Chapter 2
An Overview of Transient Fault Detection Techniques

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Abstract This chapter overviews the theory and strategies of transient fault detection, considering both active and passive systems, and contrasting the more common frequent approaches with time-domain methodologies. The chapter contends that real complex systems may have mimics, where one characteristic can locally impersonate another. The chapter seeks to examine the "state of play" in these areas, providing a factual summary of what has been shown and demonstrated to date, along with a more speculative set of reflections about challenges and about which methods appear to the authors to have the greatest promise for deployment and commercialization.

2.1 Introduction

Transient events occur whenever flow or pressures' conditions change in a pressurized conduit. These unsteady flow conditions are created by local adjustments to the systems' operation. Through a combination of pipeline and system characteristics, the first created waves propagate from their origin to other parts of the system, undergoing reflections and refractions along the way and possibly inducing secondary changes in system status where they are received.

What makes these waves important is that they are the mechanism of change: the way a system changes its status from what it is currently doing to a sequence of complex intermediate states on the way to what it will do next. The waves bring "news" of the change and send the signals that are required to achieve the next equilibrium state. What makes these waves dangerous is that large pressure variations are sometimes produced. What makes the transient events particularly interesting is the fact that they both convey and send signals. Thus, by listening to the waves, one can potentially learn a great deal about system states and how they are coupled to physical attributes like the presence of a leak, blockage or the state of repair of a pipe. What makes the waves difficult, though, is really the flip side of the same things that

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make them powerful; they have some sensitivity to many systems' characteristics. Thus, the problem of determining what physical characteristic is linked to what signal response can be quite challenging in realistic cases.

2.1.1 Flow Characteristics

Transient Flow. Transient flow is often defined as the intermediate-state flow describing the transition between two steady states (Chaudhry 1979). Any change or disturbance, whether it is planned or accidental, can initiate transient conditions. Common boundary conditions that may introduce transients in pipeline systems include sudden changes in pump or valve settings, starting or stopping of pumps, and changes in the level of reservoir (Wylie and Streeter 1978).

Typically, the term transient flow describes an unsteady fluid flow phenomenon in pipeline systems. If the fluid is water, the phenomenon is known as water hammer effect. The instantaneous pressure rise in a pipe system initially having a steady flow is sometimes caused by the sudden closure of the valve. In this case, the pressure change is directly proportional to the velocity change. The basic water hammer equation has been derived to express the pressure head produced by the surge in the pipes, as shown in (2.1).

$$\Delta H = -\frac{a}{g}\Delta V \tag{2.1}$$

where ΔH = the head produced by surge (m), a = wave velocity (m/s), g = gravitational acceleration (m/s^2), and ΔV = the sudden change in velocity (m/s).

Transient flow is often represented in a single-pipe system with an upstream of a constant level reservoir and a valve or another constant level reservoir with a valve at the downstream end. The former system configuration is referred to as the reservoir-pipeline-valve (RPV) system while the latter is known as the reservoir-pipeline-reservoir (RPR) system. The RPV system has received intense attention by researchers because of its simplicity. The layouts of the two types of system configuration applied for fault detection are shown in Figs. 2.1 and 2.2. According to (2.1), the pressure surge wave propagates along the pipe after the instantaneous closure of the valve. At least one pressure transducer is located close to the valve to detect the transient signal from the reservoir and from the fault.

Steady Oscillatory Flow. The successful application of many related fault detection methods requires periodic (e.g., sinusoidal) valve operations to establish steady oscillatory flow to the system. Steady oscillatory flow, or periodic flow, occurs if the flow conditions are repeated at every fixed time interval (Chaudhry 1979). The minimum time interval of a repetitive condition is called as the oscillating period.

Considering a simple RPV system as illustrated in Fig. 2.1, the downstream valve is open and closed sinusoidally at a prescribed frequency. In a pipe system with friction, the flow oscillates at the same frequency with the valve, while the

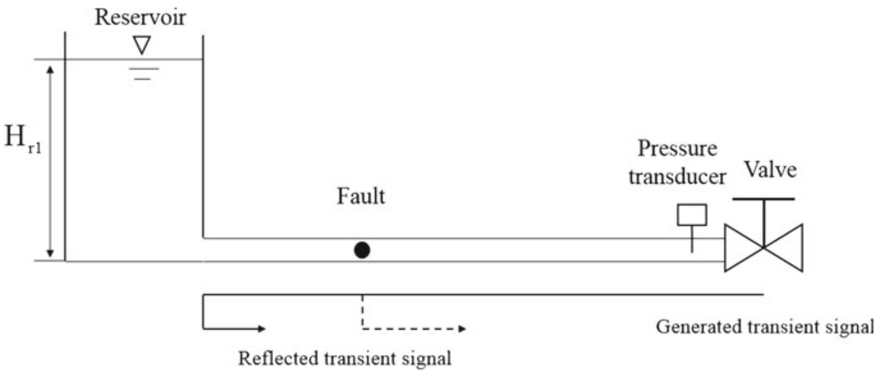

Fig. 2.1 RPV system layout with a fault

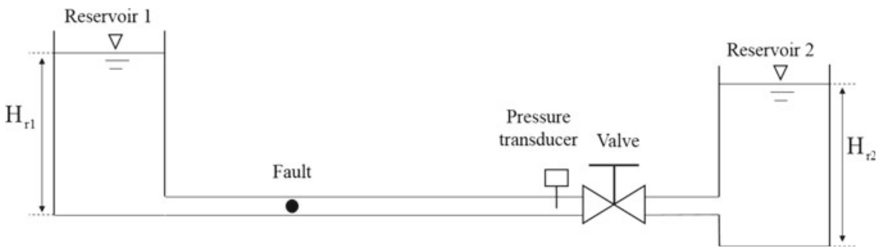

Fig. 2.2 RPR system layout with a fault

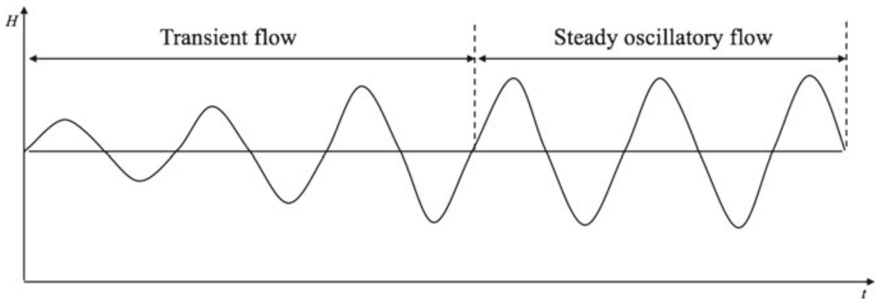

Fig. 2.3 The development of steady oscillatory flow at the downstream valve

amplitude increases until the energy provided by the oscillating valve is dissipated. The steady oscillatory state is established as shown in Fig. 2.3. The periodic excitation of the valve generates a complex transient flow until conditions settle into a constant amplitude response at the excitation frequency.

2.1.2 Governing Equations

Hydraulic transient models are developed based on the conservation rules of mass and momentum that govern transient flows. Since the flow velocity and pressure head of transient flow in closed conduits are functions of both time and distance, the governing equations are simplified one-dimensional partial differential equations that describe the unsteady flow in pressurized pipes (Chaudhry 1979; Wylie and Streeter 1978):

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{2.2}$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{\partial H}{\partial x} + h_f = 0 \tag{2.3}$$

where H = instantaneous piezometric head at the centerline of the pipe, t = time, A = pipe cross-sectional area, Q = instantaneous flow, and x = distance along the pipe axis.Furthermore, h_f is the head loss per unit length and is usually expressed as (2.4)

$$h_f = \frac{fQ|Q|}{2gDA^2} \tag{2.4}$$

where f = Darcy–Weisbach friction factor and D = pipe diameter.

Equations (2.2) and (2.3) are commonly referred to as the continuity and momentum equations, which are developed in the assumed system of elastic pipes and weakly compressible fluids. The flow velocity also must be significantly lower than the wave speed if the advective terms are to be ignored.

The governing equations can be solved to perform the transient simulations either in the time or in the frequency domain. By assuming that the flow and pressure vary sinusoidally from a steady mean value, (2.2) and (2.3) can be solved in the frequency domain. The instantaneous head and flow of steady oscillatory flow are functions of time and are separated into two components: mean flow (Q_0)/ pressure head (H_0), and flow (q^*)/ pressure head (h^*) deviations from the mean. Figure 2.4 depicts how the flow at a certain section varies with time and repeats in accordance with the period.

$$Q = Q_0 + q^* \tag{2.5}$$

$$H = H_0 + h^* \tag{2.6}$$

In practice the deviation from the mean state is usually assumed to vary sinusoidally with time (Chaudhry 1979), which can be described as follows:

$$q^* = \mathrm{Re}\left(q\,(x)\,e^{j\omega t}\right) \tag{2.7}$$

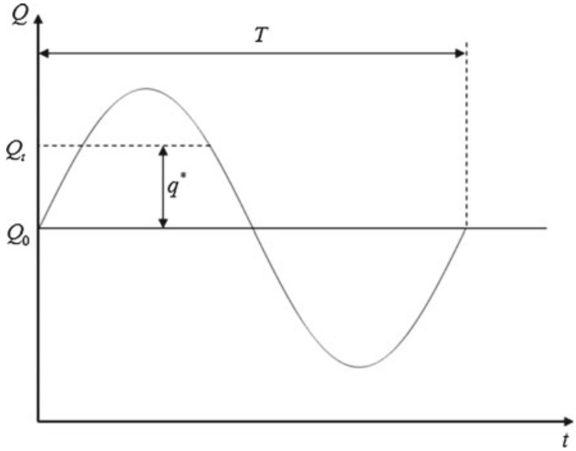

Fig. 2.4 Instantaneous flow varies sinusoidally with time

$$h^* = \text{Re}\left(h\,(x)\,e^{j\omega t}\right) \tag{2.8}$$

where $j = \sqrt{-1}$, q and h are complex variables as the function of x, Re is the real part of the complex variable, and ω is the frequency of oscillations, which is usually expressed in rad/s or $\omega = 2\pi/T$ if T is the period in seconds.

Substituting the average and oscillating components of head and flow into (2.2) and (2.3), the linearized equations are derived as (2.9) and (2.10) for the frequency analysis.

$$\frac{\partial q^*}{\partial x} + \frac{gA}{a^2}\frac{\partial h^*}{\partial t} = 0 \tag{2.9}$$

$$\frac{\partial h^*}{\partial x} + \frac{1}{gA}\frac{\partial q^*}{\partial t} + Rq^* = 0 \tag{2.10}$$

where R = unit friction term. For laminar flow,

$$R = \frac{32\upsilon}{gAD^2} \tag{2.11}$$

where υ = fluid viscosity. For turbulent flow,

$$R = \frac{fQ_0}{gDA^2} \tag{2.12}$$

Typically, the numerical method utilized in the time domain is the method of characteristics (MOC), by which the partial differential equations are transformed into a system of ordinary differential equations. The MOC is a well-developed method which describes nonlinear equations and various boundary conditions of simple to complex pipe systems. The commonly used schemes for the analysis in frequency domain are the transfer matrix method (TM) and the impedance method (IM). The theorem of the above methods has been explored in detail by several standard references (Chaudhry 1979; Wylie and Streeter 1978).

2.1.3 Detection Principle

Transient-based methods for the purpose of pipe fault detection all employ the same principle, which is to extract information about potential pipe or system faults by analyzing the measured trace of fluid transient behavior.

The internal and external characteristics of the pipeline can affect the transient response by altering the flow and pressure in the system. Considering pipeline features such as constrictions, expansions, ends, branches, valves, junctions and bends, leaks, blockages and deteriorations, there are many faults that commonly exist in pipe systems. The occurrence of a leak is a hydraulic phenomenon but one associated with various troubles. An amount of pressurized fluid released from the leaks, providing transient protection for the system and modifying the character of transient pressure wave. The pressure fluctuations can be identified collectively in the time or frequency domain to determine the location and size of the leak.

As the transient signal propagates throughout the pipe network, theoretically the information concerning the integrity and features of the pipe system can be detected hydraulically by using the transient signal as a kind of probe. The reflected transient signal and its damping pattern are the critical properties to be accessed for achieving fault detection. Their magnitude is generally proportional to the level of deterioration at the fault. After measuring the transient response at accessible locations along the pipeline, potential fault information is extracted. Typically, pipe system behaviors are studied in order to infer the system state (e.g., flow or pressure) under the assumption that all system characteristics are known. By contrast, all fault detection techniques can be regarded as solving an inverse problem, in which the system state is analyzed to determine the unknown system parameters such as faults and pipeline features.

Pipe fault detection techniques based on fluid transients have gained popularity over the last decades. Intensive numerical simulations, laboratory verifications and a few field tests have so far been conducted by researchers, generally based on the conviction that transient-based methods are superior to the other techniques. One reason for this belief is that they are nonintrusive and cost-effective. A nonintrusive technique used for evaluating the internal surface condition of pipelines is necessary for their planning and rehabilitation. When the fluid flow is in a transient state, the information about a long pipe can be obtained in a very short period of time at a great distance from the measurement point because the transient wave quickly travels through the fluid filled pipe. Another advantage is, compared to the performance of a pipe system under steady state, the system under transient state provides a vast amount of data, which is rewarding for the purpose of fault detection because the problem can be solved more accurately. Moreover, the results from fault detection using the transient are less susceptible to pipe friction factors. Theoretically at least, the fault detection and system calibration can be conducted simultaneously without knowing the precise friction value. Of course, these benefits are not the whole story, however.

2.1.4 Major Considerations and Categorizations

A number of transient-based techniques for pipeline fault detection have been developed in the last two decades (Wang et al. 2001; Colombo et al. 2009; Puust et al. 2010). These methods share some characteristics with each other but each has its own special advantages and disadvantages.

Objectives. While developing transient fault detection techniques, it is vital to have a clear picture of the objectives that should be met. The possibility of balancing the expectations of all these objectives must be continually considered.

- reliability—the technique is expected to show its effectiveness over time, and the performance of monitors should be stable in long-term identification of faults.
- accuracy—it is evident that the errors in detecting and identifying false positives and negatives can lead to unnecessary pipe maintenance costs. Although developing a perfectly accurate fault detection method is difficult, a high degree of detection accuracy is obviously desirable.
- cost—After completing the fault diagnostics, the economic aspect associated with the application of the proposed method is evaluated considering the costs of deployment, maintenance, and the management of diagnostic errors. One of the goals in developing a fault detection technique is to reduce the operational cost while improving the performance.
- sensitivity—For the cost saving, developing an efficient method which can detect small anomalies from a long distance is important. The sensitivity of a fault detection method is optimized by increasing its sensitivity with respect to the target faults and by enhancing its ability to eliminate noise from other disturbances.
- acceptance—Fault detection techniques are an application-oriented approach, which means the acceptance of the method must be established ideally both in the lab and in realistic field installations to prove its performance in laboratory or practical applications. The techniques should have simple and clear procedures, and be nondisruptive to the system.

Based on these objectives, various transient fault detection techniques are presented, with the following major concerns addressed in different ways.

Transient generation. The transient signal that is analyzed in the test can rely upon natural sources of fluid excitation, generated by an induced event (e.g., pump failure or pipe leak/burst) (Misiunas et al. 2005) or artificial events, such as injecting a prescribed transient signal into the pipe flow typically through valve operations. The subsequent behavior of the transient event is analyzed to acquire the system properties. The fault detection performed in passive systems obtain the transient signals directly from the system and exploit special features to detect and locate leaks and other faults. The systems that take advantage of information from transient events generated artificially are referred to as active systems, where the injected signals are customized and must be distinct from background noise.

Fault-induced effect. The transient signal contains two types of fault-induced effect. The reflection and damping effect, which can be utilized alone or can consider two types of information at the same time.

Domain type. After the time history of the pressure transient signal (i.e., the piezometric head) is measured by the transducers, the analysis of the data can be completed in the time domain or/and frequency domain. The time-domain methods analyze data straightforwardly in the time domain, while the frequency-domain methods require mathematical conversion.

Analysis approach. Signal processing and hydraulic transient model simulation are analysis approaches that are being considered. Signal processing is a method to extract information from measured data and compare it with the data sets from a fault-free benchmark on the basis of properties of leak-induced effect on a flow or pressure signal. Hydraulic transient models simulate data and reproduce pressure traces in the time or frequency domain. Based on the degree of coincidence between the data from accurately modeled systems with faults and measured data, information related to faults is determined. Two detection procedures with different configurations can be developed based on the propagation analysis of the pressure signal. A signal processing approach locates the generator and the transducer of the transient at the end of a pipeline, and the inverse method using a hydraulic model generates the transient and measures the pressure response at multiple locations along the pipe.

In summary, according to the manner in which transient signals are utilized, the methods described in existing literature can be divided into four types: the transient reflection method (TRM), the transient damping method (TDM), the system response method (SRM), and the inverse transient method (ITM). These methods are briefly introduced in the following sections. Their key features and categorization are systematically summarized in Fig. 2.5.

2.2 Current Transient Fault Detection Techniques

2.2.1 Transient Reflection Method (TRM)

Generally, a transient pressure wave is partially reflected, partially transmitted and partially absorbed wherever the system shows discontinuity (Burn et al. 1999). Faults and pipeline features cause additional reflections of transient pressure waves as shown in Fig. 2.1 and may create multiple wave paths in the pipe system. Figure 2.6 shows the hypothetical pressure trace at a transducer. The transient wave is detected by

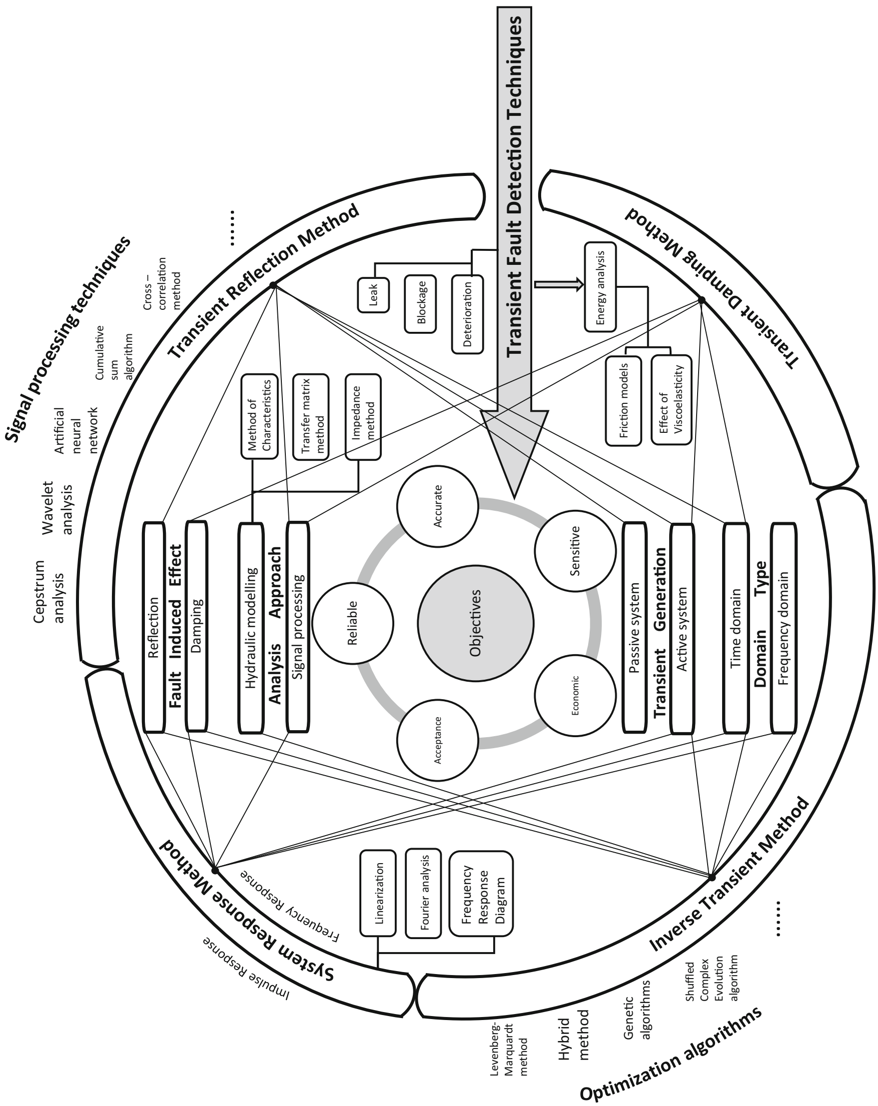

Fig. 2.5 Summary of current transient fault detection techniques

the transducer at t_1, and the passage of the reflected signal, normally the first signal reflected, is recorded at t_2. In addition, the distance between measurement point and fault location can be given by multiplying the half wave traveling time T by the wave speed.

The transient reflection method (TRM), often referred to as the time-domain reflectometry (TDR) technique, relies on differentiation of a reflected signal by identifying the discrepancies between measured results with the fault-free benchmark results. The benchmark results can be obtained from a fault-free laboratory system, or from an accurate numerical model of the pipe system. For a typical system with unknown characteristics, however, it is hard to determine the leak-free benchmark: only the changes from the benchmark results can be detected.

Jönsson and Larson (1992) were one of the first to use the generated transient to detect leaks by measuring the arrival time of a reflected wave. Brunone (1999) introduced the theory and verified it by an experiment in a single polyethylene pipe, while the background noise disturbed the identification of signals. The experimental validation was improved by Brunone and Ferrante (2001) to identify the leak location more accurately. Beck et al. (2005) used the cross-correlation method to reduce the problem of disturbance and detected more pipeline features in a T-junction network. Meniconi et al. (2011a) applied the TRM to detect the location of illegal side branch in a laboratory complex pipe system. The experiment performed well, but uncertainty about factors like friction and unaccounted for reflections in real systems may complicate practical application. Recent studies have improved the application of TRM by utilizing methods and algorithms such as cepstrum analysis (Taghvaei et al. 2006), wavelet analysis (Ferrante and Brunone 2003; Ferrante et al. 2007), cumulative sum method (Lee et al. 2007), and artificial neural network (ANN) (Stoianov et al. 2001).

Artificial intelligence methods have also attracted attention. For example, an artificial neural network (ANN) constructs relations between input and output data without any explicit mathematical model and has been effectively used to solve many classification problems including transient fault diagnosis. An ANN technique was applied for leak detection in a liquefied gas pipeline with 74,668 m in length and 0.203 m in diameter (Belsito et al. 1998). The ANN training uses data generated by a transient model using different leak and flow conditions. The method could detect and locate leaks down to 1% of the total flow rate in about 100 s according to the numerical results. When using measured data, however, the average error of the detected leak locations increases to about 7000 m for a leak of 1% of the total flow and 1645 m for a leak of 10% of the total flow (Belsito et al. 1998). Similarly to the problems that exist in the inverse methods, without the accurate simulation of the transients using a transient model, the information concerning leaks could be lost in the training process. A novel leak detection method was developed by integrating the wavelet transforms with artificial neural networks for signal identification and leak feature extraction (Stoianov et al. 2001). A supervised Kohonen network is applied to classify wavelet coefficients of the pressure response for transient events in a pipeline rig. Their potential has only been demonstrated using laboratory rigs, however.

The TRM has a basic concept and simple procedure, and previous works have also shown that the analysis of the reflected transient signal is effective in identifying pipeline features and faults (Beck et al. 2005; Lee et al. 2007; Ferrante et al. 2009; Gong et al. 2012b); nevertheless, its verification so far has rarely been extended to field tests. The accuracy of the method would be much lower without the assumption of a single-phase flow and rigid pipes. In addition, complicated geometries like loops in real complex pipe networks create complex reflected patterns that are less distinguishable. Therefore, it is difficult to obtain satisfactory results from pipe networks. The TRM does not require a precise mathematical model; however, it requires fault-free benchmark data sets from the controlled pipe system to extract and classify signal features. Thus, its scheme is not applicable to existing real pipe systems because the faults in the system would particularly perturb the benchmark data sets. It is also difficult to detect the integrity of the system if the induced transient signal in a fault-free system is not perfectly regular and reproducible.

2.2.2 Transient Damping Method (TDM)

The transient signal that propagates in a pipeline decays because of the presence of friction, faults, and pipeline features. The faults usually modify the damping pattern, so they can be detected by comparing the induced damping pattern with the fault-free benchmark in the same pipe system. Figure 2.6b uses the presence of leak as an example.

The transient damping method is a fault detection approach designed solely on the damping effect of the transient signal. It was first proposed by Wang et al. (2002). The approach introduced by Wang et al. performed a Fourier series analysis to solve the linearized differential equations. The approach detected the leak by utilizing the first two Fourier components in the transient signal based on the fact that the damping

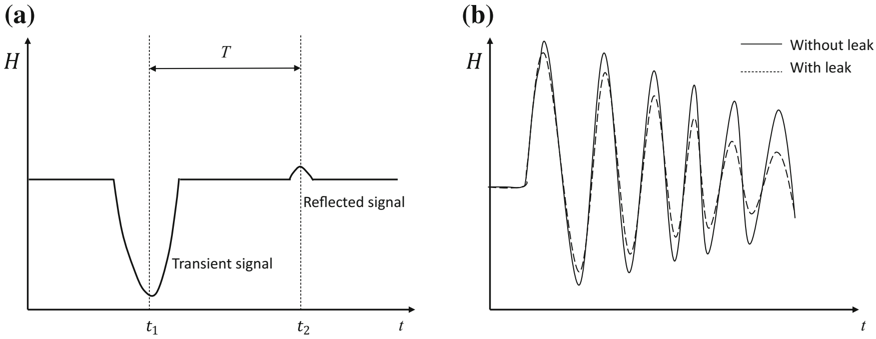

Fig. 2.6 Pressure trace modified by leak-induced reflection **a** and damping **b** effect

ratio of the two components is the same for friction factor, while the ratios are different for the leak factor. Wang et al. (2005) investigated another partial blockage detection method using the damping of fluid transient. The proposed method locates the blockage by the different damping ratios and uses the magnitude of the damping rate to determine the blockage size.

TDM is a simple and creative method. It has been applied in numerical simulation and lab experiments, which shows its ability to successfully locate and quantify the faults with small errors (Wang et al. 2005, 2002). Its application is restricted to single-pipe systems for damping is not only caused by friction and faults, so other physical features in complex systems would make the identification of damping difficult or even impossible. TDM assumes a linear system with steady friction. A study by Nixon et al. verified this assumption through a transient model and indicated the importance of unsteady friction in the applicability of the TDM (Nixon et al. 2006). The accuracy of the method is not influenced only if the unsteady friction effect is represented correctly in a simple system (Nixon et al. 2006; Nixon and Ghidaoui 2007). The TDM would be suitable in the field only if the difficulty of modeling unsteady friction is overcome. Aside from the characteristics of leaks, the leak-induced damping rate also relies on pipe pressure, the shape of the transient signal and the location of the generated transient, whereas the blockage-induced damping rate only depends on the position and size of the blockage. Because the damping functions induced by leaks and blockages have different modes (Wang et al. 2005), the accuracy of detecting leaks and blockages differs depending on the measurement location, making it hard to detect all faults at the same time.

2.2.3 System Response Method (SRM)

The main principle of the system response method is to utilize all the information (i.e., reflection and damping effects) contained in the transient signal of the system response to identify and locate the faults by comparing the results from a pipeline with and without faults.

The pipe system is considered as a transformation that can produce an output of the measured pressure response by using each given input of the transient injected to system. A complicated input signal is divided into a series of weighted unit impulses, and the overall system response is obtained by a process known as convolution, which adds the contributions from the entire input signal. The function relating the input and output signals indicates all information pertaining to the behavior and features of the pipe system.

The impulse response function converts the output signal in the trace into sharp impulses with well-defined spikes (Fig. 2.7). In the time domain, the system output can be calculated for any input by a convolutional integral:

$$y\left(t\right)=\int_{-\infty}^{+\infty}x\left(t^{'}\right)I\left(t-t^{'}\right)dt^{'} \tag{2.13}$$

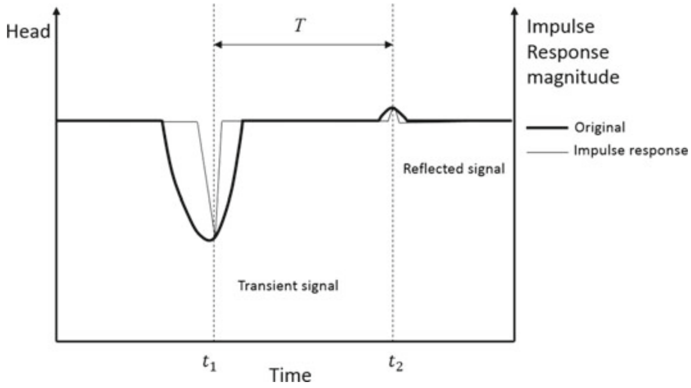

Fig. 2.7 Comparison between original reflected transient signal and impulse response function

where $I(t)$ is the impulse response function (IRF) of the system, and $t^{'}$ is the previous time step.

The application of the impulse response method (IRM) in fault detection was first presented by Liou (1998), who extracted the impulse response of the system by using the cross-correlation method and applied the technique in a real-time pipeline leak detection. The study is limited by its assumption of a linear system and can only easily be applied in single pipeline. Vitkovsky et al. (2003) extracted impulse response from a pipe system with a leak and blockage and compared it to the response from the fault-free pipe system. The numerical study shows that the use of IRF increased the accuracy of fault location. The genetic algorithm was integrated into the impulse response method by Kim (2005) in a study in which the location and size of a leak were calibrated. The study also considered the impact of unsteady friction by assuming different friction under the conditions of laminar and turbulent flow. Lee et al. (2007) validated the impulse response method by an experiment and demonstrated the impact of signal bandwidth and background noise on the extracted IRF. Gong et al. (2012a) utilized IRF to detect the distributed deterioration by determining the variation of pipe wall thickness. This novel distributed deterioration detection method was validated in the lab on a single pipeline.

Other sources of disturbance in real pipe systems, such as pumps, valves and turbines, can also modify the pressure trace by making it smooth, so identifying the fault-induced information becomes more difficult. By employing IRF, the conversion of output from pressure trace to sharp impulse enables an easier and more accurate estimation of signal arrival time. The IRF also has the advantage that it is independent of the input signal shape and is specific for each pipe system (Lee et al. 2007).

After applying a Fourier transform, the system response function in (2.13) is transferred to the frequency domain, known as frequency response function (FRF).

$$F(\omega) = \frac{Y(\omega)}{X(\omega)} \tag{2.14}$$

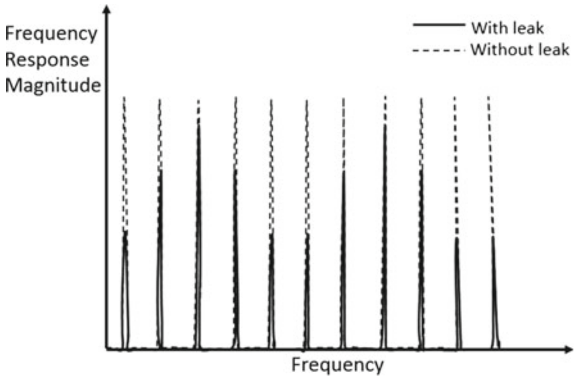

Fig. 2.8 Comparison between the frequency response of the intact and leak pipe

where ω is frequency, $F(\omega)$ is the Fourier transform of the function, $X(\omega)$ is the system input, and $Y(\omega)$ is the system output.

Mpesha et al. (2001) first proposed the frequency response method for pipe leak detection. The presence of a leak is revealed in the frequency response diagram by a relatively lower amplitude peak than an intact pipe, which is shown in Fig. 2.8. The numerical tests which used several different construction forms of pipe network verified the applicability of this method in detecting and locating small leaks in pipe systems. A new approach was put forward by Covas et al. (2005) by using the standing wave difference method for leak detection. The method is based on the steady oscillatory state generated by a sinusoidal valve operation, the principles of spectrum analysis, and the analysis of system frequency response. Although the method is effective and promising, it has some practical difficulties and has not been validated by experiment or field test. Lee et al. (2005) proposed an analytical solution in locating single as well as multiple leaks by explaining the nature of resonance peaks in a frequency response diagram. Duan et al. (2011b) presented the method in series' pipelines of different diameters and indicated the effect that the junction has on leak-induced information. Meniconi et al. (2011b) investigated the interaction between transient waves and in-line-valves within a viscoelastic pipeline and used wavelet functions to locate the blockage. Recently, Duan et al. (2014) observed the blockage-induced changes to the resonant frequencies and developed another method for blockage detection. The resonant frequency shifts caused by blockages in a pipe system is studied by conducting a transient wave perturbation analysis. The accuracy of the method is validated in the numerical application and experimental tests.

Unlike the IRM, the performance of FRM is closely related to the shape of the input transient. FRM analyzes transient response in the frequency domain, and it is equivalent to the impulse response method in the time domain in describing the system response from a transient excitation.

2.2.4 Inverse Transient Method (ITM)

The inverse transient method is a well-known and powerful approach for the fault detection and parameter calibration in pipe systems. The method involves the following procedures. First, the transient state is initiated by opening or closing a controlled valve over a short time period. Afterwards, transient flow characteristics (mostly the pressure fluctuations) are measured at multiple selected points in the system. The measurement points are usually located close to the transient generation point. The transient condition of the pipe system is then numerically modeled as a function of pipeline features, fault parameters and friction factors. The successful application of the method hinges on the modeling of pipe system behavior under transient state. After that, defining a nonlinear programming problem with an objective function to minimize the absolute difference between the actual measured data and simulated data from transient model must be achieved. An optimization tool is finally employed to solve the problem. The location and magnitude of the faults are determined by the minimization of the deviation between the actual measured data and simulated data by the transient model as shown in (2.15).

The objective function for optimization can be expressed as

$$\text{min:}\quad \text{OF} = \sum_{i=1}^{N} \left| H_i^m - H_i^p \right| \tag{2.15}$$

where OF is the objective function, i is the time step points, N is the number of data points, H_i^m is the measured pressure head, and H_i^p is the predicted pressure head.

Various algorithms have been used to solve the objective optimization function of (2.15). Liggett and Chen (1994) introduced an inverse transient method for pipe network leak detection and calibration for the first time. They utilized the Levenberg–Marquardt (LM) method to solve the inverse problem. A simple small pipe network consisting of 11 pipes and seven nodes was theoretically developed to examine the model generated data. Their work shows that LM applied in ITM has good performance. Nash and Karney (1999) applied ITM in a series-connected pipeline and conducted a sensitivity analysis of the calibration results. Vítkovskỳ et al. (2000) applied an improved unsteady friction model to increase the accuracy of transient simulation. The study improved the solution of the inverse problem by using a genetic algorithm (GA) instead of LM in previous research. The obtained numerical results of leak detection in a small pipe network was satisfactory. Kapelan et al. (2003) developed a novel optimization method in which two previously used methods, LM and GA, are combined into a hybrid genetic algorithm. The more reliable results were obtained after analyzing a benchmark pipe network. Stephens et al. (2004) used ITM to detect air pockets and blockage for the first time and successfully verified the ITM approach in the field. Vítkovskỳ et al. (2007) presented the further improvement of ITM in exploring data and model errors by reducing the minimization complexity. The analysis was proved by experimental observations of detecting both single and multiple leaks in a laboratory pipeline. Covas and Ramos (2010) assessed the effectiveness of the technique by running ITM with the data collected from the laboratory and the field. Soares et al. (2011) verified ITM by an experiment in a complex system using PVC pipes with viscoelastic behavior. The experiment located leaks with a satisfactory accuracy, which was between 4 to 15% of the total length. More recently, Kim (2014) detected leaks and blockages considering unsteady friction in a branched RPR system. The impedance method for ITM was developed for the numerical verification. The results indicated that the impact of unsteady friction causes difficulty in locating faults, but the calibration of leak parameters was accurate.

ITM utilizes both the fault-induced reflection and the damping effect in producing the transient trace. Given enough measurements, the ITM can be used for pipe system fault detection as well as parameter calibration. The mathematical-related problems for ITM have been well exploited since the technique was introduced. Compared to other methods, the application of ITM has generality, since it can be applied without the restriction of topography and system configuration. Therefore, it is promising to extend the application of ITM to complex pipe networks in field. More efforts should be directed to experimental and field validation.

Traditionally, the measured data is analyzed by MOC and optimization algorithms such as GA, while the transient models are developed based on steady friction and the calculated damping rate (Wylie and Streeter 1978). The unsteady friction effect and boundary conditions that are not accurately considered in transient models can result in undesirable deviations between modeled and measured data. The key challenge in the satisfactory application of ITM lies in the accuracy of the transient model.

2.3 Critical Remarks

2.3.1 Evaluation of Techniques

Transient fault analysis usually needs to use the information generated by transient events, which is usually induced by several cycle-driven devices, such as modulation of valves. The difference between time-domain analysis (TDA) and frequency-domain analysis (FDA) is the way of analyzing the pressure monitoring data. The TDA method analyzes the pressure monitoring data directly in time domain, which does not involve any mathematical conversion, so it is intuitive and precise. In contrast to TDA, FDA must convert the pressure signal from time domain to frequency domain by using methods such as the fast Fourier transform and wavelet transform.

In most of the early studies, the transient flow is simulated and analyzed in the time domain by using the MOC, which must discretize the system in both time and space. In order to capture all the propagating waves and increase the model's accuracy, the system must be discretized into short reaches, resulting in tiny computational time steps, which with earlier computers rendered the MOC method computationally uneconomical. Modern computer technologies now allow us to do the calculations without these concerns, but the TDA is still practically limited to simple systems and boundary conditions. The FDA has become more popular in recent years. Pressure monitoring data does not only show the change over time, but also contains the information such as frequency and phase. The FDA method does not need discretization and is computationally very fast. It has been shown that transient fault diagnostics in the frequency domain allow the fault to be isolated from complex system phenomena such as unsteady friction and pipe wall viscoelasticity. Moreover, it provides an increased tolerance to random noises (Lee et al. 2006; Duan et al. 2011a). The fault parameters are more clearly evident in the frequency response diagram of the system and, therefore, the predicted fault parameters would be more reliable.

Note that TDA and FDA are applied under different demands and circumstances such that neither of them has a full advantage over the other. The FDA has some limitations associated with linearization of the governing equation as well as the detection of multiple faults directly from the system frequency response diagram. The TDA is a powerful analysis approach which is superior in describing the time history of transient response in pipe systems, and is effectively applied when the time history of the transient needs to be determined.

Advances in the development of the four principle techniques are summarized in Table 2.1. It is observed that all the techniques are feasible and accurate in numerical studies or in the laboratory, but are lacking any kind of comprehensive validation in the field. Although development is still in process, it is obvious that the application of methods like TDM is restricted, since TDM can only be applicable in simple pipe system, even if the fault detection accuracy is high. TRM is simple to use and apply, so its theory has been verified in various experimental systems of many studies. In complex systems, however, it does not have high accuracy and efficiency compared to the SRM. ITA is the most generally applicable method in dealing with complex pipe networks, but the general system condition must be quite well known.

Each one of these techniques requires specific and suitable system characteristics to trade off in complexity, precision and costs, so various techniques exist in this field. The overview of diverse transient-based fault detection techniques given in Sect. 2.2 also reveals that there is no perfect method that always meets all requirements, for each technique has its merits and drawbacks under different scenarios.

2.3.2 Obstacles in Application

The limitation of transient-based fault detection techniques can be concluded from the previous development and application of each method. Furthermore, the current techniques face the difficulty of identifying and characterizing a transient response from systems with complex configurations. The obstacles in solving the problem include any or all of the following issues.

System Assumptions. Most transient models assume ideal system conditions such as constant system demand, known pipe materials, and steady friction in the application

Table 2.1 Significant researches for principle techniques, Num* = numerical

Technics	References	Method/algorithm applied	System configuration	Pipe feature/fault	Key attribute		
					Num*	Lab	Field
TRM	Belsito et al. (1998)	ANN training	a single pipe	leak	√		√
	Brunone (1999)	MOC, inverse calculation	a single outfall pipe	leak	√	√	
	Stoianov et al. (2001)	wavelet analysis, ANN	six loop system	leak	√		√
	Beck et al. (2005)	cross-correlation method	T-junction pipe network	bend, joint, leak	√	√	
	Misiunas et al. (2005)	cumulative sum algorithm	a dead-end branch pipe	leak	√	√	√
	Lee et al. (2007)	cumulative sum algorithm	simple RPR system	leak	√	√	
	Ferrante et al. (2009)	wavelet analysis; Lagrangian model	Y-shape pipe network	dead end, leak, Y-junction	√	√	
	Gong et al. (2012b)	MOC	simple RPV system	distributed deterioration	√	√	
	Tuck et al. (2013)	MOC, visual comparision	simple RPR system	blockage	√	√	
TDM	Wang et al. (2002)	MOC; Fourier series analysis	simple RPR system	leak	√	√	
	Wang et al. (2005)	Fourier series analysis	simple RPR system	blockage	√	√	
SRM	Liou (1998)	impulse response; cross-correlation method	simple RPV system	leak	√		
	Mpesha et al. (2001)	frequency response, transfer matrix method	single, series, parallel, branched RPV system	leak	√		
	Vitkovsky et al. (2003)	impulse response, transfer matrix method	simple RPR system	leak, blockage	√		
	Lee et al. (2005)	frequency response, transfer matrix method	simple RPR system	multiple leak	√		
	Kim (2005)	impulse response, genetic algorithm	simple RPR system	leak	√		
	Covas et al. (2005)	frequency response, standing wave difference method	simple RPV system	leak	√		
	Lee et al. (2007)	impulse response CUSUM algorithm	simple RPR system	leak	√	√	

(continued)

Table 2.1 (continued)

Technics	References	Method/algorithm applied	System configuration	Pipe feature/fault	Key attribute		
					Num*	Lab	Field
	Sattar et al. (2008)	frequency response, MOC, transfer matrix method	simple RPV system	blockage	√	√	
	Duan et al. (2011b)	frequency response, transfer matrix method	complex pipe series	multiple leak	√		
	Gong et al. (2012a)	impulse response, sensitivity analysis	a single pipeline	distributed deterioration	√	√	
	Duan et al. (2014)	frequency response, analytical derivation	simple RPV system	extended blockages	√	√	
ITM	Liggett and Chen (1994)	Levenberg–Marquardt method	small pipe network	leak	√		
	Nash and Karney (1999)	Levenberg–Marquardt method	series RPR system	N/A	√		
	Vítkovskỳ et al. (2000)	genetic algorithm	small pipe network	leak	√		
	Lee (2002)	SCE algorithm	simple RPR system	leak	√		
	Kapelan et al. (2003)	hybrid genetic algorithm	a looped pipe network	leak	√		
	Stephens et al. (2004)	Shuffled Complex Evolution global search algorithm	field network	air pocket, blockage	√		√
	Vítkovskỳ et al. (2007)	Model Error Compensation Approach, Model Parsimony Approach	simple RPR system	single and multiple leak	√	√	
	Shamloo and Haghighi (2009)	Sequential Quadratic Programming method, backward MOC	simple RPV system	leak	√		
	Covas and Ramos (2010)	Levenberg–Maquardt method, genetic algorithms	complex pipe system	leak		√	√
	Soares et al. (2011)	Levenberg–Maquardt method, genetic algorithms	complex PVC pipe system	leak	√	√	
	Kim (2014)	impedance method genetic algorithm	branched RPR system	leak, blockage	√		

of fault detection techniques. Specifically, the assumption of steady friction and elastic behavior of pipe material in the experimental application (Wylie and Streeter 1978) results in deviation in phase and damping between measured and calculated results. By applying this, the results are far from satisfactory since the model does not correctly consider the unsteady friction and viscoelasticity effects. Steady or quasi-steady friction loss is a reasonable assumption for slow transients, while it is less valid for rapid transient events in fault detection techniques. Duan et al. (2010) also demonstrated the dominant effect of viscoelasticity with respect to unsteady friction in plastic pipes. The energy loss resulting from friction and fluid viscosity is uncertain, which is critical for the modeling of transient flow in real pressurized pipe system. Therefore, there have been a number of studies exploring the field of unsteady friction in the last two decades. Previous studies have pointed out, however, that unsteady friction leads to a more rapid attenuation of a transient signal (Chaudhry 1979). The improved unsteady friction transient model has not been developed to ascertain the accuracy and effectiveness of fault detection.

Transient Excitation. Transient signals in pipe system are excited by adjusting system elements such as in-line valves, side-discharge valves, or pumps. The first pressure transient oscillation is commonly analyzed for fault detection, so the periodic operation of the valve to generate steady oscillatory flow is required. These methods show that fault detection techniques based on odd harmonics of frequency are superior among the FRF-based methods (Lee et al. 2005; Duan et al. 2011b; Gong et al. 2013). The accuracy of the method increases with the number of resonant peaks in frequency response, so the input signals that have a wide bandwidth of frequency containing a number of harmonics are preferable. The requirement is not only for the frequency-domain method, but also the need for the application of time-domain fault detection techniques. Producing signals with resonant frequency is a risky decision, however, for it is likely to damage the pipe system. The practical difficulty of a rapid periodic maneuver operation at high frequency is also obvious. A desirable signal-to-noise-ratio (SNR) is difficult to achieve because of the limitation of existing transient generators. Modeling valve operations, especially steady oscillatory operation, can also be challenging in the field tests.

Signal Attenuation. All the applications of transient-based fault detection methods, regardless of whether they are used in the time or frequency domain, rely on the reflection information in transient trace (Lee et al. 2014). The energy contained in the transient signal attenuates along the propagation of the transient wave, so it is likely that in real-life application, the transient signal is incapable of traveling to the fault location and carrying fault-induced reflection information to the measurement point. Moreover, since the magnitude of reflection is proportional to the level of pipe's internal damage at a fault location, the small areas subjected to damage, such as cracks and rust patch, might not cause significant reflection, as it can be noticed on transient reflection. The problem of effectively extracting a useful weak transient signal created by a small leak or the decay along the pathway is still to be solved.

Hydraulic Impersonation. The complicated geometries, including junctions, branches and loops, in complex pipe systems create complex wave paths, which make the faults-related information difficult to extract. Previous work has improved the detection techniques and extended the experiments to identify pipeline features as well as the faults. Applying the methods in field tests, however, is still difficult. Reflections from multiple sources in a single pipe can distort the pattern of response trace. A normal pipe feature can introduce a pressure trace which is a good mimic of the response of a fault. In addition, system noises arise from a vast range of disturbances and events (e.g., pump failures, a change in demands) in a complex system and overshadow the useful transient pressure signals. Duan et al. (2014) indicated the highly nonlinear and nonstationary conditions of transient signals in complex systems for detecting multiple faults. The above-mentioned vexing phenomenon of hydraulic impersonation exists in all real pipe systems. Currently used data analysis techniques have the limitation of accurately distinguishing true positive from false positive results in fault diagnosis applications.

Other Factors. According to the previous real-life application of transient-based fault detection techniques in the literature, other limitations of current methods can also attributed to the following practical complications.

- The selection and relative position of the transient measurement and generation points. Features and faults close to the transducer are prone to be discernible;
- The automatic monitoring and detection of transient signals;
- Error in measuring actual wave speed; and
- The difficulty in determining the exact arrival time of transient signal because of the intrinsic error of time lag.

In brief, the developed techniques perform much better in ideal numerical simulations, since the hydraulic condition, valve operation, experimental uncertainties, and model inaccuracy can easily hinder the validation of transient-based fault detection techniques in realistic cases.

2.4 Promising Research Directions

On the basis of the discussions in previous sections, for better operating of pipe systems in industries, the following research directions are promising in achieving deployment and commercialization of transient-based fault detection techniques in the future.

Application in Complex System with Multiple Faults. All transient-based leak detection techniques face difficulties in locating faults in systems with a high level of complexity. The validations are expected to extend from a single-pipe system to a multiple-series pipe system, even to the pipe networks. Some consideration must be given on how the current methods can handle the practical complexity. The methods are mostly applied only in laboratory conditions in which the pre-known faults and features exist in grounded pipe. Fault detection applied to pipe systems in complex underground situations with unknown multiple types of faults is inapplicable in previous studies, and must be explored in the future. A comprehensive understanding of the system behavior for developing new effective transient-based detection techniques is critical.

Combination of ITM and FRM. The merits of the frequency response method in identifying the transient system characteristics are highlighted in recent research. Transient hydraulic simulation in the frequency domain does not require numerical computations' procedures and presents the presence of a fault evidently in the frequency response diagram. Previous studies mostly utilized the frequency response method for fault detection without the optimization. Therefore, the inverse transient frequency method (ITFM), which is the combination of ITM and FRM, would make the fault detection more precise and reliable compared to using ITM in the time domain. Formulating the system frequency response with the inverse problem has became a frontier in the field.

Higher Harmonics. Many experimental tests verify that obtaining more resonant peaks from the frequency response diagram can improve the fault detection performance. Hence, the rapid maneuvers resulting in the generation of high harmonics are preferable for application in the field. The rapid valve operation involved in the generation of high frequency, however, may cause the destructive water hammer in the pipe system. Furthermore, more distortion in high frequency components of the transient signal would be present in the field. Research which focuses on high harmonics is also lacking, since the mechanical device that can generate measurable high frequencies is currently unavailable. Further research in this field is needed to validate the applicability and to improve the performance of frequency-domain methods in practice.

2.5 Conclusions

This chapter introduces and evaluates a number of currently developed transient-based techniques of fault diagnosis in pipe systems. The fault detection principle and the method for analyzing the transient trace are presented. There is no unified framework for the identification and classification of these techniques. To tackle this problem, a systematic diagram is created to summarize the knowledge in the research area. The possible solutions with respect to the criterion of performance are different, since the selection of an optimal technique can only be performed considering the detection objectives, i.e., the need for reliable, economic, and robust methods applicable to complex and dynamic systems.

Selected literature on the development and verification of the described principal transient fault detection techniques are provided. The development of diagnostic techniques are based on numerical transient modeling and the theories of estimation and identification of fault information by the signal processing. The four discussed methods are mostly widely used in the active systems. Particular attention has been paid to the way of analyzing measured data, including the analysis in time domain and frequency domain.

The main drawback to all the proposed fault detection techniques is that they are remain difficult to apply in real and complex systems. This is caused by the fact that for each method one must give ideal system assumptions prior to its deployment, which reduces the accuracy and generality of the method. In addition, the problem of signal attenuation and technical difficulty in transient excitation are always challenging in real applications.

The possibility of joining the frequency response method with inverse analysis has vital advantages, which will be a subject for further investigations. The process of developing pipe fault detection techniques is a complex optimization problem. Computational requirements and errors grow together with system complexity. In this case, the fault detection is usually connected with the phenomenon of hydraulic impersonation. Further research on the techniques presented in the chapter is expected to address such issues, and certainly much research work still remains be done for minimizing the problem of both false positive and false negative field results.

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