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Leak detection in liquid transmission pipelines using simplified pressure analysis techniques employing a minimum of standard and non-standard measuring devices

Paweł Ostapkowicz *

Bialystok University of Technology, Faculty of Mechanical Engineering, Wiejska Street 45C, 15-351 Bialystok, Poland

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ABSTRACT

This paper deals with issues of detecting leaks in liquid transmission pipelines. It presents solutions of procedures (algorithms) applied to both negative pressure wave and gradient methods. These algorithms are aimed at achieving a satisfactory level of efficiency of a single leakage diagnosis. The methods are evaluated in terms of their implementation with a minimum number of measuring devices. In the case of the negative pressure wave method, apart from the standard pressure transmitters to measure the pipeline pressure, also the use of non-standard measuring devices, conventionally the so-called correctors, is considered. The signals generated by the correctors are characterized by good correspondence of the measured signal representing a change in the pressure to measurement noise level and the overall pressure transmitter range. All this, in combination with the developed algorithm, which apart from detecting a leak, is aimed at precise identification of a change in the signal related to the wave pressure front, i.e. the so-called inflection point, provides a high efficiency of leak detection. This has been proven by carrying out a number of experimental tests on a laboratory water pipeline. The tests involved simulations of both sudden as well slow leakages.

1. Introduction

Of various methods currently used to detect leaks in transmission pipelines, the so-called *indirect (analytical, internal) methods* appear to have fundamental significance. These methods are based on measurements of flow parameters in the pipeline, such as mass/volume flow, pressure and temperature.

Practical implementation of the internally based methods takes the form of leak detection systems (LDS) installed on the pipelines. The overall scope of the operational tasks involving such systems includes detection, location and estimation of leak intensity. Importantly, such systems allow for 24-h monitoring of the integrity of the pipeline.

Nowadays, there are a great number of various internal methods in use. Their review can be found in [1,5,10,11,19,21]. However, by themselves, these methods fail to ensure the implementation of all the above mentioned detection tasks as their use is limited exclusively to some specified pipeline operating conditions and leakage characteristics. In order to develop an effective and reliable LDS, it is necessary to apply, at the least a few concurrently running internal methods controlled by appropriately synchronized algorithms making it possible to monitor changes in pipeline operations, as mentioned by [19].

The easiest way of leak detection appears to be mass or volume balance methods [14]. Their advantages include possibilities of both detection of leaks and their intensity assessment, however they give no possibility of leak location. To implement the methods, it is required to install flowmeters to measure the intensity of flow rare at the beginning and the end of the monitored pipeline section. The efficiency of diagnosis, in this case, depends mainly on the accuracy of the installed flowmeters. The methods work well in steady states but they are not so reliable in transient states, for which there is a high susceptibility to false alarms. However, to diagnose low intensity leaks (<2% nominal flow rate) may take a lot of time. Among other factors, this is due to the fact that the changes in the flow measured at the pipeline's inlet and outlet are delayed with respect to the pressure changes.

For comparison's sake, using other internal methods based on pressure measurements in the pipeline offers not only a quicker detection but also make it possible to locate leakages. These methods include negative pressure wave methods [2,5,17] wave reflection methods [6], pressure point analysis methods [3] as well as the gradient method [4,5]. Generally, these methods can only

* Tel.: +48 571443060; fax: +48 857469210.
E-mail address: p.ostapkowicz@pb.edu.pl

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operate during steady-state pipeline conditions [22]. But, as it was confirmed in [18], they can also be successfully used for leakage diagnosis in transient states, i.e. for specific operational conditions. The described case was related to changing nominal parameters of pumping (i.e. the pipe's operating point) in a water pipeline, by increasing the pump's rotation velocity (and thus the change by around 10% of the nominal flow rate) in conjunction with a simultaneous simulation of a single leakage in the transient state.

The most advanced internal methods are considered the ones that are based on the use of process dynamics models in combination with computational techniques operating in real-time. An example are the inverse analysis methods [7,21], whose operational principle involves a comparison of model-generated data with measured data and accurate model fitting, i.e. minimizing the obtained deviations to enable leak detection and its location. Additionally, the so-called automatic control approach methods [1,10,11] can be mentioned here, where the mathematical model of liquid flow dynamics is mainly described in the state-space and a common solution for further analysis is an implementation of state observers. Without doubt, the main advantage of these advanced methods is the ability to detect leaks in both steady as well as in transient states, i.e. the ones related to an operating point change, valve's aperture and closure, pump's start-up or stoppage. However, these methods are very complex and costly. For example, the former methods, i.e. the inverse analysis methods usually require to perform additional tests consisting in a generation of a transient state, using valves specially mounted on the outer point of the pipeline [7]. Therefore, it might be required to introduce certain constrains to operating conditions of the pipeline due to a risk caused by an uncontrolled closing of a valve. A well-know problem is also building the pipeline's mathematical model and developing its solutions. As observed by [10], the modeling of a typical section of a transmission pipeline of 30–100 km in length requires dividing the pipeline model into several dozen elements. The result is an extensive system of equations, most often differential equation systems, whose solutions frequently pose a serious computational problem often requiring the use of estimation techniques involving a number of process parameters, such as the coefficient of friction [10,11]. In addition, parts of the sections of the model should be provided with appropriate measuring devices mounted both on the inlet and outlet and along the pipeline. In practice, this means high costs associated with the LDS, which include: appropriate number of very accurate measuring devices, data transmission systems with highly rigorous time synchronization as well as powerful computers. Such an LDS should also be operated by a highly qualified staff.

Thus, taking into account the practical requirements and various operational cases, simpler internal methods are still being used and developed.

This paper focuses on two simplified methods based on pressure measurements dealing with non-large liquid transmission pipelines that operate under steady state conditions. They are the negative pressure wave method (NPWM) and the gradient method (GM). The solutions presented for the both methods are designed to improve leak diagnosis while, at the same time, trying to ensure reliability of the LDS using a minimum number of sensors.

In the case of the NPWM the use of non-standard measuring devices, conventionally the so-called correctors, is proposed. They are intended to improve diagnostic susceptibility that, according to diagnosis theory, is related to the possibility of carrying out measurements of qualitatively and quantitatively available diagnostic information. Limitations concerning pipelines' diagnostic accessibility can be a serious problem. According to [24], there occur quite common situations in which the LDS acquires only a part of useful measurement data. Consequently, the effectiveness of leak detection is greatly reduced.

In practice, a similar problem also occurs when we use standard (ordinary) pressure transmitters for measuring absolute pressure changes in the pipeline related to leakage occurrence. Such changes take the form of characteristic pulses which correspond to the propagation of the pressure wave. Typically, the changes are relatively so small in relation to the levels of measurement noise and the whole pressure transmitter range that they may be difficult to detect. In particular, this refers to small leaks and also when the sensor is located at a considerable distance from the leak point. The above is due to a reduction in the amplitude of the wave as a result of the phenomenon of attenuation. Unfavorable conditions for measurements may also trigger more false alarms and leak location errors resulting from additional problems with the identification of the wavefront.

Hence, instead of the typical absolute pressure sensors non-standard measuring devices are used. Their essential feature is improved dynamic sensitivity. In such devices, which are presented in [22,23] as measuring elements, a piezoelectric sensor was used; and in order to obtain the output signal, also other electronic modules. Such a device generates an output signal that is characterized by large amplitudes corresponding to pressure fluctuations (including transient pressure changes associated with the occurrence of leakage), and importantly, showing a very favorable ratio of these amplitudes with respect to the level of measurement noise. Moreover, the signal is free of the impact of the absolute static pressure, which facilitates its analysis.

In addition to the sensors used, the method of signal analysis is especially important. A main objective of the analysis is to detect changes in the signal corresponding to the pressure wavefront, the so-called inflection point [23]. The analysis should result in a precise determining of the moment when the wave passes a given measurement point. As a consequence it has a significant impact on the accuracy of the location of the leak. The analysis can also be extended to the identification of pressure changes, i.e. whether it is the result of a leak or other operational changes [9]. However, the latter is not considered here.

It is therefore necessary to combine an appropriate measuring technique with an effective method of processing and analysis of the acquired signals. Currently accessible and used methods of signal analysis include, among others, an approach based on sequential energy percentage combined with power spectrum [22], and a more effective signal feature extraction method based on wavelet packet entropy [23]. Both of them were designed for the use of non-standard signals obtained from piezoelectric dynamic pressure transducers and were implemented on real pipelines. We can also mention a combination of empirical node decomposition and instantaneous frequency analysis as well as other instantaneous frequency techniques [6] and also joint time–frequency analysis [20] based on the use of standard pressure signals. These approaches were tested only on a water network. However it is possible to apply it to transmission pipelines. Moreover, according to [8], the following can also be mentioned: fast difference algorithm, Kalman filter, correlation analysis.

However all these techniques, despite the fact that they use advanced solutions, have proved rather ineffective with a high level of signal interference (measurement noises), for example, in the case of small leaks – even less than 2% of the nominal flow rate, as it mentioned by [8]. Another well-known limitation concerning the NPWM are the difficulties in detecting and identifying pressure wavefront for slow leakages. As a result of these problems, the location of a leak is not very accurate, with errors ranging from a few hundred meters up to several kilometers.

The non-standard measuring devices proposed in this work are significantly different, unlike the dynamic pressure transducers mentioned earlier. They are generally much larger in size, even with respect to the size of the pipeline tube itself. The main part