Transient influence zone based decomposition of water distribution networks for efficient transient analysis

Yuan Huang[1] • Huan-Feng Duan[2] • Ming Zhao[1] • Qingzhou Zhang[1] • Hongbin Zhao[1] • Ke Zhang[3]

Abstract

Computational efficiency and accuracy of transient analysis for urban water distribution networks (WDN) become progressively important to the design and management of the system. In addition to the improvement of numerical model and computational capacity, which has been widely studied in the literature, efficient and accurate treatment of practical and complex WDN is another potential way to enhance the transient analysis. This paper aims to develop a zonal method for effective decomposition of WDN, which is mainly based on the transient sources and their influence regions in the system, in order to achieve efficient transient analysis. A concept of transient influence zone (TIZ) is firstly proposed and implemented to demonstrate the critical influence region of transient wave propagation in the system under specific design criteria. The obtained TIZ for each transient source is then

Y. Huang • M. Zhao (*) • Q.Z. Zhang • H.B. Zhao

[1]School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin, 150090, China. E-mail: zhaoming_hit@163.com (primary corresponding author)

H.-F. Duan (*)

[2]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, China. E-mail: hf.duan@polyu.edu.hk (co-corresponding author)

K. Zhang

[3]College of Civil Engineering, Sichuan Agricultural University, Dujiangyan, 611830, China.

mapped by introducing appropriate and equivalent boundaries so as to separate the TIZ from the entire WDN. To this end, the efficient Lagrangian model for prior-estimating pressure fluctuation extremes, the pressure fluctuation limitation for mapping TIZ borders and the quasi-reservoir condition for representing border boundaries are applied for characterizing the TIZs. A realistic network is adopted to demonstrate the applicability and accuracy of the proposed method. The application results and analysis indicate that the developed TIZ-based decomposition method provides a considerable efficiency improvement for transient analysis with sufficient modeling accuracy.

Keywords： Water distribution networks (WDN); transient analysis; transient influence zone (TIZ); efficient Lagrangian model (ELM); decomposition

1 Introduction

Various studies and practical observations have evidenced the necessity and importance of transient analysis for water distribution networks (WDN) due to potential transient-induced system damages and/or water quality deterioration (e.g., Fleming et al. 2006; Besner 2007; Ebacher et al. 2011). In spite of such many studies on the transient methods and applications, there is still substantial knowledge gap between the theory and the practice of transients in WDN. One of important reasons for this gap may be attributed to the huge computational requirement for the transient analysis of practical and complex networks. For instance, the one-dimensional (1D) model based on the method of characteristics (MOC) generally requires numerous steps and calculations at all interior points of each pipe to adhere to the accuracy and stability conditions in the studied WDN, which results in a huge computational effort and thus poses a great challenge to computer capacity. As a result, the runtime for such transient analysis could range from several minutes to a few hours on modern personal computers (Ramalingam et al. 2009), not to mention the increasing popular optimization models incorporated with hundreds of thousands of transient simulations (e.g., Kapelan et al. 2003; Duan et al. 2010; Haghighi 2015; Duan 2015; Skulovich et al. 2016; Duan 2016). With this background, significant efforts have been taken by the researchers on solving this critical and practical issue, with aim to achieve efficient transient analysis for practical WDN. These previous works can be divided into two main types: (1) the improvement, enhancement or exploitation of numerical schemes; (2) the skeletonization and decomposition of transient systems.

With regard to the former type relating to numerical modeling, numerous studies have been dedicated to the efficient transient analysis with various numerical schemes developed over the decades. The MOC is one of the well-developed and commonly used methods for transient analysis with the advantages of numerical efficiency, high feasibility and programming simplicity, etc (e.g., Goldberg and Benjamin Wylie 1983; Yang and Hsu 1990; Sibetheros et al. 1991; Shimada and Vardy 2013), yet the discrete time-space grid scheme fundamentally sets its efficiency barrier with huge computational efforts for an increasing number of pipes and boundaries in complex WDN. In addition, some mesh less schemes have also been developed for transient analysis, in order to against the deficiency of the numerical discretization problems, such as the Wave Characteristic Method (WCM) (Wood et al. 2005a, b; Boulos et al. 2006; Ramalingam et al. 2009) and Global Algebraic Water Hammer (GAWH) approach (Nault et al. 2016). For these mesh less methods, the calculations at interior pipe nodes are generally reduced or eliminated, thus the methods can be more time- and memory-efficient than the general schemes (e.g., MOC). However, these studies also indicated that potential limitations are also existent for the applications of current mesh less methods.

With regard to the skeletonization and decomposition of WDN, it has been widely studied and conducted based on the system steady-state results, which will become questionable for transient analysis of such WDN, with referring to a conspicuous reason that the steady-state hydraulic equivalency theory ignores the interaction of transient pressure waves through the complex system configurations. Actually, these pitfalls of traditional steady-state based skeletonization and decomposition for transient models have been investigated and analyzed by many researchers in the literature (e.g., Walski et al. 2004; Jung et al. 2007; Ebacher et al. 2011). These researches demonstrated clearly that the accuracy of transient simulation results can be greatly affected by inappropriate system skeletonization and decomposition (e.g., steady-state based treatment way), such that detailed representative models remain essential to accurately determine transient pressure extremes.

In summary, the state-of-the-art approaches for efficient transient analysis, both the numerical schemes and the system decomposition, have made great process to improve transient analysis in realistic WDS. However, further steps are still impending to put forward to fill the gap of theory and practice for transient analysis. This current study aims to propose a novel and effective methodological framework of transient-based system decomposition for efficient transient analysis from an alternative perspective. The concept of transient influence zone (TIZ) is firstly introduced to demonstrate the critical region of transient propagation from each transient source, which is then mapped in an appropriate way from the whole WDN in order to achieve efficient transient analysis. To this end, an efficient TIZ-based decomposition method is developed with a general application procedure to map out each TIZ for each specific transient source. Ultimately, the transient analysis is performed individually to each obtained TIZ of all transient sources in the whole WDN, with the aim to achieve efficient and accurate transient analysis.

2 Methods and Models

2.1 Transient Influence Zone (TIZ) and Its Mapping Method

Transient flows in closed conduits are pressure waves from transient exciters that can travel through the pipelines at relatively high speed (e.g., 1000 m/s for elastic pipes) and then are transmitted and reflected at boundaries or discontinuities in the system where new waves are generated and propagate through the system (Ramalingam et al. 2009; Ferrante et al. 2009). Meanwhile, the amplitudes of pressure waves are commonly modified by boundaries and dissipation factors in the system, e.g. pipe frictions and demands/leaks, leading to changes (magnification or attenuation) of transient pressures and flows in the pipelines (Karney and Filion 2003). With such typical wave propagation mechanism, the transient system responses and wave behaviors may become very complicated for complex system configurations such as WDN with plenty of loops and branches (Karney and Filion 2003). However, with the existence and unavoidable boundaries and dissipation factors in the realistic system, the generated pressure waves will finally be fragmented into tiny sections with rather low amplitudes, and become insignificant enough to be discarded for practical design and management purposes. From this perspective, transient analysis can be focused on and mapped in this relatively small-scale and localized zone instead of the whole network system, which is defined as transient influence zone (TIZ) in this study, so as to improve the computational efficiency of transient analysis for complex WDN. As a result, the whole system of WDN can be decomposed into different TIZs for efficient transient analysis based on the situations of transient exciters and system configurations, which is the scope of this study.

To this end, the TIZ-based method for efficient transient analysis is proposed in this study with the following general procedure: (1) An efficient Lagrangian model (ELM) is developed and adopted to prior-estimate the pressure extremes of the whole system, which provides the important basis for estimating and mapping out the TIZs. (2) Appropriate pressure fluctuation limitations (PFL) are then set to separate the TIZ from the entire WDN. (3) Finally, appropriate and equivalent boundaries, termed as quasi-reservoir boundary condition (QRBC) in this paper, are introduced to define the border conditions of the obtained TIZ. The details of the ELM, PFL and QRBC are presented in the following study.

2.2 Efficient Lagrangian Model (ELM)

2.2.1 Model development

The ELM used in this study is developed from a traditional Lagrangian-based scheme except WCM, termed as Lagrangian model (LM) in the literature, which was used recently as a simple numerical tool to detect the discontinuities in systems (Ferrante et al. 2009). In practical WDN, in addition to the reflections and transmissions of pressure waves from various BCs, many dissipation factors such as demands/leaks, pipe-wall frictions and viscoelasticity may also disturb and damp the transient states in a persistent and slow manner. As a result, the traditional LM may become inapplicable to such complex situations, which is further developed and extended in this study.

The ELM proposed in this paper inherits the simplicity and efficiency of LM for transient state evaluation, and at the same time, is further developed by considering the more complex wave effects in the system. The method framework of the proposed ELM is shown in Fig. 1. Specifically, the procedure of ELM can be divided into three main parts: (1) the right-hand-side part of the model flowchart (as the core execution unit), which is used to demonstrate the time-advance process of transient initialization, generation and propagation of pressure waves; (2) the left-hand-side part of pressure wave set (as the core memory unit), which is used to memory the generation and propagation of any pressure wave during transient procedure; and (3) the middle part of three wave actions, which is to indicate the wave transmission and reflection and also the interaction between the former two parts. Note that, each pressure wave is localized on a pipe and is defined by four basic attributes (Fig. 1a): (i) Pipe Index (i.e., the located pipe index); (ii) Wave Amplitude (i.e., the pressure fluctuation associated with the wave); (iii) Scheduled Time (i.e., the time when the wave arrives at the other BC of the located pipe); and (iv) Scheduled Position (i.e., the BC that the wave arrives at the scheduled time). In a summary, with this framework, the ELM is developed and applied to model the wave actions throughout the system and associated calculations at BCs in the time-advance scheme.

2.2.2 Efficiency and accuracy control strategies

Since the pressure wave set section is aimed for the core data storage and operation of the proposed ELM, the grouping and sequencing strategies (Figs. 1b and c) are utilized in consideration of the efficiencies of the data storage and the input/output interfaces (i.e., wave selection and addition). With the two strategies, the data searching effort for wave selections and additions can be greatly reduced, which thus can facilitate the robustness of the input/output interfaces for an increasing number of boundaries in complex WDN.

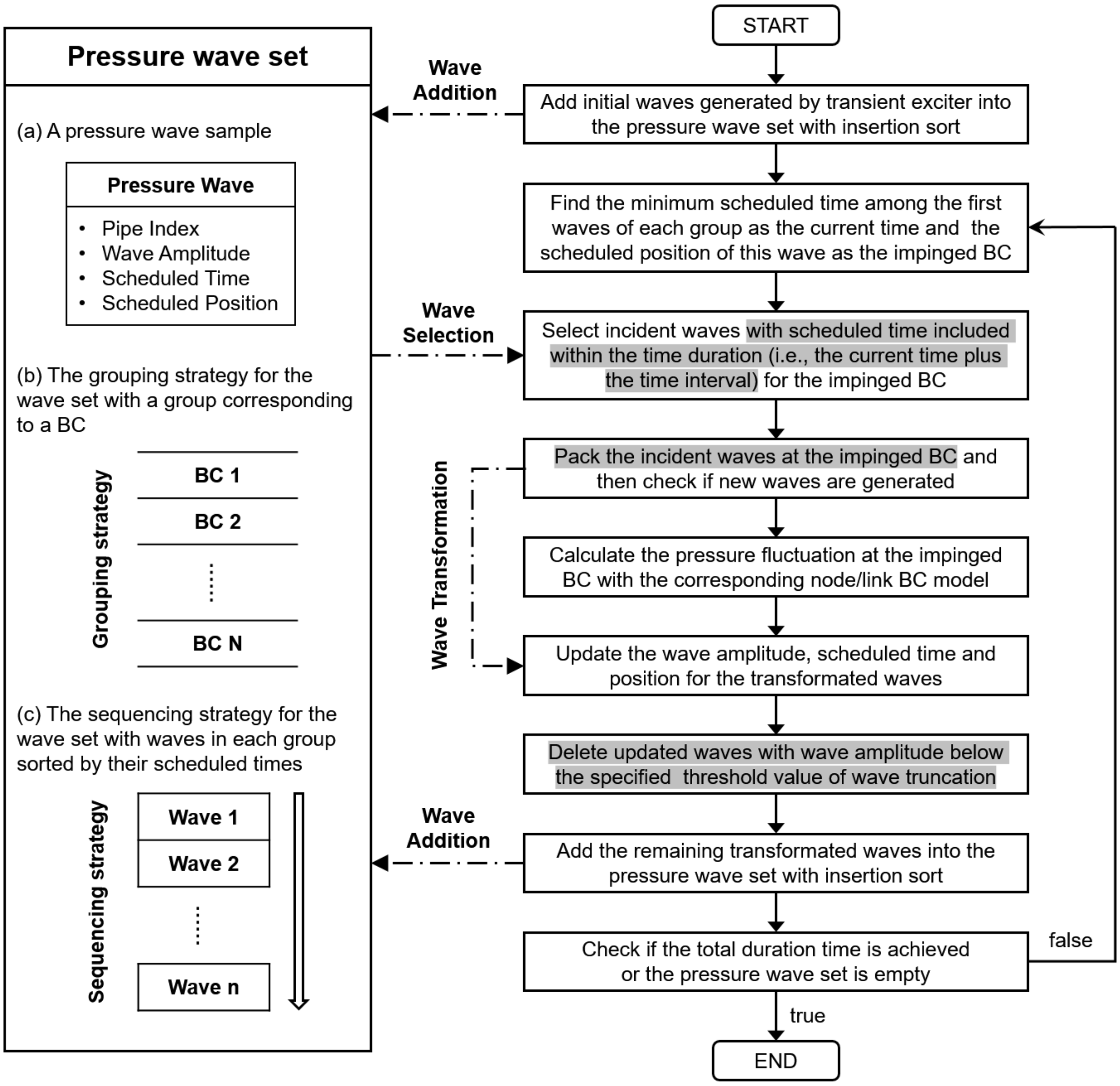

Fig. 1 Framework of ELM with three main parts: the pressure wave set (the left-hand-side part) and the flowchart of the model (the right-hand-side part), interacted by three wave actions (the middle part)

Another efficiency related issue of the ELM application is the time-advance scheme of ELM, due to the fact that an uneven time-dependent discretization for each BC will depend on the actual wave superimpositions at the BC. For practical WDN system with huge complexity of numerous BCs, the number of wave signals will grow exponentially with time advancement, leading to significantly high frequent wave additions to the pressure wave set in ELM, which not only increases the memory requirement, but also increases greatly the computational effort. Therefore, to against this potential deficiency, two control strategies are taken and embedded within the application process of ELM for efficiency and accuracy improvement, as shown by the procedure steps with gray background in Fig. 1, and the principles detailed in Fig. 2.

The first control strategy (denoted as Strategy 1 herein) is the time interval that expanding the wave selection from the first wave to first several waves with scheduled time included within the time duration (i.e., the current time plus the time interval) for the impinged BC. The other control strategy (denoted as Strategy 2 herein) is the wave truncation that deleting waves with amplitude below a specified threshold value after the wave transformation at the BC. It can be obviously noticed that, with the use of these two control strategies, the discrepancies of simulation results are inevitably introduced for the ELM. The logical settings of wave truncation and time interval for ELM and the implications are illustrated and discussed through the numerical application in the following study.

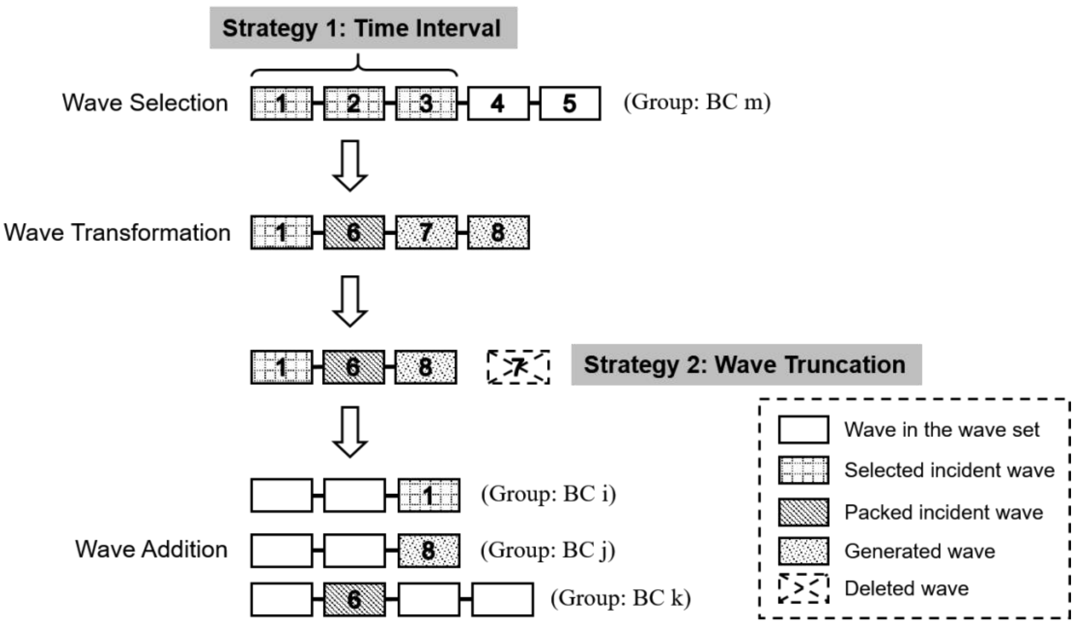

Fig. 2 Efficiency and accuracy control strategies embedded in the wave actions for the time-advance flowchart

2.2.3 Implementation of BCs with external flows

In addition to wave transmission/reflections by the inherent boundary characteristics, the external flows (e.g., nodal demands, leaks and associated devices), which commonly exist in practical WDN, can also affect greatly the wave transformation. This external flow condition is incorporated herein into the developed ELM in this study, with following expression:

$$\Delta H^{t} = \sum_{k=1}^{N} S_k \Delta H_k^{t-} - 1 \bigg/ \left(g \sum_{l=1}^{N} \frac{A_l}{a_l} \right) \left(Q_e^{t} - Q_e^{t-} \right) \tag{1}$$

where ΔH represents the pressure fluctuation of the incident wave at the node; Q_e indicates the external flow at the node, with the superscript t^{-} and t denoting the time instants before and after the wave transformation at the node (i.e., before and after the moments that pressure waves impinging on the BC), respectively; subscripts k and l denote the k^{th} and l^{th} pipe section connected to the node; N is the total number of connected pipe sections at the node; $S_k = \left(2A_k/a_k\right) \Big/ \sum_{l=1}^{N} \left(A_l/a_l\right)$ is the transmission coefficient at the node for k^{th} pipe section (Chaudhry 1987; Ferrante et al. 2009); A is the pipe sectional area; a is the acoustic wave speed; and g is the gravitational acceleration. With this implementation, the potential external flows at nodes in WDN, e.g. demand, leak, intrusion from air valve, discharge through side-valve, etc., can be derived and calculated from Eq. (1) by expressing the external flow with relevant pressure-flow model, such as the head-driven model for demand nodes (Jung et al. 2009).

2.3 Pressure Fluctuation Limitation (PFL)

As shown in Fig. 1, the obtained TIZs from the estimation of ELM are mapped out by setting a proper PFL that is a threshold value for pressure fluctuations on the border of the decomposed zone. The PFL condition is artificially determined in this study with a general consideration that the threshold value should be quite minor so that the associated pressure waves have little impact when they are transmitted or reflected throughout the system. Generally, it can be expected that the smaller PFLs, the less errors, but the larger scales of the obtained TIZs, which means more computational burdens. Hence, it comes to be an intensely pragmatic trade-off between the accuracy and the computational requirement for setting PFLs. The selection and analysis of PFLs are discussed in details in the following numerical studies in this paper.

2.4 Quasi-Reservoir Boundary Condition (QRBC)

After that the TIZ has been obtained and mapped out for each transient exciter in the WDN, all the elements outside each TIZ will be excluded for the transient analysis of this TIZ so as to reduce calculation effort. Since the system configuration and hydraulic influence beyond this zone are all discarded, which may lead to an unpredictable deterioration in transient response throughout the TIZ borders, an appropriate boundary condition is necessary to reproduce approximately such external influences. For this purpose, the quasi-reservoir boundary condition (QRBC) is applied in this study for representing the TIZ borders, with the following expression form in the transient model:

$$H = \frac{t_f - t}{t_f - t_a} H_0 + \frac{t - t_a}{t_f - t_a} H_f, \qquad when\ t_a < t \le t_f \tag{2}$$

where H is the transient pressure for the border node in a given instant t with the subscript 0 and f denoting the initial and final steady state conditions before and after the transient condition, respectively; The instant t_a denotes the arrival time of pressure waves to the border node, which can be identified as the instant that the pressure starts to fluctuate; and the instant t_f is the final instant of the total duration time for transient simulation. With Eq. (2), the pressure fluctuations of the border nodes are artificially scheduled with a slowly linear variation manner from H_0 to H_f, which assures the initial and terminal transient states of the border nodes. It should be noted that the fluctuation mode of the transient pressures at border nodes is supposed to be unknown before the transient analysis, and thus modeling errors are inevitably introduced by applying this boundary condition.

3. Numerical Application and Discussions

3.1 Description of WDN

To demonstrate the method feasibility and application procedures of the TIZ-based efficient transient analysis, a realistic Modena Network (MOD) in Italy from previous studies of Bragalli et al. (2012) is adopted herein for numerical analysis. As sketched in Fig. 3, the MOD system is composed of 317 pipes, 268 nodes and 4 reservoirs with highly intricate loops, which is a typical situation of practical WDN and thus is suitable for the demonstration study here. The full transient model developed for the original MOD system in Fig. 3, which is solved by the classic 1D waterhammer model, is used as the benchmark for the evaluation of the accuracy and efficiency of the method developed in this study. For simplification, a constant wave speed of 500 m/s is assigned for all pipes and only the quasi-steady friction is considered in this numerical application, in order to highlight the effectiveness of the developed method in this study. In addition, it is assumed that all transient conditions in this system are initiated by the closure of a virtual control valve located at the middle of any specified pipe with an operation duration of 2.0 s. Specifically, the transient exciter of a virtual valve located at pipe no. 123, as marked in Fig. 3, is taken for the illustration.

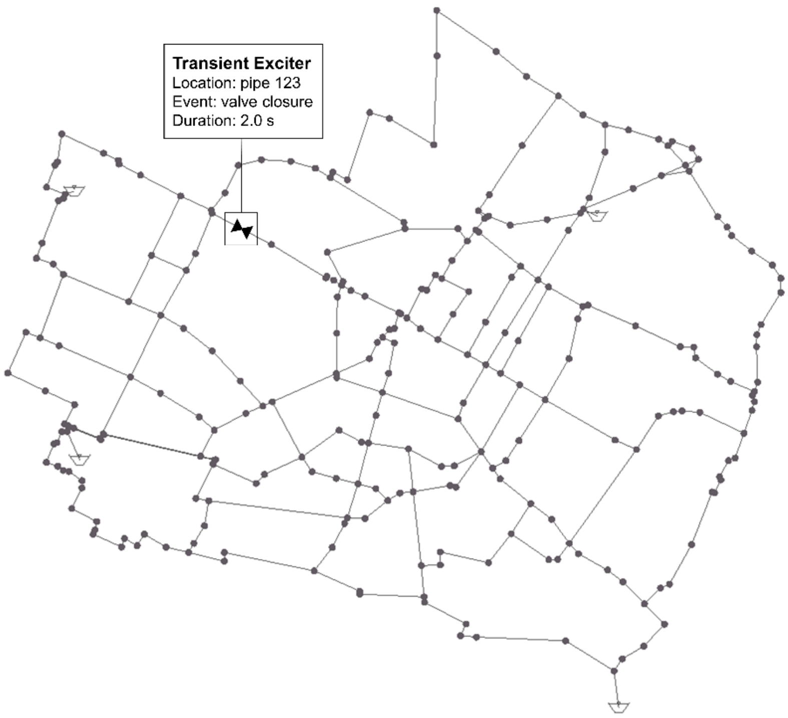

Fig. 3 Schematic of the Modena network with the transient exciter located at pipe no. 123

3.2 Efficiency and Accuracy Analysis of ELM

As illustrated in the former section, the efficiency and accuracy of ELM become crucial to the achievement of TIZ-based transient analysis. Therefore, prior to the application of TIZ-based decomposition, it is necessary to investigate the efficiency and accuracy of ELM with appropriate control strategies for the studied WDN system, so as to obtain optimal schemes of time interval and wave truncation for TIZ analysis. In order to allow for a comprehensive evaluation, the accuracy of ELM is assessed by both the mean and maximum errors of all the connection nodes for transient pressure fluctuation extremes between the ELM results with and without efficiency control strategies. Meanwhile, the efficiency of ELM is measured approximately by the cumulative quantity of calculated BCs during the ELM procedure, which is further converted to the quantity percentage of that for the ELM with efficiency control strategies with regard to the raw ELM with no strategies.

Figure 4 shows the efficiency and accuracy analysis results of ELM with wide variations of time interval and wave truncation selections (denoted as TI and WT respectively in the following study for simplicity) for a transient duration time of 20 s. For efficiency analysis, the cumulative quantity of calculated BCs for the raw ELM with no strategies is about 2.0×10^6, indicating a great computational effort for ELM with no strategies. As shown in this figure, the efficiency of ELM has been improved to different extents with the different settings of time interval and wave truncation schemes. Specifically, even at a minor level of TI = 0.01s and WT = 0.01 m, the quantity percentage can also be reduced (and thus the efficiency can be improved) to 13.7% and 26.9% respectively. It can also be found that both the mean and maximum errors are increasing with (that is, the accuracy is decreasing with) the incremental settings of both time internal and wave truncation, which is opposite to that variation trend of efficiency (represented by quantity percentage), indicating that the accuracy and efficiency of ELM are mutually exclusive with both the selections of time interval and wave truncation. Therefore, in practical application, a pragmatic trade-off between the accuracy and efficiency is necessary for the use of ELM.

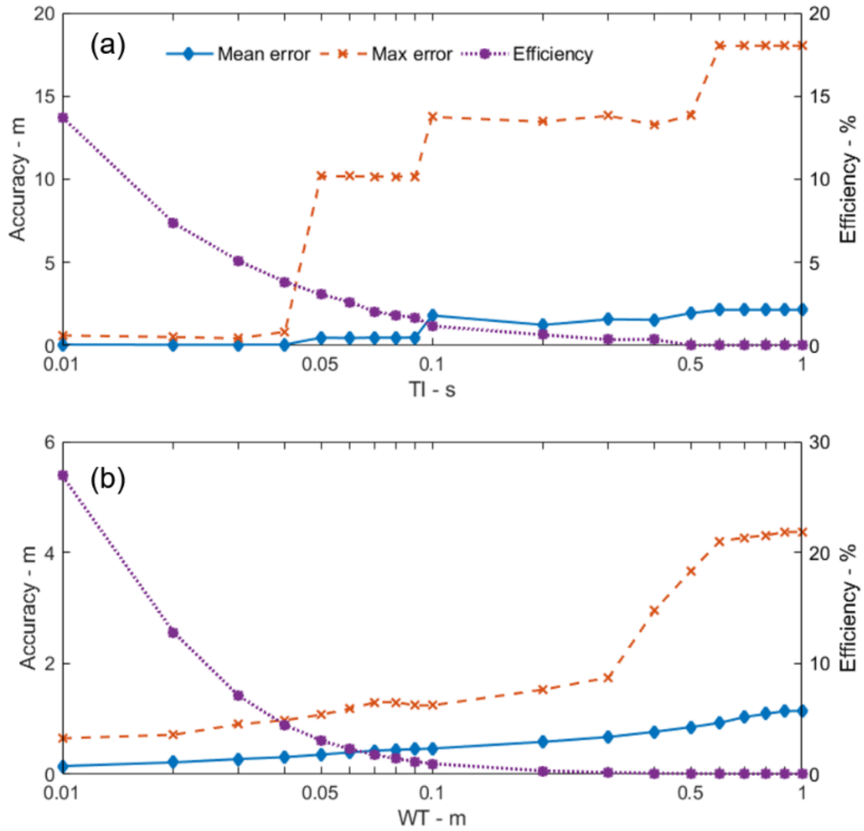

Fig. 4 The efficiency and accuracy analysis of ELM for different settings of the two efficiency control strategies

To inspect the detailed impact of efficiency control strategies and the causes of introduced errors, the results of transient pressure traces at the upstream of exciter at pipe no. 123 are retrieved from the analysis process and shown in Fig. 5. For comparison, the pressure traces of the original MOC, the ELM with no strategies, and the ELM with different time intervals and wave truncations respectively are plotted in the same figure. As for time interval (Fig. 5a), it is obvious that the calculated pressure trace of ELM with this strategy migrates in advance with time from that of ELM with no strategies, and the extent of migration increases with the incremental setting of time interval, resulting in the increase of both the phase and amplitude errors of pressure fluctuation.

As for wave truncation (Fig. 5b), the difference of pressure traces between the ELM with and without strategies is also increasing with the settings of wave truncation. Overall, the influence of wave truncation is relatively smaller on the first several waveforms of the pressure traces, which induces the relatively slow and even increasing errors (Fig. 4b). In addition, compared with the full transient model results by MOC, appropriate selection of the control strategies (e.g., the results of TI = 0.03 s and WT = 0.1 m shown in Figs. 4 and 5) may provide acceptable simulation results of the pressure traces, but with much higher computation efficiency, which indicates the effectiveness of ELM for reproducing transient responses.

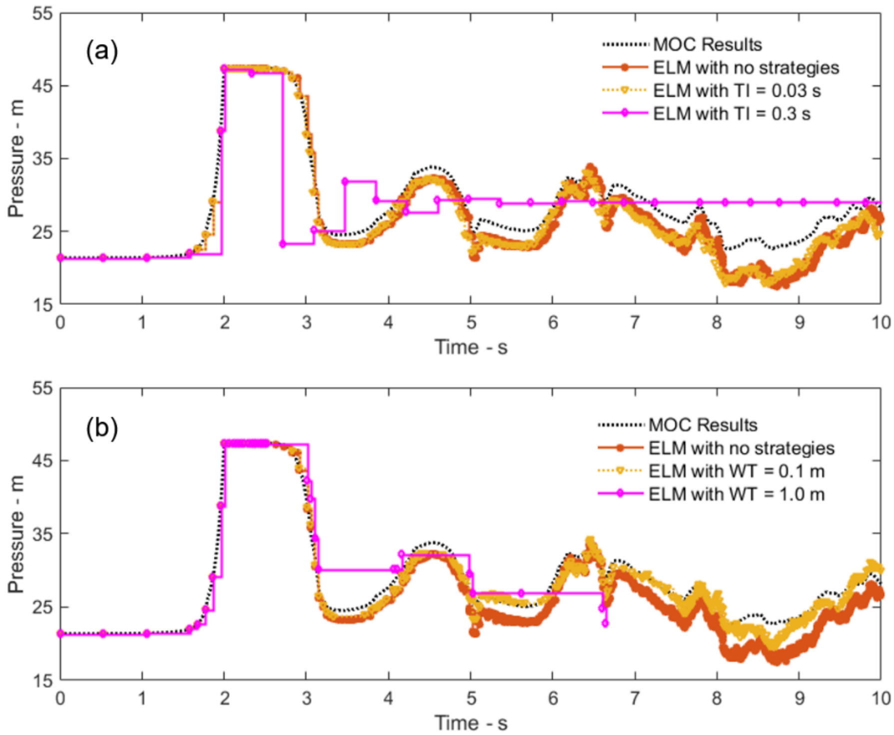

Fig. 5 Pressure traces at the upstream of exciter at pipe no. 123 for different control strategy settings of time interval (TI) and wave truncation (WT)

3.3 The Mapping of TIZ

With the prior-estimation of pressure fluctuation extremes of all the nodes by ELM, and following the TIZ mapping method procedure, the TIZs for a specific transient condition can be mapped out by setting a proper PFL, which is shown in Fig. 6a for the transient condition induced at pipe no. 123 with different PFL selections of 1.0, 3.0, 5.0 m, respectively. It should be noted that the TIZs determined by ELM is only an estimation of the actual TIZs determined by MOC results, which is also shown in Fig. 6a for comparison. Figures 6b and 6c show the estimation errors of pressure fluctuation extremes between the ELM and MOC results and both the results of ELM with no strategies and optimal strategies are illustrated for comparison. According to Figs. 6b and c, it can be concluded that: (1) The estimation errors of ELM for the transient condition are basically within 1.5 m and the extreme estimation of ELM with no strategies (Fig. 6b) is generally overestimated, which reveals the effectiveness and conservatism of ELM for prior-estimation of pressure fluctuation extremes; (2) The distribution of estimation errors of ELM with optimal strategies (Fig. 6c) is different from that of ELM with no strategies (Fig. 6b), with some extremes underestimated, which is mainly due to the settings of efficiency control strategies as analyzed in the former section. In spite of this, the underestimated extremes mainly occurred at the distant nodes away from the transient exciter (see the latter sequence of node identifications in Fig. 6c).

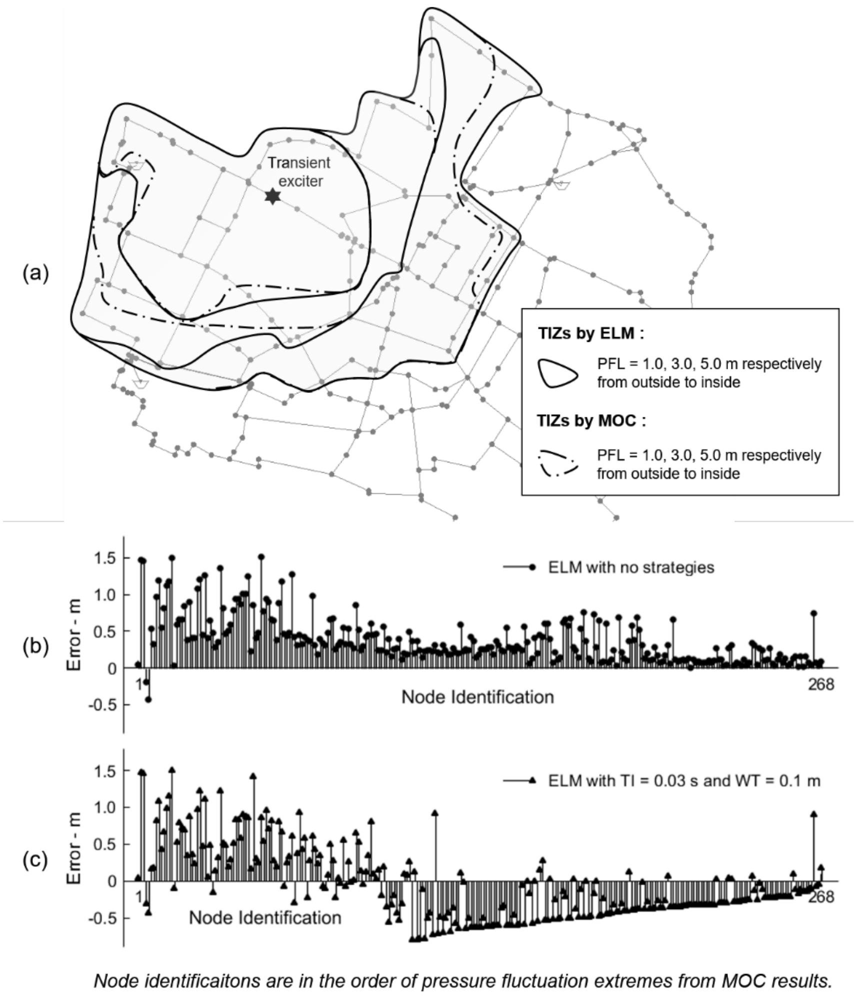

Fig. 6 Mapping results of TIZ: (a) obtained TIZs with different selections of PFL; (b) and (c) pre-estimation errors of pressure fluctuation extremes between ELM and MOC

3.4 The Application of TIZ-Based Transient Analysis

After obtaining the TIZs by the above mapping procedure, the regional transient system for each TIZ can be constructed by resetting corresponding border nodes of this TIZ as QRBCs. To verify the applicability of TIZ for efficient transient analysis, the errors of pressure fluctuation extremes at different nodes between the TIZ-based transient analysis and the original MOC-based full transient modeling are investigated, which are calculated and shown in Fig. 7a, b and c. Note that the node identifications in this figure are only the nodes inside the TIZ (excluding the border and outside nodes). According to Figs. 7a, b and c, the errors for pressure fluctuation extremes are minor (all below 1.0 m) for the obtained three TIZs under different PFL conditions, which demonstrate the general validity and acceptable accuracy of the TIZ-based transient analysis method. Meanwhile, it can be also observed from the results that the relatively large errors mainly occurred around the TIZ borders and very minor errors are introduced to critical areas around the transient exciter. This result will be useful for practical applications where usually the maximum magnitudes of pressure fluctuations (i.e., pressure extremes) are concerned for transient system design.

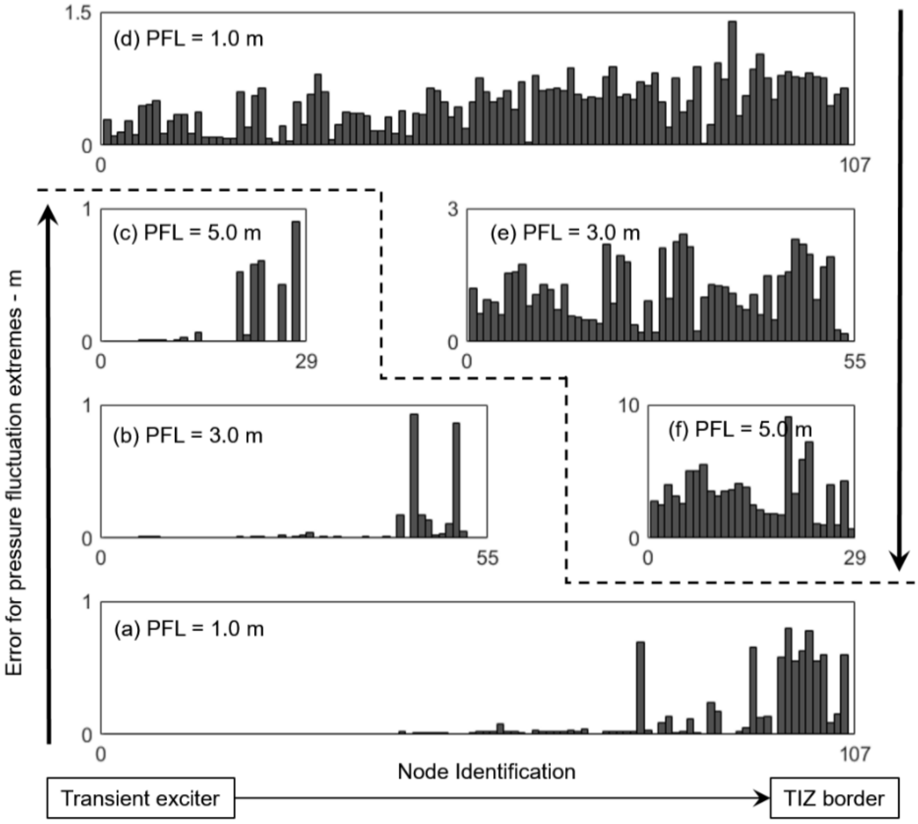

Fig. 7 The errors between the TIZ-based decomposing model and original full-scale model under different PFL conditions, with: (a-c) error for pressure fluctuation extremes; (d-f) maximum error for pressure courses

Furthermore, the difference between the detailed pressure traces by the TIZ-based and MOC-based models is also investigated by the maximum errors of pressure courses as shown in Fig. 8d, e and f. It can be observed that the level of maximum errors for pressure courses increases with the incremental selection of PFL, e.g., about 1.5 m, 3.0 m and 10.0 m for PFL = 1.0 m, 3.0 m and 5.0 m respectively. Therefore, the results of Figs. 7a-f indicate that the TIZ-based transient analysis is applicable and the accuracy will be highly dependent on the selection of PFL in the system. The results further suggest that the selection of PFL for the application of TIZ-based transient analysis is more sensitive and important for transient utilization such as defect detection where the detailed pressure courses are required, than for transient design where usually only the extreme amplitudes are concerned.

In addition to the accuracy analysis of TIZ-based transient analysis, the computational efficiency of the method is also worthy of quantitative investigation. For quantitative comparison, all the programs including ELM and MOC are encoded on the MATLAB platform and running on a personal computer equipped with an Intel Core I7-4710HQ central processing unit (CPU). Specifically, the MOC-based model is adopted for the full-scale system simulation (total 268 nodes and 317 pipes), with time step = 0.01 s and transient duration = 20 s; and the ELM with optimal strategies of TI = 0.03 s and WT = 0.1 m is used for TIZ-based transient analysis under different PFL conditions. The efficiency results of different models are calculated and summarized in Table 1, which provides clear evidence for the computational efficiency of TIZ-based transient analysis. Note that the difference between Reduction[1] and Reduction[2] indicates the time consumption of the TIZ mapping procedure and it is clearly that the efficiency of transient analysis can be greatly improved at the cost of a little bit of computational effort for the efficient mapping method. Meanwhile, the memory requirement of this efficient method has also been greatly reduced.

It is necessary to mention that the application results and analysis for the transient condition initiated at pipe no. 123 in Fig. 3 indicate that the proposed method can provide a considerable efficiency improvement for transient analysis with sufficient modeling accuracy. To generalize the results and findings, more general transient conditions, with different locations of transient exciters in Fig. 3, have also been investigated beyond this paper, by utilizing the developed TIZ-based decomposition method for transient analysis. Overall inspection of the results for various conditions can verify and confirm the above findings in terms of the generic applicability, improved efficiency and acceptable accuracy of this TIZ-based model for transient simulation. The detailed results and discussion are neglected herein due to the space limitation of this paper.

Table 1 Result summary of zone scale and time efficiency for different PFL cases

TIZ-based model	Zone scale (%)		Time efficiency (%)	
	Node	Pipe	Reduction[1]	Reduction[2]
PFL = 1.0 m	39.9	42.0	49.3	39.3
PFL = 3.0 m	20.5	22.1	66.4	56.4
PFL = 5.0 m	10.8	12.3	77.1	67.1

Reduction[1]—the regional time reduction considering only the TIZ-based transient model;
Reduction[2]—the overall time reduction including the mapping procedure and TIZ-based model.

4 Summary and Conclusions

This paper develops an effective approach as alternative, termed as transient influence zone (TIZ) based method, to the efficient decomposition and transient analysis of water distribution networks (WDN). The implementation of TIZs allows conducting efficient and accurate transient analysis individually for each influence region of transient sources in WDN. The methodological framework of applying the TIZ to effective decomposition and efficient transient analysis for WDN has been presented in the paper, in which the efficient Lagrangian model (ELM) with two efficiency control strategies is used for prior-estimating the pressure fluctuation extremes, the pressure fluctuation limitation (PFL) is set for mapping the TIZ border, and the quasi-reservoir boundary condition (QRBC) is applied for reproducing the border influence.

The application procedure and validity of the developed methodological framework has been demonstrated through a realistic WDN available from the literature under different transient conditions. The effectiveness of the TIZ-based system decomposition for transient analysis is assessed and discussed from the obtained results of the case study. The results and analysis of this study have revealed the applicability and accuracy of the developed method for efficient transient analysis in realistic and complex WDN. Meanwhile, the application procedures and strategies of the developed method and framework are also discussed for practical purpose in the paper.

Acknowledgements

This work was partially supported by the grants from: (1) the Hong Kong Research Grant Council (RGC) under projects no. 25200616 and no. T21-602/15-R; (2) the Hong Kong Polytechnic University under projects no. 1-ZVCD and no. 1-ZVGF; and (3) the National Science and Technology Major Project (2014ZX07406003).

Conflict of Interest

The authors declare that they have no conflict of interest.

References

Besner M (2007) Risk evaluation of drinking water distribution system contamination due to operation and maintenance activities. PhD Dissertation, University of Montreal, Quebec

Boulos PF, Lansey KE, Karney BW (2006) Comprehensive water distribution systems analysis handbook for engineers and planners. American Water Works Association

Bragalli C, D'Ambrosio C, Lee J, Lodi A, Toth P (2012) On the optimal design of water distribution networks: a practical MINLP approach. Optim Eng 13(2): 219-246

Chaudhry MH (1987) Applied hydraulic transients, 2nd edn. Litton Educational/Van Nostrand Reinhold, New York

Duan HF (2015) Uncertainty analysis of transient flow modeling and transient-based leak detection in elastic water pipeline systems. Water Resour Manag 29(14): 5413-5427

Duan HF (2016) Sensitivity analysis of a transient-based frequency domain method for extended blockage detection in water pipeline systems. J Water Resour Plan Manag 142(4): 04015073

Duan HF, Tung YK, Ghidaoui MS (2010) Probabilistic analysis of transient design for water supply systems. J Water Resour Plan Manag 136(6): 678-687

Ebacher G, Besner MC, Lavoie J, Jung BS, Karney BW, Prévost M (2011) Transient modeling of a full-scale distribution system: comparison with field data. J Water Resour Plan Manag 137(2): 173-182

Ferrante M, Brunone B, Meniconi S (2009) Leak detection in branched pipe systems coupling wavelet analysis and a Lagrangian model. J Water Supply Res T 58(2): 95-106

Fleming K, Dugandzik JG, Lechavellier M (2006) Susceptibility of distribution systems to negative pressure transients. American Water Works Association

Goldberg D, Benjamin Wylie E (1983) Characteristics method using time-line interpolations. J Hydraul Eng 109(5): 670-683

Haghighi A (2015) Analysis of transient flow caused by fluctuating consumptions in pipe networks: a many-objective genetic algorithm approach. Water Resour Manag 7(29): 2233-2248

Jung BS, Boulos PF, Wood DJ (2007) Pitfalls of water distribution model skeletonization for surge analysis. J Am Water Works Ass 99(12): 87-98

Jung BS, Boulos PF, Wood DJ (2009) Effect of pressure−sensitive demand on surge analysis. J Am Water Works Ass 101(4): 100-111

Kapelan ZS, Savic DA, Walters GA (2003) A hybrid inverse transient model for leakage detection and roughness calibration in pipe networks. J Hydraul Res 41(5): 481-492

Karney BW, Filion YR (2003) Energy dissipation mechanisms in water distribution systems. ASME/JSME 2003 4th Joint Fluids Summer Engineering Conference: 2771-2778

Nault J, Karney B, Jung B (2016) Algebraic water hammer: global formulation for simulating transient pipe network hydraulics. World Environmental and Water Resources Congress: 191-201

Ramalingam D, Lingireddy S, Wood D (2009) Using the WCM for transient modeling of water distribution networks. J Am Water Works Ass 101(2): 75

Shimada M, Vardy A (2013) Nonlinear interaction of friction and interpolation errors in unsteady flow analyses. J Hydraul Eng 139(4): 397-409

Sibetheros I, Holley E, Branski J (1991) Spline interpolations for water hammer analysis. J Hydraul Eng 117(10): 1332-1351

Skulovich O, Sela Perelman L, Ostfeld A (2016) Optimal closure of system actuators for transient control: an analytical approach. J Hydroinf 18(3): 393-408

Walski TM, Daviau J, Coran S (2004) Effect of skeletonization on transient analysis results. Proc. ASCE EWRI Conf., Salt Lake City

Wood DJ, Boulos PF, Lingireddy S (2005a) Pressure wave analysis of transient flow in pipe distribution systems. MWH Soft

Wood DJ, Lingireddy S, Boulos PF, Karney BW, Mcpherson DL (2005b) Numerical methods for modeling transient flow in distribution systems. J Am Water Works Ass 97(7): 104-115

Yang J, Hsu E (1990) Time-line interpolation for solution of the dispersion equation. J Hydraul Res 28(4): 503-520