localization procedure that uses gradient increments instead of the gradients themselves. We consider this procedure to localize single low intensity leaks in the event of the use of unfiltered as well as filtered measurement data. A localization error in function of time response determined as a performance index is used in the assessment of compared variants of procedure implementation.

Two different single leak scenarios are considered. The first one concerns an occurrence of a leak in a steady state. The other scenario assumes a leak in a transient state. The research used measurement data obtained during experiments carried out on a model pipeline. Intensity of simulated leaks was between 0.2–0.8% of the nominal flow rate.

11.1. SCENARIOS OF SINGLE LEAK OCCURRENCE – PHENOMENA RELATED TO LEAK

In general, analytical methods consider hydraulic phenomena related to leak occurrence. An in depth understanding of these phenomena and their impact on the measured flow parameters is crucial.

Knowledge of these issues is also important for the leak localization procedure and its application to the two single leak scenarios described below. In addition, it also makes it easier to determine the requirements that the expected use of measurement data filtration should meet.

11.1.1. Scenario #1: single leak occurred during steady-state pipeline conditions

Let us consider a leak free (leak proof) pipeline that works under stationary conditions. As a result, the pressure measured at the inlet and outlet, as well as at some points along the pipe and also the flow rate signals (measured both at the inlet and outlet) have stabilized values. This is illustrated by Figs. 1a and 1b, corresponding to the time interval A. If a leak occurs at the coordinate point z_{leak}, it results in pressure and flow changes in the pipeline. In the case of a pressure change, two distinct phenomena are observed.

The first one involves the spread of negative pressure waves in the pipeline. Such waves originate due to a sudden drop in pressure at the leak point, and spread downstream and upstream through the pipeline at the sound speed. These waves are recognized as a change in the measured pressure signals which, in the time domain, typically takes a shape of a slope. The slope is usually curvilinear in shape with varying degrees of inclination. The beginning of the change i.e. bending point corresponds to the wavefront. It should be noted that the waves take evidently visible fronts in the case of sudden leaks whereas for gradually growing leaks, the wavefronts are more smoothed. Behind the wavefront, the pressure in the pipeline gets lower with the increase in the distance from the leak point.

The other phenomenon consists in the change of the pressure distribution along the pipeline, in comparison with a steady state with no leak. Assuming that pressure gradient $G_0 = dp/dz$ is constant over the whole length of the pipeline, then pressure distribution is represented by a straight line, as shown in Fig. 11.2a (curve 0). After a certain time, the transient state is transformed into a new steady state. This new steady state is shown in Fig. 11.1a as the time interval C. Then the pressure drop line is composed of two straight segments, as shown in Fig. 11.2a (curve 1). The inclinations of both lines are described by pressure gradients G_{in} and G_{out}, where $G_{in} < G_0$ and $G_{out1} < G_0$.

In the case of a flow rate change, we can observe an increase of the flow rate in the section from the inlet to the leak point, and the decrease in the section from the leak point to the outlet. More detailed description of the phenomena related to this scenario of leak occurrence can be found in [6].

11.1.2. Scenario #2: single leak occurred during transient-state pipeline conditions

This scenario is represented by pressure (measured at the inlet and the outlet, and also at several points along the pipe) and flow rate signals (measured at the inlet and the outlet) which are shown in Fig. 11.1c and 11.1d.

At the very beginning, the pipeline operates in a steady state without leakage. It is marked by the time interval A. Next, a technological operation is carried out involving a change of the delivery rating of a pump, which is actually aimed at changing the flow rate of the medium pumped through the pipeline. The implementation of this operation results in a transient state, marked by the time interval B1. During this operation, i.e. in the transient state, a single leakage appears at the coordinate point z_{leak}. The occurrence of a leak causes an additional transient state, marked by the time interval B2. This state will overlap with the transient state caused by the change in the delivery rating of a pump.

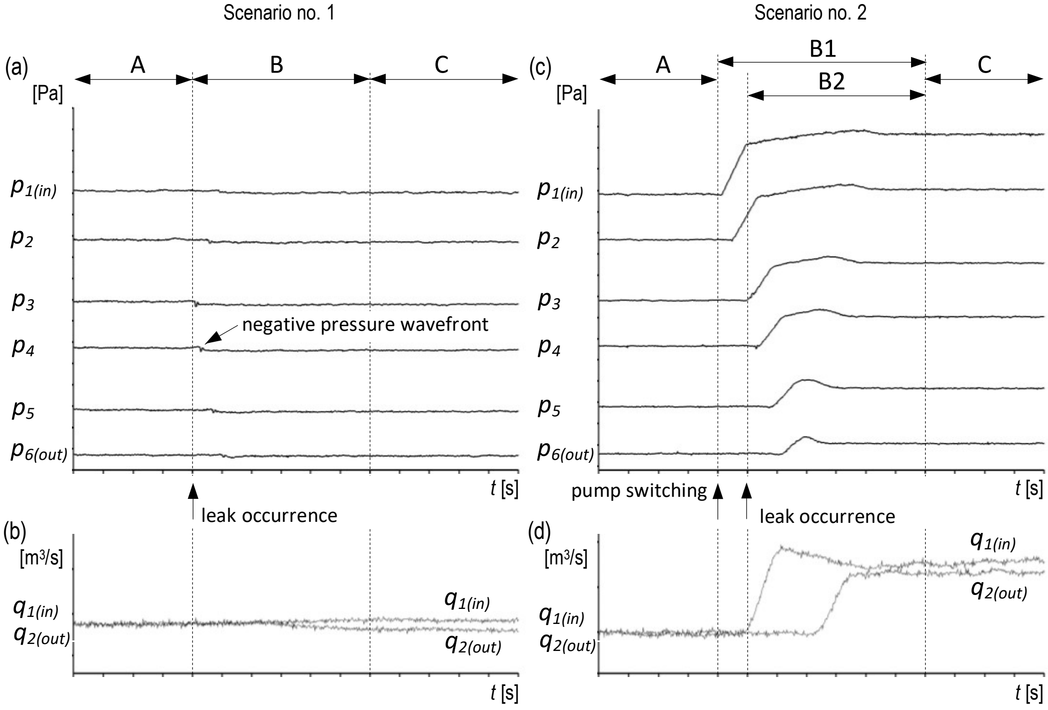

Fig. 11.1. Signals in the pipeline before and after leak occurrence:
(a), (b) pressure and flow rate; (c), (d) pressure and flow rate

As in the previous scenario, the resulting leak is accompanied by the propagation of negative pressure waves. The visibility of the fronts of these waves, apart from the previously mentioned conditions, will depend on the dynamics of pressure changes caused by the technological operation.

Assume further that the technological operation of changing the pump's rotation velocity is completed and that the failure of the pipeline at the point of leakage will have fixed dimensions. Thus, after a certain time, medium flow in the pipeline gets stabilized in a new steady-state operating point represented in Figs. 11.1c and 11.1d as the time interval C. Then, the measured pressure and flow rate have stabilized values. Similarly, as in the previous scenario, the new line of pressure drop along the pipeline is different from the line of pressure drop prior to the leak, i.e. corresponding to the time interval A. Now, the line is composed of two straight segments.

11.2. CHARACTERISTICS OF GRADIENT BASED LEAK LOCALIZATION PROCEDURES

Gradient based localization procedures [5, 9, 10, 11] take advantage of the accompanying leakage of pressure changes (drops) in the pipeline. Such procedures may be useful for leaks that occurred at one or even several locations along the pipeline. Two variants of such procedures can be distinguished.

The first variant, so-called classical procedure uses phenomenon of change in the pressure distribution along the pipeline described above in section 11.1. This procedure consists in the calculation of the abscissa of the intersection point of two straight lines, which are shown in Fig. 11.2a (curve 1), using the following relationship

$$z_{leak} = \frac{p_{out} - p_{in} - G_{out} \cdot l}{G_{in} - G_{out}}, \tag{11.1}$$

where: l - length of the pipeline, G_{in}, G_{out} - pressure gradients after the leak occurrence in the section between the beginning of the pipeline and the leak point and in the section between the leak point and the end of the pipeline, p_{in}, p_{out} - pressure after the leak occurrence for the initial and final cross-section of the pipeline.

In order to determine gradients G_{in} and G_{out}, it is necessary to install at least four pressure sensors in the pipeline, two in the front and two behind the leak point. However, in practice, the other variant is used more often. This procedure, instead of pressure distribution $p(z)$ (Fig. 11.2a), uses the distribution of pressure increases $\Delta p(z)$ in the pipeline (Fig. 11.2b), which allows the reduction of the negative impact of pressure measurement errors. In particular, it relates to systematic errors of measurement.

The method of locating the leakage site is similar here, i.e. it involves determining the abscissa of the two straight lines that correspond to the pipeline sections before and after the leak point. These two straight lines are shown in Fig. 11.2b. Then, a calculation is made using the following relationship

$$z_{leak} = \frac{\Delta p_{out} - \Delta p_{in} - \Delta G_{out} \cdot l}{\Delta G_{in} - \Delta G_{out}}, \qquad (11.2)$$

where: $\Delta G_{in}, \Delta G_{out}$ - increments of pressure gradients in the section between the beginning of the pipeline and the leak point and in the section between the leak point and the end of the pipeline, $\Delta p_{in}, \Delta p_{out}$ - increments of pressure for the initial and final cross-section of the pipeline.

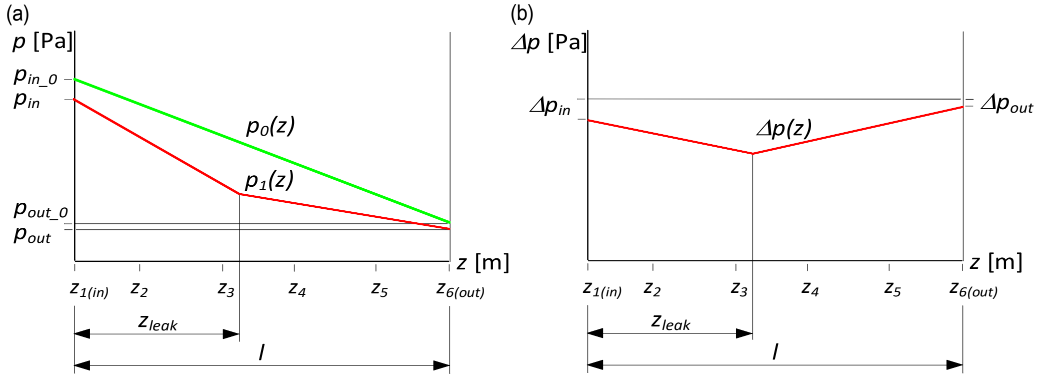

Fig. 11.2. Lines of distributions during no-leak conditions and after leak occurrence: (a) pressure, (b) pressure increases

Both procedures do not require the measured pressure signals to be sampled at very short periods, unlike in the case of the localization procedures based on negative pressure wave detection. In real pipelines, sampling periods range from a few seconds to several minutes.

Fig. 11.3. Laboratory model of the pipeline used during experiments

The increase in pressure and gradients taken into account in (11.2) are usually calculated as the differences between the values of pressure and gradients in steady state before and after the occurrence of the leak. It refers to the use of measurement data corresponding to the intervals A and C (Fig. 11.1). Using the measurement data that correspond to both these ranges, the nominal pressure values used in the calculations are estimated. In practice, such estimation requires the use of time windows covering a certain number of data samples. A significant disadvantage may be the fact that the accuracy of the estimate increases with the amount of the data available, which means extension of the total time needed to localize leak (response time). Hence, there is a need to determine the localization error in function of the time response.

11.3. EXPERIMENTAL IMPLEMENTATION OF THE SELECTED LOCALIZATION PROCEDURE WITH USED DATA FILTERING

11.3.1. THE PILOT PIPELINE INSTALLATION

The laboratory model of the transmission pipeline for water pumping (Fig. 11.3) has been built in the Faculty of Mechanical Engineering of the Bialystok University of Technology in Poland. Its total length is close to 400 m, including the main pipe section of 380 m long which is made of polyethylene tubes (HDPE) of 34 mm internal diameter and 40 mm external diameter.

The pipeline installation is equipped with a variable flow pump, two semi-open tanks (on inlet and outlet) of 300 dm^3 capacity each. On the pipeline, two electromagnetic volume flow meters (at the inlet and outlet at coordinates $z_{in} = -6.5$ and $z_{out} = 382.2$ m) and seven pressure transducers (in the main pipe section at coordinates $z_{1(in)} = 1$, $z_2 = 61$, $z_3 = 141$, $z_4 = 201$, $z_5 = 281$, $z_6 = 341$ and $z_{7(out)} = 378$ m and one thermometer (at the inlet) have been installed.

In order to simulate leakages, automatically controlled proportional solenoid valves equipped with interchangeable diameter orifices are used. The valves can be installed at selected points along the entire length of the main pipeline section.

11.3.2. CONDITIONS OF EXPERIMENTS

An overview of the experiments is shown in Fig. 11.4. These experiments correspond to the two leakage scenarios as described in section 11.1.

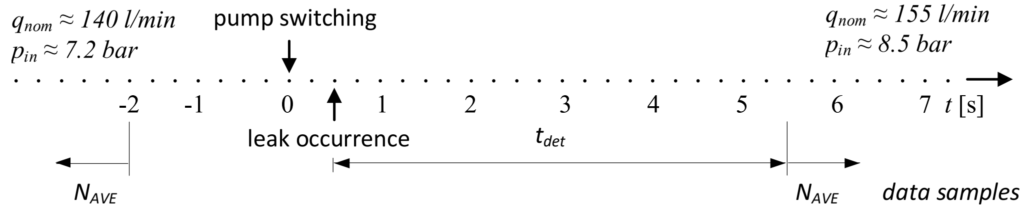

Fig. 11.4. Time scenario of experiments

The leaks were simulated at some selected points in the pipeline with the coordinates 75, 195 and 315 m by rapid opening of electromagnetic valves. The data on leakage intensity is given in Table 11.1. During the experiment, the flow rate and pressure signals were sampled at the rated frequency equal to $f_p = 100$ Hz. In addition to the experiments with simulated leaks, similar experiments deprived of leakage simulation were carried out.

Table 11.1. Places and intensities of simulated leaks

Leaks					
[m]	[%]	[m]	[%]	[m]	[%]
75	0.21	195	0.26	315	0.23
	0.21		0.26		0.24
	0,43		0.44		0.43
	0,43		0.44		0.49
	0.81		0.69		0.73
	0.81		0.69		0.81

11.3.3. PROPOSED FILTERS

For liquid transmission pipelines, the measured pressure signals usually contain the disturbing noise and interference caused by the flow and measurement effects. Very often, a high level of signal interference can make it difficult to observe the changes in the signal value. In particular, this refers to small leaks when pressure changes in the pipeline caused by the leaks are relatively small. Then, if ratio of the measured signal value of pressure changes to the interference and the level of measurement noises is not satisfactory, the identification of such changes seem to be very difficult. Another important problem is the lack of suitable relation of the level of the pressure changes to the whole pressure transmitter range as well as with respect to uncertainty and systematic errors of the measurement.

Therefore, it is necessary to utilize appropriate filtering of the measured pressure signals. Taking into account the specificity of the selected localization procedure, we consider the use of time series data filtering techniques. For such a digital filtering approach, the following requirements should be defined:

- possibly good mapping changes of the measured pressure signals,
- smoothing fluctuations of the measured pressure signals.

At the beginning, we assume the use of the following three time series data filtering techniques.

- Moving average filter.
  Such filtering is effective in reducing the noise component of the signal data set, but has the tendency to blur slopes. We use this filter according to formula

$$y(n) = \frac{x(n-k) + x(n-k+1) + \cdots + x(n) + \cdots + x(n+k-1) + x(n+k)}{N}, \quad (11.3)$$

where: $y(n)$ is the output, $x(n)$ are samples of the input signal, N is number of samples.

- Moving median filter.
  This type of filtering possesses good noise reduction, particularly impulsive type noise and has very good ability to track slopes. We employ a variant of this filter corresponding to formula

$$y(n) = med[x(n-k), x(n-k+1), \ldots, \ x(n), \ldots, x(n+k-1), x(n+k)]. \qquad (11.4)$$

- Recursive filter.
  This type of filtering is also called recursive averaging with fading memory (exponential smoothing). It has noise reduction advantage and depending on the weight factor, is also able to retain signal data that are changing rapidly. The filter is described by formula

$$y(n) = \alpha \cdot y(n-1) + (1-\alpha) \cdot x(n), \qquad (11.5)$$

  where: $y(n-1)$ is the output in the previous moment resulting from the applied sampling period, α is the weight factor $0 < \alpha < 1$.

11.3.4. THE RESULTS

All the above filtering techniques are relatively simple to implement. An exemplary result of their implementation with respect to the measured pressure signals are shown in Figs. 11.5 and 11.6. The results in Fig. 11.5 relate to the first leak occurrence scenario, whereas the ones in Fig. 11.6 refer to the second scenario. The pressure signals correspond to extreme external pressure sensors mounted in the pipeline.

It should be explained here that the pressure signals shown in Figs. 11.5 and 11.6, correspond to the sampling frequency after it has been reduced to the level equal to $f_p = 10$ Hz. This value is sufficient to observe the dynamics of pressure change, especially in the case of the second leak scenario. The same parameter is also used in further analysis.

The moving average filter is implemented with a number of samples $N = 41$, and the median filter also utilizes the same number of samples. The recursive filter has the weight factor equal to $\alpha = 0.900$.

Analyzing the plots in Fig. 11.5, we can observe that the best mapping changes of the measured pressure signals are achieved for both the average and median filters, whereas the recursive filter generates the output with a time delay. The outputs of individual filters are different with respect to the smoothing of fluctuations of the original signals. The best result is observed for the average filter, whereas the output of the median filters is not very smoothed. Similarly, this refers to the output of the recursive filter.

The plots in Fig. 11.6 show significant differences for each of the compared filters. In particular, this is true of the slope mapping ability that is an effect of pump switching. Such a signal change is only satisfactorily mapped by the median filter. The averaging filter distorts the slope due to the data averaging process. As a result, the filter output overtakes the edge of the slope, whereas behind the slope, it is set to a new level with a delay. On the other hand, the recursive filter generates an output that lags considerably behind the beginning of the slope, and its stabilization behind the slope is slow. We can also observe that the original signals have been smoothed differently by these filters.

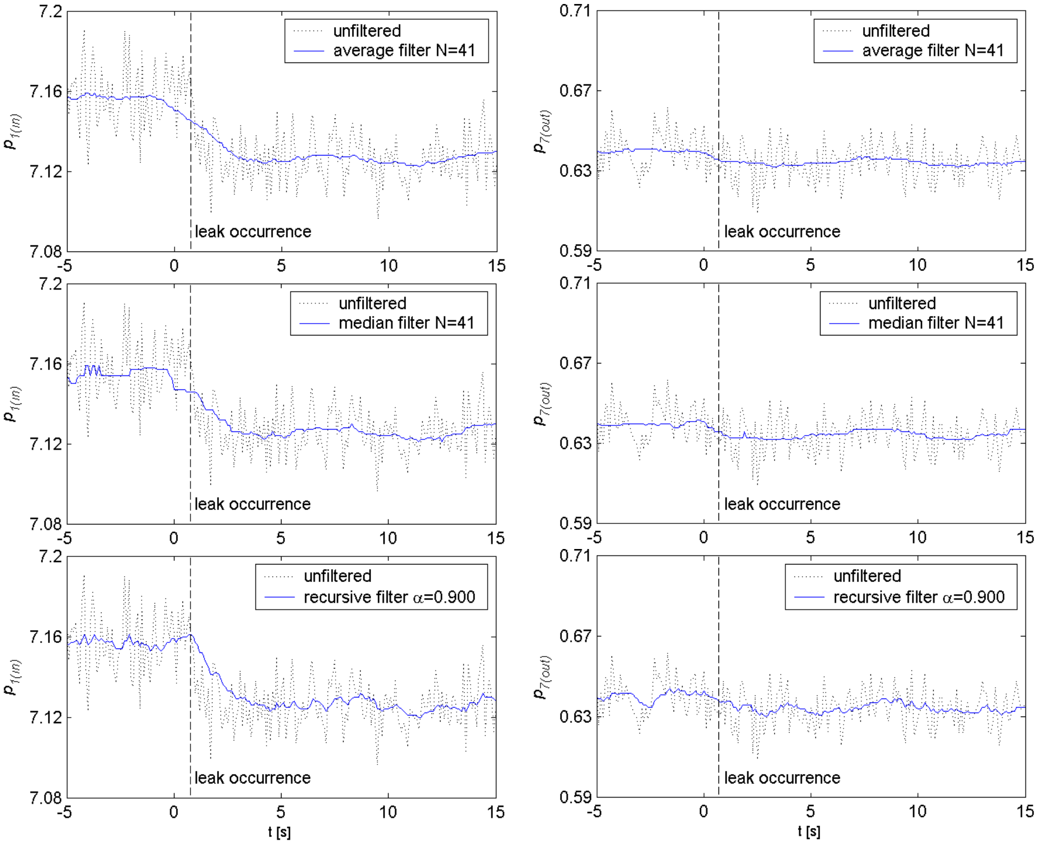

Fig. 11.5. Unfiltered and filtered data refer to the leak about 0.45% of the nominal flow rate (the scenario #1)

A more precise definition of the conditions and requirements for the implementation of the leak localization procedure will be helpful in solving the problem of filter selection and its settings.

The moment of starting the procedure should be taken into account. This moment should correspond to the detection of a leak by a relevant algorithm. It is also important to bear in mind the general assumption that we are interested in achieving the best possible accuracy of the leak localization in the shortest possible time.

Let us assume that for all the experiments, the leak detection time counted from the moment of its occurrence is $t_{det} = 5\text{s}$. Such value corresponds to the results of the experimental studies presented in [6, 8], where the algorithms designed to detect a leak were tested for similar scenarios of leak occurrence.

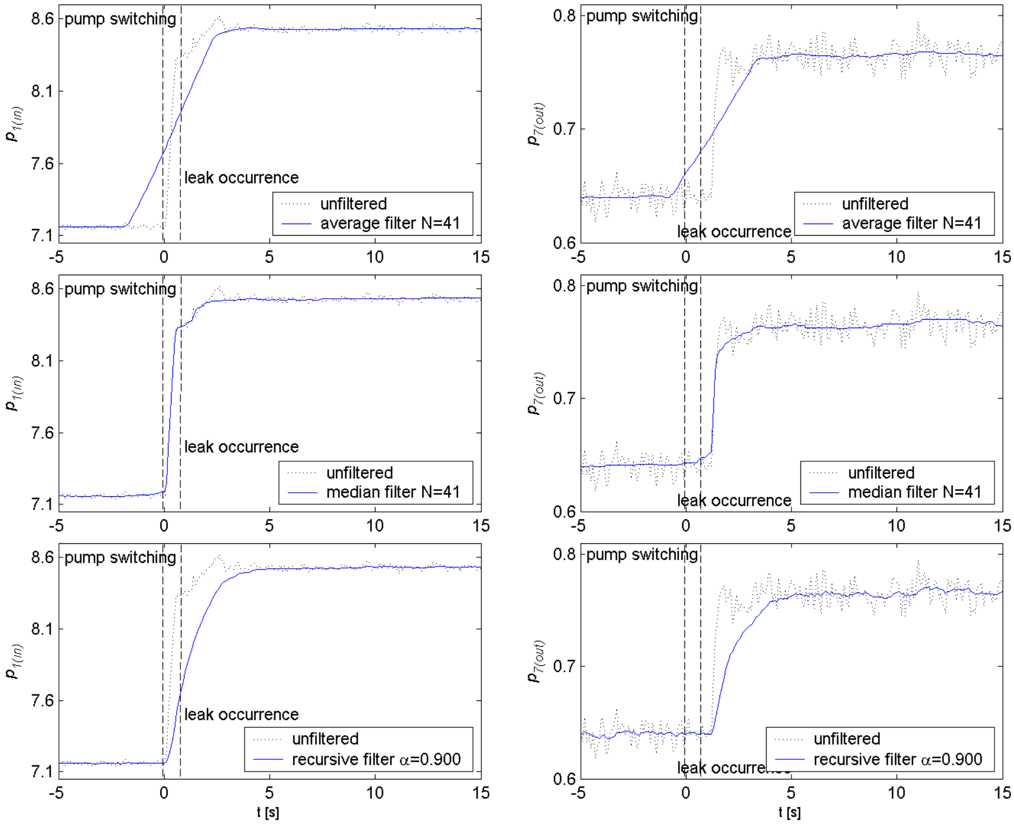

Fig. 11.6. Unfiltered and filtered data refer to the leak about 0.45% of the nominal flow rate (the scenario #2)

In view of the above, it seems unreasonable to further increase the number of input samples N in the case of both the average and median filters. We must remember about the $(N-1)/2$ samples that should be additionally taken into account when determining the time of leak localization. Another problem that can be seen in Figs. 11.5 and 11.6 is the need to backward shift the end of the range used to calculate the nominal pressure values in a non-leakage condition. Initially, the end of the interval was supposed to correspond to 0 on the timeline. To avoid this requirement, it is possible to move the filter output from sample $y(n)$ to sample $y(n + k - i)$, that is related to the average filter. However, the existing option, i.e. with the filter output corresponding to the sample $y(n)$, is further considered. Therefore, the end of this interval has been moved to -2 on the timeline (Fig. 11.4). In the case of a recursive filter, further improvement of the signal smoothing effect can be achieved by changing the setting of parameter α. Yet, this will further increase the output delay.

It should also be kept in mind that apart from the signal filtration itself, the averaging of the obtained output samples of the filters will also be used. In order to obtain the best results of leak localization in the shortest possible time, this effect may be actually caused by the applied signal filtering in terms of reducing its fluctuations. It is important here to obtain stable values of the filter output signal. Hence, for the purpose of further analysis, additionally a recursive filter setting was adjusted, assuming $\alpha = 0.980$.

The averaged leak localization errors in function of time response obtained for both leak scenarios are shown in Fig 11.7. The results concern the use of both unfiltered and filtered measured signals.

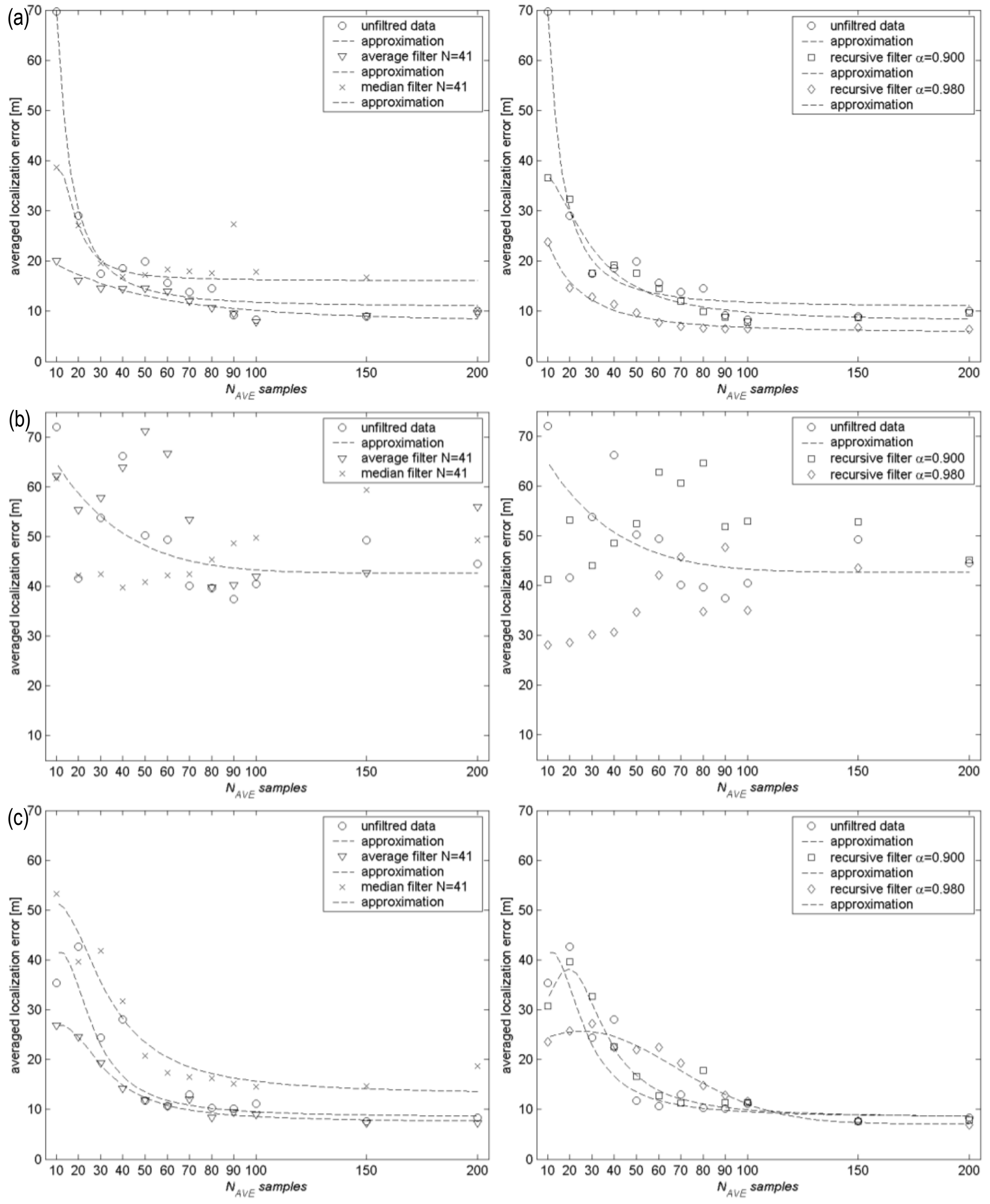

Fig. 11.7. Distributions of the averaged leak localization error:
(a) scenario #1, (b) scenario #2, (c) scenario #2, when data corresponding to the non-leak state are used from another experiment without simulated leak

The mean error was calculated by making use of the localization errors obtained for each of the experiments (Table 11.1). The leakage site calculations were performed according to procedure (11.2). For the calculation of both gradients and their increments, the data corresponding to four sensors were used, including two sensors located at the inlet or the outlet of the pipeline, and another two sensors nearest to the leak point. The response time is represented by the number of samples N_{AVE} that were taken into account when estimating the nominal pressure values for the non-leaked and leaked states (Fig. 11.4). Such estimates were made using the calculated mean value for the considered set of samples. Identical numbers of samples N_{AVE} were taken into account for both states. If, for a given experiment, the calculated leakage point exceeded the coordinates of the pipeline length, its value was assumed to be the appropriate extreme coordinate.

While analyzing the results obtained for the first leak scenario (Fig. 11.7a), we might state that the proposed filtering techniques have made it possible to achieve a significant reduction of the localization error in function of time response. In particular, it relates to the use of recursive filtering with the setting $\alpha = 0.980$.

It can be also noticed here (Fig. 11.7a) as for the others examined variants (Figs. 11.7b and 11.7c) that the amount of the data used for the estimation of nominal pressure values exerts a substantial influence on the accuracy of the localization of a leak point.

It is worth noting that the median filter is not the best averaging filter, hence for virtually all considered variants, the final location errors always have the highest level.

For the second scenario, averaged location errors have much higher levels and dispersion (see Fig. 11.7b). Of the filters used, only recursive filters reduce the levels of average leakage localization errors compared to the results obtained for unfiltered signals. For both of these filters, it is worth noting the build-up of a location error along with an increase of the amount of the samples N_{AVE}. This may be due to delays in the operation of filters, where slow stabilization of the filter response significantly affects the resulting averaging result. In general, the results obtained here confirm known problems with the exact localization of the leak point in the case of transient states.

However, in the case of the additionally examined variant for the second leak scenario (Fig. 11.7c), when the data corresponding to the non-leak state are used not from the time period before pump switching, but from another experiment without simulated leak where identical time period is considered as for standard calculation (Fig. 11.4), we can observe decreasing errors.

Such a variant is purely theoretical. But, it can show, that except for the above mentioned problems related to the second leak scenario, there may be errors of pressure measurement. In fact, the errors in function of the whole pressure transmitter range are taken into account here. This additional improvement of the localization procedure based on gradient increments may require applying metrological characteristics of pressure sensors, i.e. calibration data given by their producers.

11.4. CONCLUSIONS

This work presents very simple and efficient filtering techniques to improve the accuracy of the localization procedure based on gradient increments. The procedure can be successfully used to localize a location of leakage that occurred during steady-state pipeline conditions. It also shows possibilities of using the procedure to localize a leak point related to the occurrence of a leak in transient state.

The effectiveness of the filtering techniques has been proven by the results of localization errors in function of time response. They relate to the use of real measured pressure signals obtained for the experiments with simulated small leaks between 0.2–0.8% of nominal flow rate. The experiments were carried out on the pilot pipeline described earlier.

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