Sensitivity Analysis of Transient-Based Frequency Domain Method for Extended Blockage Detection in Water Pipeline Systems

H.F. Duan, *M.ASCE*

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: hf.duan@polyu.edu.hk.

Abstract: Partial blockages are commonly formed in water supply pipelines due to many factors such as deposition, biofilm and corrosion in natural water supply process as well as valve throttle in artificial construction and operation process, which may cause additional energy losses and serious water supply accidents in the system. Recently a transient-based frequency domain method (TBFDM) has been developed for extended partial blockage detection by the author and it was found to be efficient, non-intrusive, and inexpensive to apply. While this method has been validated and applied for numerical and laboratory experiments in previous studies for a variety of blockage and hydraulic conditions, the application results revealed that the accuracy of the TBFDM may be easily affected by uncertainties in experimental process. This paper investigates the sensitivity of the developed TBFDM to different uncertainty factors that commonly exist in water pipeline systems, with perspective to better understand and use this efficient and economic method in practice. The methods of first-order second-moment analysis and Monte-Carlo simulation are adopted in this paper for the investigation. The obtained results are discussed for the validity range and limitations of current TBFDM for practical applications.

Author keywords: Water pipelines; Uncertainty; Sensitivity analysis; Transients; Extended blockage detection; Transient-based frequency domain method (TBFDM)

Introduction

Pipe faults such as leakage and blockage commonly exist in water supply pipelines due to many natural and/or artificial factors such as pipe-wall corrosion, sediment decomposition, biofilm build-up and device operations, which can cause various and serious problems in the water conveyance process (Stephens 2008). Therefore, identification and detection of such pipe faults become important and urgent to improve and enhance the water supply capacity as well as to conserve water and energy resources in urban water piping systems. While there are many different methods developed and applied for pipe faults detection, e.g., physical inspection, acoustic method, steady-state hydraulic analysis and devices based method (Lee 2005), the current severe situation of over 30% of water and associated energy losses in urban water supply systems worldwide indicates the inadequacy of the use and development of these detection methods (Colombo et al. 2009; Lee et al. 2015).

Recently, transient analysis has been used for pipe condition assessment for its efficient, non-intrusive, and inexpensive applications (Lee et al. 2013). For this purpose, transient-based methods have been developed for detecting leaks and blockages in pipeline systems of different topologies (e.g., Brunone 1999; Ferrante and Brunone 2003; Wang et al. 2002, 2005; Covas et al. 2005; Mohapatra et al. 2006; Lee et al. 2006, 2008, 2013; Sattar et al. 2008; Stephens 2008; Vítkovský et al. 2000; Meniconi et al. 2011a, 2012a, 2013; Duan et al. 2011, 2012, 2013, 2014; Duan and Lee 2015). Particularly for the pipe blockage detection, previous numerical and experimental studies have shown that the extended blockage in the system could cause the additional damping and the phase/frequency shift of transient responses (Brunone et al. 2008; Duan et al. 2011, 2012, 2014). This characteristic of transient-blockage interaction was thereafter used in the literature for developing the transient-based methods for the extended blockage detection in both time and frequency domains (Duan et al. 2012, 2013; Meniconi et al. 2013).

Compared to the time domain analysis, the frequency domain method for blockage detection uses the similar information of transient reflection and damping, but it has additional advantages of increased tolerance to random noises and unidentified factors such as turbulence and flow stabilities during transient processes (Lee et al. 2006, 2013; Zhao et al. 2007; Meniconi et al. 2012b, 2013). The principle of the transient-based frequency domain method (TBFDM) for pipe blockage detection is to inject a customized and controlled pressure wave into the pipeline and conduct the spectral analysis of the responses measured at certain accessible location(s) along the pipeline, and then to determine inversely the potential fault information (size and location) in the system (Duan et al. 2012; Lee et al. 2013).

The TBFDM has been successfully applied and validated for single and multiple extended blockage detection in numerical and laboratory experimental test systems (Duan et al. 2013; Meniconi et al. 2013; Lee et al. 2015). But the application results from these studies revealed that the developed TBFDM was much more accurate in the ideal numerical tests than the realistic experimental cases, which was explained by possible experimental test uncertainties and model inaccuracy in these studies. Consequently, it is necessary to systematically investigate the influences of different uncertainty factors in the pipe system to the applicability and accuracy of this developed method that was thought to be efficient and non-intrusive in the literature, which is the scope of this study. Two different analysis methods – First-Order Second-Moment (FOSM) and Monte-Carlo Simulation (MCS) – are adopted in this paper to study the sensitivity of the TBFDM for the blockage detection by considering different uncertainty factors that commonly exist in water pipeline systems. A simple numerical test system with single extended blockage is used for this investigation. Results discussion and implications of the current

TBFDM applications are conducted in the end of this paper.

Investigation Methods

The main methods and expressions used for the investigation are described briefly in this section.

Transient-Based Frequency Domain Method (TBFDM)

The TBFDM and solution procedures developed in Duan et al. (2012) are used in this study for pipe blockage detection. A simple pipeline system with single extended blockage is considered for the analysis in this paper. The pipeline system is bounded at the upstream boundary by a constant head reservoir, and a valve at the downstream boundary. The analytical expression of resonance condition for a pipeline system with a single extended blockage was derived in Duan et al. (2012) and mathematically given by,

$$\begin{pmatrix} (Y_u + Y_b)(Y_b + Y_d)\cos[(\lambda_u + \lambda_b + \lambda_d)\omega_{rf}] \\ +(Y_u - Y_b)(-Y_b - Y_d)\cos[(\lambda_u - \lambda_b - \lambda_d)\omega_{rf}] \\ -(Y_u + Y_b)(Y_b - Y_d)\cos[(\lambda_u + \lambda_b - \lambda_d)\omega_{rf}] \\ -(Y_u - Y_b)(-Y_b + Y_d)\cos[(\lambda_u - \lambda_b + \lambda_d)\omega_{rf}] \end{pmatrix} = 0, \quad (1)$$

where, $\omega_{rf} = \omega_{rf}(n)$ is frequency for the n^{th} resonant peak; $\lambda = C_R \frac{l}{a}$ is wave propagation operator; l is pipe length; a is wave speed; $C_R = \sqrt{1 - i\frac{gAR}{\omega}}$ is friction influence coefficient; $Y = -C_R \frac{a}{gA}$ is transient impedance coefficient; A is pipe cross-sectional area; i is imaginary unit; $R = \frac{fQ_s}{gDA^2}$ is friction damping factor; f is friction factor; Q_s is initial steady state flowrate; D is pipe internal diameter; g is gravitational acceleration; and subscripts "u, b, d" represent pipe section at upstream of the blockage, the pipe section with the blockage and the pipe section at downstream of the blockage respectively. For single extended blockage cases, $Y_u = Y_d = Y_0$ in Eq. (1) with subscript "0" representing the quantity of original intact (blockage-free) pipeline. The total friction effect (steady and unsteady components) contained in the damping factor R is determined by the formulations in Vítkovský et al. (2003).

In the application of this blockage detection method, the resonant frequencies (ω_{rf}) are firstly obtained from measurement; and the blockage properties (e.g., Y_b for size, λ_b for length, and λ_d for location) can then be inversely determined by solving Eq. (1). The genetic algorithm (GA) based optimization was proposed for solving the implicit Eq. (1) in Duan et al. (2012), and the applicability and accuracy of this method has been validated through numerical and experimental applications in Duan et al. (2013) and Meniconi et al. (2013). Thereafter, to simplify the solution process and understand directly the blockage-wave interaction, a first-order approximation of Eq. (1) is derived in Duan et al. (2013), as expressed by,

$$\delta\omega_{rf}^{*} = -\frac{2\varepsilon_b}{\pi}\sin\left[(\lambda_d - \lambda_u)\omega_{rf0}\right]\sin\left[\lambda_b\omega_{rf0}\right], \tag{2}$$

where $\delta\omega_{rf}^{*}$ is the difference in the resonant frequencies between the intact (blockage-free) and blocked pipeline systems for a particular harmonic, normalized by the theoretical resonant frequency of the intact system (ω_{th0}); $\omega_{rf0} = \omega_{rf0}(n)$ is n^{th} resonant frequency of intact pipeline system; and $\varepsilon_b = 1 - A_b/A_0$ is constriction severity percentage of the blockage section. Eq. (2) can be solved more easily and efficiently than the original form of Eq. (1) and was successfully used in Duan et al. (2013) to provide initial estimations for the GA-based solution of Eq. (1).

Sensitivity Analysis Methods

Two different methods are adopted in this study for the sensitivity analysis, with the First-Order

Second-Moment (FOSM) method used for analytical analysis of the approximate and efficient Eq. (2) and the Monte-Carlo Simulation (MCS) method for quantitative (numerical) analysis of the original and complete expression in Eq. (1).

First-Order Second-Moment (FOSM) analysis

As preliminary understanding and analysis, it is convenient to start the investigation from the simplified Eq. (2), where an analytical analysis can be applied for this purpose. In this study, the FOSM method, which is based on the first-order and linearization assumptions, is adopted for this analytical analysis (Ang and Tang 1975; Tung et al. 2006; Duan et al. 2010a, 2010b). Firstly, Eq. (2) describes the relationship between the system properties (e.g., system parameters, operation conditions and measurement) and the extended blockage information to be detected (size, length and location), which can be generally expressed as multi-variable functions:

$$F_p = F_{\varepsilon,\lambda_b,\lambda_d} = G_p\left(\delta\omega_{rf}^*, Q_s, L_0, D_0, a_0, \cdots\right) = G_p\left(X_1, X_2, X_3, \cdots X_k\right), \tag{3}$$

where F_p is the information of extended blockage to be detected (size ε_b, length λ_b, and location λ_d); $G_p()$ is function; subscript p is indicating each parameter of the blockage; X_1 to X_k are uncertainty factors considered in the system; k is the number of uncertainty factors. The stochastic characteristics of each function in Eq. (3) can be approximated by the FOSM analysis as (Ang and Tang 1975; Tung et al. 2006) (with subscript p neglected here for simplicity):

$$\mu_F \approx G\left(\mu_{X_1}, \mu_{X_2}, \mu_{X_3}, \cdots \mu_{X_k}\right), \tag{4}$$

$$\delta_F^2 \approx \Delta_G^2 + \frac{1}{\mu_F^2}\sum_{j=1}^{k}\sum_{i=1}^{k}\left(\gamma_{ij}c_i c_j \sigma_i \sigma_j\right), \tag{5}$$

in which μ = mean value of variable X_i or the function $G()$; δ = coefficient of variation (COV); Δ_G = bias of the model formula; $c_j = \partial G/\partial X_j$ is sensitivity coefficient evaluated at (μ_1, μ_2, μ_3,…μ_k)

based on Eq. (2) in this study; $\sigma_i = \mu_i\delta_i$ representing the standard deviation of variable X_i; γ_{ij} = correlation coefficient between X_i and X_j; i, j = counting number. Since the main objective in this study is to inspect the influence of the different input uncertainties on the system responses and the TBFDM, the bias of the transient model is not considered in this FOSM analysis here. Therefore, it is assumed that $\Delta_G \approx 0$ and $\gamma_{ij} \approx 0$ for $\forall(i \neq j)$ in Eq. (5), the contribution of each input uncertainty variable X_j to the total variability of the response function (i.e., dimensionless resonant frequency shift) is given by (Tung et al. 2006),

$$\eta_{X_j}(\%) \approx \left(\frac{c_{X_j}\sigma_{X_j}}{\mu_F\delta_F}\right)^2 \times 100, \tag{6}$$

in which η is representing the individual contribution coefficient of each factor (X_j) to the total variability of the response, and other symbols refer to the definitions above.

Monte-Carlo Simulation (MCS)

While the simplified Eq. (2) and the FOSM is convenient and useful to obtain the uncertainty and sensitivity analysis results, a more comprehensive method is necessary for analyzing the original and complete form of Eq. (1) used for the TBFDM in order to understand the exact influences of each uncertainty factor and also to quantify the accuracy of that simplified method. In this study, the rigorous tool of the MCS is used to provide numerical estimations for the uncertainty response and sensitivity analysis of the TBFDM for extended blockage detection. The flowchart and general procedures of the MCS applied for this purpose is shown in Fig. 1. Based on the pre-calibration results for the test cases of interest in this study, the maximum runs of MCS for the analysis is set at 5000 in this paper to obtain enough results for statistical analysis (Tung et al. 2006; Duan et al. 2010a, 2010b; Duan 2015). The uncertainty characteristics of different inputs and parameters considered for sensitivity analysis in this study are analyzed and presented later in this paper.

Numerical Application System and Uncertainty Factors

As preliminary investigation of sensitivity analysis of the TBFDM, a simple pipeline system with single extended blockage shown in Fig. 2 is used in this study for illustration, which was commonly adopted in previous studies for the development and validation of the TBFDM (e.g., Duan et al. 2012, 2013; Meniconi et al. 2013). The pipeline (including all sections) is assumed to be smooth with constant friction factor f_0 = 0.02 and its total length L_0 = 1000 m in all the test cases. The parameter settings for this numerical test system are also given in Fig. 2. The transients in this system are generated by the discharge valve operation at downstream end (i.e., fast closure from initial open state); and the transient response (pressure head) is collected at the same location for analysis if necessary.

In practical transient pipe flow systems, it has been evidenced that many factors including pipe system parameters and operation conditions as well as the data measurement system are usually subject to uncertainties (e.g., Wiggert 1999; Rougier and Goldstein 2001; Duan et al. 2010a, 2010b; Zhang et al. 2011; and Duan 2015). In this study, the following uncertainty factors (X_j) with the assumed probabilistic distribution functions (PDFs) are considered for investigation,

(1) Total pipeline length (L_0): with lognormal distribution;

(2) Intact pipe diameter ($D_0 = D_u = D_d$): with uniform distribution;

(3) Pipe friction factor (f_0): with uniform distribution;

(4) Initial flowrate (Q_s): with uniform distribution;

(5) Intact pipe wave speed ($a_0 = a_u = a_d$): with lognormal distribution;

(6) Measured peak frequency (ω_{rf}): with uniform distribution.

For sensitivity analysis in this study, the mean values of these uncertainty factors are adopted as the deterministic case (shown in Fig. 2), and their COVs (δ_{Xj}) are assumed to be 0.1 for a numerical and comparative study. The sensitivity results of the blockage detection (ε_b, λ_b, and λ_d) by the TBFDM can then be examined to each uncertainty factor by the two methods described above in this study.

Application Results and Analysis

Under the conditions of the system information in Fig. 2 and different uncertainty factors (1) to (6) given in the above section, the sensitivity analysis of extended blockage detection results by TBFDM is conducted using two different analysis methods in this section.

FOSM Based Analysis

To apply the FOSM method in Eq. (3) through Eq. (6), Eq. (2) for blockage detection is firstly rewritten in terms of different blockage information as follows:

$$F_{\varepsilon} = \varepsilon = -\frac{\pi}{2}\frac{\delta\omega_{rf}^{*}}{\sin\left[(\lambda_d - \lambda_u)\omega_{rf0}\right]\sin\left[\lambda_b\omega_{rf0}\right]}, \tag{7}$$

$$F_{\lambda_b} = \sin\left[\lambda_b\omega_{rf0}\right] = -\frac{\pi}{2\varepsilon}\frac{\delta\omega_{rf}^{*}}{\sin\left[(\lambda_d - \lambda_u)\omega_{rf0}\right]}, \tag{8}$$

$$F_{\lambda_d} = \sin\left[(\lambda_d - \lambda_u)\omega_{rf0}\right] = -\frac{\pi}{2\varepsilon}\frac{\delta\omega_{rf}^{*}}{\sin\left[\lambda_b\omega_{rf0}\right]}. \tag{9}$$

The analytical results of the FOSM analysis can then be obtained by applying the implicit derivative rules to each of above equations in terms of different uncertainty factors considered in this study. Under the system condition depicted in Fig. 2, the results of sensitivity coefficient (c_j) and contribution coefficient (η_j) for different uncertainty factors are calculated and listed in Table 1. Meanwhile, the total coefficient of variation (COV) of the detection results under the uncertainty conditions can be obtained as follows:

$$\delta_{\varepsilon} = 0.4679\,;\ \delta_{\lambda_b} = 0.3658\ ;\ \delta_{\lambda_d} = 0.2573\,. \tag{10}$$

The result of Eq. (10) shows the blockage size is the most sensitive parameter of the potential blockage for detection, followed by the blockage length and location. It is also worthy of noting that the COVs of all these three detection results are over 25% under the conditions of the assumed 10% variations of the six uncertainty factors based on the FOSM analysis. From this perspective, the application result of TBFDM is very sensitive to these uncertainty factors considered herein which are commonly encountered in practical situations (e.g., laboratory experiments and field tests). Furthermore, the results of Table 1 demonstrate clearly that the wave speed (a_0) and the resonant frequency measurement (ω_{rf}) are relatively more important than other factors to affect the variability of the blockage detection results by the TBFDM. For example, from Table 1, these two factors contributed over 99.9% of the variability of these blockage detection results. Meanwhile, in the detection of blockage size and length, these two factors are almost in similar importance (i.e., each provides about 50% contribution), while in that of blockage location, the frequency data measurement (ω_{rf}) with 88.8% contribution behaves much more important than all others including the wave speed (a_0). It is also shown in Table 1 that the factors of total pipeline length (L_0) and pipe diameter (D_0) become more important for the detection of blockage location than for that of blockage size and length, although their contributions are still smaller enough compared to the former factors of wave speed (a_0) and resonant frequency measurement (ω_{rf}). Finally, the results in Table 1 also reveal that the initial hydraulic conditions, e.g., friction factor (f_0) and initial flowrate (Q_s) here, have little impact to the variability of the detection results by using the TBFDM, which is actually consistent with the findings of previous studies (e.g., Duan et al. 2012, 2013; Meniconi et al. 2013). More discussions on the results and implications of this FOSM analysis are presented later in this paper.

MCS Based Analysis

Compared to FOSM, more complicated simulations are required to achieve MCS analysis based on the flowchart given in Fig. 1. For simplicity, it is again assumed that the input uncertainty factors are independent in order to examine and highlight the individual contribution of these factors in this study. With the 5000 MCS runs conducted for the blockage detection by the TBFDM, the statistical results of the variability of the blockage detection (i.e., COVs) can be obtained as follows:

$$\delta_{\varepsilon} = 0.7341;\ \delta_{\lambda_b} = 0.3868\ ;\ \delta_{\lambda_d} = 0.2566\,. \tag{11}$$

By the comparison of Eq. (10) and Eq. (11), it is clear to show that the variability range of the blockage size detection (ε_b) by the MCS analysis is much higher than that by the FOSM analysis; while that of blockage length and location detection results (λ_b and λ_d) are comparable for the two methods. Specifically, the FOSM has underestimated the variability of blockage size detection under the given uncertainty conditions, which indicates that the nonlinear relationships of different parameters and variables in the TBFDM may have great influences and thus cannot be neglected to the blockage size detection. Meanwhile, both the results of Eq. (10) and Eq. (11) imply a higher sensitivity of the TBFDM for the detection of blockage size than other blockage information (length and location), which was also widely observed in previous studies of experimental tests (e.g., Duan et al. 2013; Meniconi et al. 2013).

To quantify the influence and contribution of each uncertainty factor in the MCS results, following expression is assumed and used in this study to represent the sensitivity of blockage detection results:

$$\delta_F^2 = \frac{1}{\mu_F^2} \sum_{j=1}^{k} s_j^F \left(\sigma_j^2\right)^{e_j} , \tag{12}$$

where subscript or superscript F = quantity for different blockage detection information (ε_b, λ_b, λ_d); superscript e_j = exponential index of each factor; s_j = the equivalent sensitivity coefficient by MCS analysis; and other symbols are same as previous definitions in this study. Based on the statistical results of the MCS analysis, the equivalent sensitivity coefficient (s_j) and exponential index (e_j) can be obtained by a non-linear regression process (Tung et al. 2006) and the results are shown in Table 2. It is necessary to note that the results of MCS in Table 2 are mainly based on the assumed expression of Eq. (12), and therefore the equivalent sensitivity coefficient (s_j) here may be different from the definition of sensitivity coefficient (c_j) in Eq. (5) for the FOSM analysis. Similarly, the individual contribution coefficient (η_j) based on Eq. (6) is also calculated from the MCS results and listed in Table 2 for the comparison with the FOSM analysis results. Meanwhile, for clarity and convenience, the individual contribution percentages of different uncertainty factors are plotted in Fig. 3.

The MCS based analysis results in Table 2 and Fig. 3 show a similar trend of the uncertainty responses as in Table 1 from the FOSM analysis. For example, both results reveal that the wave speed and resonant frequency measurement are the two dominant factors affecting the detection results and the friction factor and initial flowrate are the less important ones among these six factors, which confirm further the results reported in previous studies (e.g., Meniconi et al. 2011b). However, the influence extents of these uncertainty factors are different in the two analysis results. For example, the results of MCS analysis indicate the initial pipe length may have significant impacts on the detection of blockage length and location, which has been underestimated by the FOSM results. Moreover, the results of the exponential index (e_j) in Table 2 from the MCS analysis demonstrate that the complicated transient-based flow simulations and blockage detection process cannot be well represented by the first-order second-moment assumptions used in Eqs. (4) and (5) in the FOSM method (i.e., $e_j \neq 1$), which in fact results in the main difference of the uncertainty and sensitivity analysis results in Tables 1 and 2. This similar difference between these two methods of FOSM and MCS has also been observed and analyzed in previous studies of pipe fluid transients (e.g., Duan et al. 2010a, 2010b). Consequently, all these results imply that the two factors of wave speed and data measurement and their non-linear behaviors in the blockage detection equations (1) and (2) are critical to the applications of the TBFDM. More detailed analysis and discussion on the influences of different uncertainty factors to the transient modelling and analysis are conducted later in this study.

Results Discussion and Practical Implications

To understand the influences of uncertainty factors to the variability of transient analysis results, it is necessary to investigate the transient behaviors of the system under these uncertainty conditions. For the test case in this study, the transient pressure head traces with uncertainties (i.e., with standard deviations) at the downstream valve end in Fig. 2 are obtained by the two different analysis methods and plotted in Fig. 4. In the figure, the vertical amplitude of transient pressure head is normalized by the initial transient head at downstream valve (i.e., *Joukowsky* head), and the axial time is normalized by the wave period of intact pipeline system (i.e., $4\Sigma l/a$).

The results of Fig. 4 show clearly the relatively large variation range of the transient responses with regard to the deterministic results in the studied time domain, where the maximum positive and minimum negative transient pressure heads are much larger than the original deterministic results and may be out of the design range of the pipe strength. This result could cause the failure of system strength and function (e.g., Duan et al. 2010a, 2010b), and also the inaccuracy of transient analysis and utilization such as extended blockage detection in this study.

Furthermore, the uncertainty propagation of the transient responses with time from the two different analysis methods are shown in Fig. 5, in which the uncertainty (i.e., the standard deviation of transient pressure head, σ_H) is also normalized by the *Joukowsky* head for the comparison. This result again indicates the amplified uncertainty and propagation with time in the transient responses. However, compared to the FOSM result in Fig. 5, clear oscillations are observed in the result of MCS analysis. Statistically, such oscillations and propagation of system response uncertainties during the transient process could cause additional amplitude and phase changes in the time domain and resonance frequency shifts in the frequency domain, which has important implications to the use of transient-based method for pipe faults detection. Specifically, the caused phase and amplitude changes may result in the inaccuracy of the blockage detection results by the transient-based time domain method (e.g., Stephens 2008; Meniconi et al. 2011a, 2013); and the induced resonant frequency shifts can affect the applicability and accuracy of the TBFDM for blockage detection as presented in this study.

To further explain and confirm this uncertainty influence to the TBFDM in this study, the frequency domain results of both the deterministic transient response in Fig. 4(b) and the MCS-based uncertainty response in Fig. 5 are plotted in Fig. 6, with the vertical amplitude coordinate (H_ω^*) normalized by the maximum value of the frequency domain responses, and the axial frequency coordinate (ω^*) normalized by the theoretical frequency of intact pipeline system (i.e., $\Sigma a/4l$). The comparative results reveal obvious difference of the resonant frequencies (i.e., peak locations in the figure) between these two responses, and consequently, the superposition of these two results could cause additional resonant frequency shifts from the original deterministic case, in addition to the frequency shifts by potential extended blockages. Based on this result, it is therefore understandable for the previously obtained importance orders of different uncertainty factors contributing to the variability of the blockage detection results as shown in Tables 1 and 2. Specifically, the determination of the three factors in pipeline systems, the wave speed (a_0), resonant frequency measurement (ω_{rf}), and pipe length (L_0), become especially important to the use of TBFDM because of their high relevance and potential contribution to the system resonant frequencies (e.g., $\omega_{rf0} \sim a/4L_0$).

The results and findings of this study can also be used for analyzing and explaining the error observations in many experimental applications of transient-based pipe blockage detection methods such as in Duan et al. (2013) and Meniconi et al. (2011a, 2013). Firstly, in these experimental applications (laboratory and field), uncertainties commonly exist in the estimation of acoustic wavespeed for each pipe section, which was usually based on the averaged values of many measured transient amplitudes and/or phase periods at certain locations of pipe sections in the studied system (Suo and Wylie 1990; Duan et al. 2010a; Ebacher et al. 2011). Furthermore, in practice, the accuracy of data measurement system highly depends on the precision of the used devices, which often becomes less accurate for the high frequency flows in systems of relatively small scale pipes and/or complicated pipe connections. Consequently, in practical applications, the pipe wavespeed and data measurement are the two dominant factors that affect significantly the applicability and accuracy of the transient-based methods for pipe blockage detection in both time and frequency domains.

Conclusions and Recommendations

The transient-based frequency domain method (TBFDM) has been previously developed and used for the pipe blockage detection in water pipelines, which was found to be an efficient, non-intrusive and economic method in this field. But the applications of the TBFDM are usually challenged from many practical factors such as the system uncertainties and data measurement errors. This paper investigates systematically the sensitivity of this developed TBFDM to different uncertainty factors that commonly exist in practical pipe systems. A simple pipeline system with single extended blockage has been adopted in this study for the analysis. Six uncertainty factors including the system parameters and hydraulic conditions as well as data measurement are investigated in this study. Two analysis methods of the First-Order Second-Moment (FOSM) and Monte-Carlo Simulation (MCS) are applied to study the different expression forms of the developed TBFDM respectively.

Both results of FOSM and MCS demonstrate that a large variability range of the blockage detection results by the TBFDM (e.g., δ_F > 25% in this study) can be resulted from the input uncertainty factors (e.g., with δ_{Xj} = 10% for the test case). Moreover, it is shown from the analysis results that the wave speed and the resonant frequency measurement are the two dominant factors that can significantly affect the applicability and accuracy of the TBFDM. The results of MCS also indicate that the uncertainty of total pipeline length can have potential influences to the variability of the detection results for blockage length and location, which has been underestimated in the FOSM results. Furthermore, the result analysis and discussion of this study implies the applicability and accuracy of the TBFDM will highly depend on the determination of the three important factors (i.e., wave speed, pipe length, and resonant frequency measurement) in practical applications.

Finally, it is necessary to point out that the sensitivity analysis results of this study are mainly based on the assumed uncertainty characteristics (PDF and COV) of different inputs and parameters, which may need further quantitative investigations in the future work.

Acknowledgements

The work described in this paper was partially supported by the research grants from (1) the Research Grant Council of the Hong Kong SAR, China (Project No. T21-602/15R); and (2) the Hong Kong Polytechnic University (Project Nos. 1-ZVCD, G-UC73 and G-YBC9).

References

Ang H-S., and Tang W.H. (1975). *Probability Concepts in Engineering Planning and Design, Volume II-Decision, Risk, and Reliability*. John Wiley & Sons, Inc.

Brunone, B. (1999). Transient test-based technique for leak detection in outfall pipes. *J. Water Resources Planning and Management*, ASCE,125(5), pp. 302-306.

Brunone, B., Ferrante, M., and Meniconi, S. (2008). Discussion of 'detection of partial blockage in single pipelines' by P.K. Mohapatra, M.H. Chaudhry, A.A. Kassem, and J. Moloo. *Journal of Hydraulic Engineering*, ASCE, 134(6), pp. 872-874.

Colombo, A.F., Lee P.J., and Karney B.W. (2009). "A selective literature review of transient-based leak detection methods." *Journal of Hydro-environment Research*, IAHR, 2(4), pp. 212-227.

Covas, D., Ramos, H., and Almeida, A.B. (2005). Standing wave difference method for leak detection in pipeline systems. *J. Hydraulic Eng.* ASCE, 131(12), pp. 1106-1116.

Duan, H.F., Tung, Y.K., and Ghidaoui, M.S., (2010a). Probabilistic analysis of transient design for water supply systems. *Journal of Water Resources Planning and Management*, ASCE, 136(6), pp. 678-687.

Duan, H.F., Tung, Y.K., and Ghidaoui, M.S. (2010b). "Uncertainty propagation in pipe fluid transients", *Proceedings of the 17th IAHR–APD Congress*, 21-24 February 2010, Auckland, New Zealand.

Duan, H.F., Lee, P.J., Ghidaoui, M.S., and Tung Y.K., (2011). Leak detection in complex series pipelines by using system frequency response method. *Journal of Hydraulic Research*, IAHR 49(2), pp. 213-221.

Duan, H.F., Lee, P.J., Ghidaoui, M.S., and Tung, Y.K. (2012). Extended blockage detection in pipelines by using the system frequency response analysis. *Journal of Water Resources Planning and Management*, ASCE, 138(1), pp. 55-62.

Duan, H.F., Lee, P.J., Kashima, A., Lu, J.L., Ghidaoui, M.S., and Tung, Y.K. (2013). Extended blockage detection in pipes using the frequency response method: analytical analysis and experimental verification. *Journal of Hydraulic Engineering*, ASCE, 139(7), pp. 763-771.

Duan, H.F., Lee, P.J., Ghidaoui, M.S., and Tuck, J. (2014). Transient wave-blockage interaction and extended blockage detection in elastic water pipelines. *Journal of Fluids and Structures*, 46 (2014), pp. 2-16.

Duan, H.F., and Lee, P.J. (2015). Transient-based frequency domain method for dead-end side branch detection in reservoir-pipeline-valve systems. *Journal of Hydraulic Engineering*, ASCE, doi: 10.1061/(ASCE)HY.1943-7900.0001070, 04015042.

Duan, H.F. (2015). Uncertainty analysis of transient flow modeling and transient-based leak detection in water pipeline systems. *Water Resources Management*, DOI: 10.1007/s11269-015-1126-4.

Ebacher, G., Besner, M., Lavoie, J., Jung, B., Karney, B., and Prévost, M. (2011). Transient modeling of a full-scale distribution system: comparison with field data. *Journal of Water Resources Planning and Management*, ASCE, 137(2), pp. 173-182.

Ferrante, M., and Brunone, B. (2003). Pipe system diagnosis and leak detection by unsteady-state tests-1: Harmonic analysis. *Advances in Water Res.* 26(1), pp. 95-105.

Lee, P.J. (2005). Using system response functions of liquid pipelines for leak and blockage detection. *PhD Thesis*, The University of Adelaide, South Australia.

Lee, P.J., Lambert, M.F., Simpson, A.R., Vítkovský, J.P., and Liggett J. (2006). Experimental verification of the frequency response method for pipeline leak detection. *Journal of Hydraulic Research*, IAHR, 44(5), pp. 693-707.

Lee, P.J., Vítkovský, J.P., Lambert, M.F., Simpson, A.R., Liggett J. (2008). Discrete blockage detection in pipelines using the frequency response diagram: numerical study. *Journal of Hydraulic Engineering*, ASCE, 134(5), pp. 658-663.

Lee, P.J., Duan, H.F., Ghidaoui, M.S., and Karney, B.W. (2013). Frequency domain analysis of pipe fluid transient behaviors. *J. Hydraul. Res.* – IAHR, 51(6), pp. 609-622.

Lee, P.J., Duan, H.F., Tuck, J., and Ghidaoui, M.S. (2015). Numerical and experimental illustration of the effect of signal bandwidth on pipe condition assessment using fluid transients. *Journal of Hydraulic Engineering*, ASCE, 141(2), 014074.

Meniconi, S., Brunone, B., Ferrante, M., and Massari, C. (2011a). Potential of transient tests to diagnose real supply pipe systems: what can be done with a single extemporary test. *Journal of Water Resources Planning and Management,* ASCE, 137(2), pp. 238-241.

Meniconi, S., Brunone, B., and Ferrante, M. (2011b). In-line pipe device checking by short period analysis of transient tests. *Journal of Hydraulic Engineering*, ASCE, 137(7), 713-722.

Meniconi, S., Brunone, B., and Ferrante, M. (2012a). Water hammer pressure waves at cross-section changes in series in viscoelastic pipes. *Journal of Fluids and Structures*, 33, 44-58.

Meniconi, S., Brunone, B., Ferrante, M., and Massari, C. (2012b). Transient hydrodynamics of in-line valves in viscoelastic pressurized pipes: Long period analysis. *Experiments in Fluids*, 53(1), 265-275.

Meniconi, S., Duan, H.F., Lee, P.J., Brunone, B., Ghidaoui, M.S., and Ferrante, M. (2013). Experimental investigation of coupled frequency and time-domain transient test-based techniques for partial blockage detection in pipes. *Journal of Hydraulic Engineering,* ASCE, 139(10), pp. 1033-1040.

Mohapatra, P.K., Chaudhry, M.H., Kassem, A.A., and Moloo, J. (2006). Detection of partial blockage in single pipelines. *Journal of Hydraulic Engineering*, ASCE, 132(2), pp. 200-206.

Rougier, J., and Goldstein, M. (2001). A Bayesian analysis of fluid flow in pipelines. *J Roy Stat Soc C-App*, 50(1), pp. 77-93.

Sattar, A.M., Chaudhry, M.H., and Kassem, A.A. (2008). Partial blockage detection in pipelines by frequency response method. *Journal of Hydraulic Engineering*, ASCE, 134(1), pp. 76-89.

Stephens, M.L. (2008). Transient response analysis for fault detection and pipeline wall condition assessment in field water transmission and distribution pipelines and networks. *PhD Thesis*, The University of Adelaide, South Australia.

Suo, L.S., and Wylie, E.B. (1990). Complex wavespeed and hydraulic transients in viscoelastic pipes. *Journal of Fluids Engineering*, ASME, 112(4), pp. 496-500.

Tung, Y.K., Yen, B.C., and Melching, C.S. (2006). *Hydrosystems Engineering Reliability*

Assessment and Risk Analysis. McGraw-Hill Company, New York.

Vítkovský, J. P., Lambert, M. F., Simpson, A. R., and Bergant, A. (2003). Frequency-domain transient pipe flow solution including unsteady friction. *Proc., Int. Conf. on Pumps, Electromechanical Devices and Systems Applied to Urban Water Management*, Vol. 2, E. Cabrera and E. Cabrera, Jr., eds., Swets and Zietlinger Publishers, Netherlands, pp. 773–780.

Vítkovský, J.P., Simpson, A.R., and Lambert, M.F. (2000). Leak detection and calibration using transients and genetic algorithms. *Journal of Water Resources Planning and Management*, ASCE, 126(4), pp. 262-265.

Wang, X.J., Lambert, M.F., Simpson, A.R., Liggett, J.A., Vítkovský, J.P. (2002). Leak detection in pipeline systems using the damping of fluid transients. *J. Hydraulic Eng.* 128(7), pp. 697-711.

Wang, X.J., Lambert, M.F., and Simpson, A.R. (2005). Detection and location of a partial blockage in a pipeline using damping of fluid transients. *Journal of Water Resources Planning and Management*, ASCE, 131(3), pp. 244-249.

Wiggert, D. (1999). Propagation of uncertainties in fluid transient analysis. *Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference*, San Francisco, CA, pp. 167-175.

Zhang, Q., Karney, B., Suo, L., and Colombo, A. (2011). Stochastic analysis of water hammer and applications in reliability-based structural design for hydro turbine penstocks. *Journal of Hydraulic Engineering*, ASCE, 137(11), pp. 1509–1521.

Zhao, M., Ghidaoui, M.S., and Kolyshkin, A.A. (2007). Perturbation dynamics in unsteady pipe flows. *Journal of Fluid Mechanics*, 570, 129-154.

Table 1 Sensitivity coefficient (c_j) an individual contribution coefficient (η_j) of different factors to the uncertainty of blockage detection results by the FOSM analysis

Response \ Factor		L_0	D_0	f_0	Q_s	a_0	ω_{rf}
blockage size (ε_b)	c_j	3.49E-05	0.0640	-0.0137	-0.0027	-0.0015	0.9246
	η_j (%)	0.0428	0.0361	2.65E-08	2.65E-08	50.4742	49.4469
blockage length (λ_b)	c_j	3.75E-06	-0.0098	-0.0021	-0.0004	-0.0002	0.1412
	η_j (%)	0.0214	0.0364	2.67E-06	2.67E-06	50.0524	49.8898
blockage location (λ_d)	c_j	-5.9E-05	0.1501	0.0171	0.0034	0.0004	-0.7806
	η_j (%)	0.3088	0.4999	1.03E-05	1.03E-05	10.4145	88.7768

Table 2 Statistical results of MCS analysis for the uncertainty of blockage detection results

Response \ Factor		L_0	D_0	f_0	Q_s	a_0	ω_{rf}
blockage size (ε_b)	s_j	2.34E-04	0.0081	0.0001	0.0001	-0.0034	1.7581
	e_j	0.9946	1.1231	1.04521	1.0111	0.7365	1.4625
	η_j (%)	0.4371	0.0001	3.19E-11	7.98E-10	59.0642	40.4986
blockage length (λ_b)	s_j	2.18E-04	-0.0125	-0.0011	-0.0003	-0.0003	0.2864
	e_j	0.6399	0.7436	0.0026	0.0002	0.636	1.1625
	η_j (%)	19.7466	0.0163	2.02E-07	3.76E-07	24.0435	56.1936
blockage location (λ_d)	s_j	-9.3E-04	0.1501	0.0027	0.0001	0.0013	-1.3806
	e_j	0.5714	0.7436	0.0543	0.0221	0.5683	1.6625
	η_j (%)	17.0243	0.1109	5.74E-08	1.97E-09	21.2897	61.5751

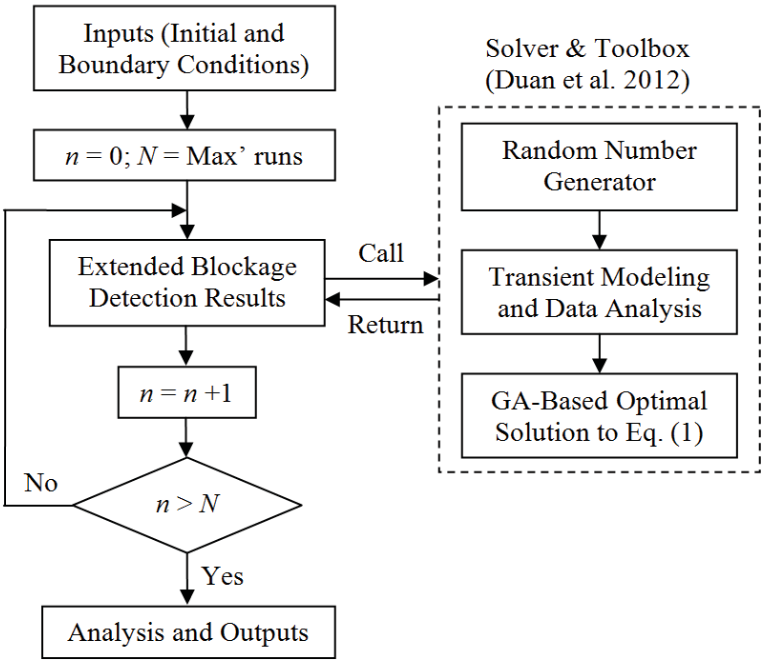


Fig. 1 Flowchart of MCS for transient analysis

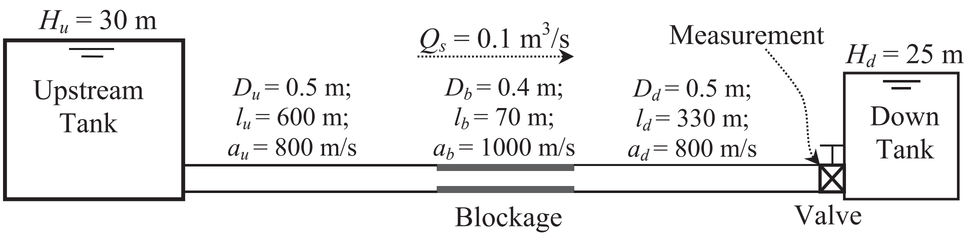


Fig. 2 Sketch and settings of numerical test system (Notations: H_u and H_d = available heads of upstream and downstream tanks; Q_s = initial steady flowrate with the arrow showing its direction)

Figure 3 Click here to download Figure Figure3.pdf

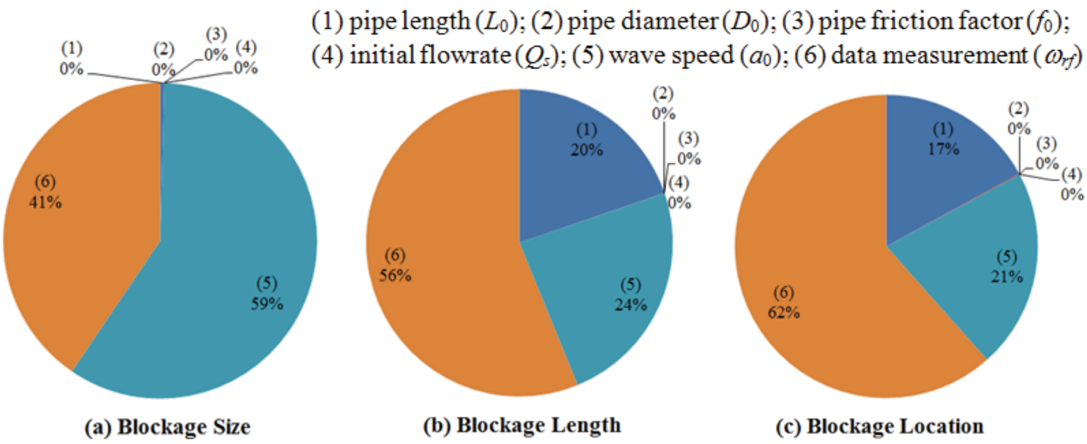
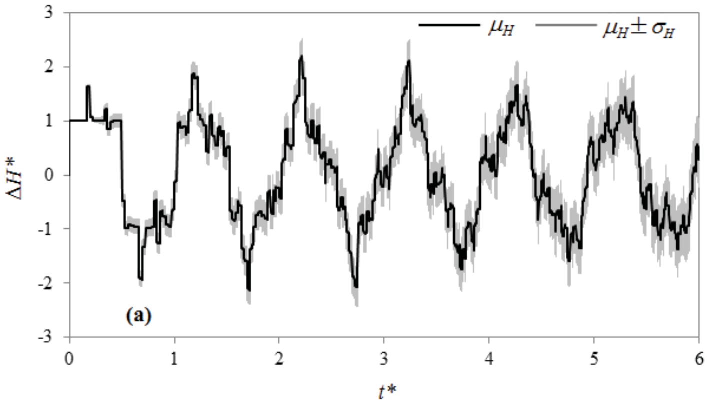


Fig. 3 Individual contribution of different uncertainty factors to the uncertainty of blockage detection results



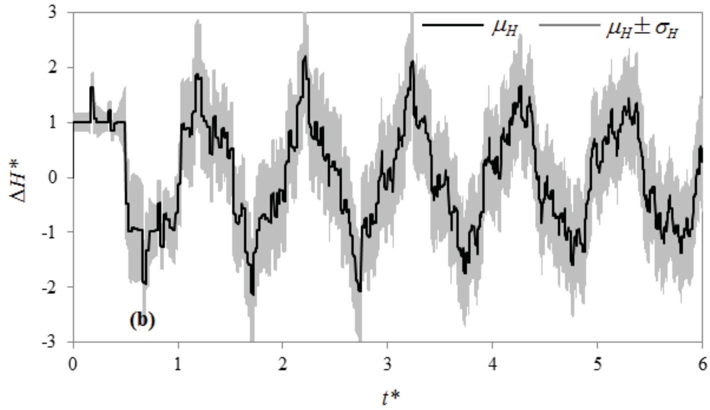


Fig. 4 Transient responses with uncertainty at downstream valve end by: (a) FOSM; (b) MCS

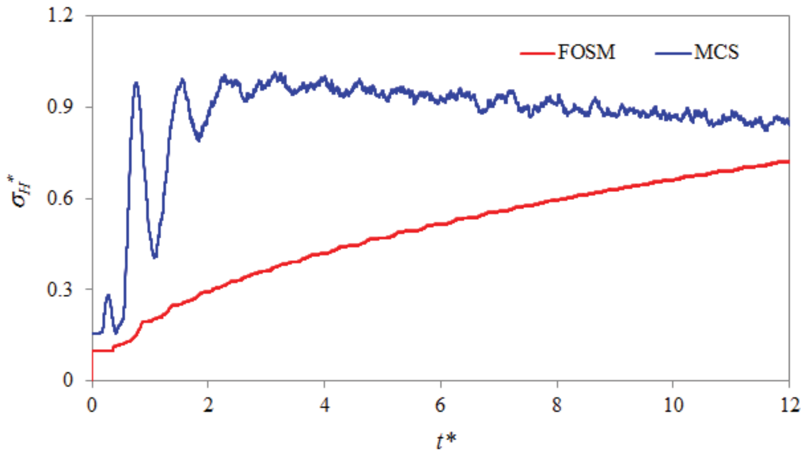


Fig. 5 Propagation of uncertainty of transient responses with time at downstream valve end

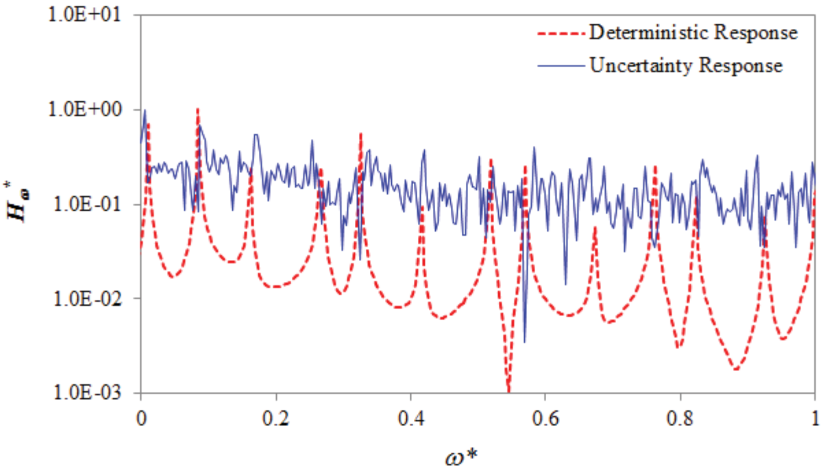


Fig. 6 Frequency domain results of the deterministic transient response and the uncertainty response by MCS analysis in the test system

Figure Caption List

Fig. 1 Flowchart of MCS for transient analysis

Fig. 2 Sketch and settings of numerical test system (Notations: H_u and H_d = available heads of upstream and downstream tanks; Q_s = initial steady flowrate with the arrow showing its direction)

Fig. 3 Individual contribution of different uncertainty factors to the uncertainty of blockage detection results

Fig. 4 Transient responses with uncertainty at downstream valve end by: (a) FOSM; (b) MCS

Fig. 5 Propagation of uncertainty of transient responses with time at downstream valve end

Fig. 6 Frequency domain results of the deterministic transient response and the uncertainty response by MCS analysis in the test system