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UNSTEADY FRICTION MODELING TECHNIQUE FOR LAGRANGIAN APPROACHES IN TRANSIENT SIMULATIONS

M. Zeidan[1] and A. Ostfeld[2]

[1,2] Faculty of Civil and Environmental Engineering, Technion- Israel Institute of Technology, Haifa 32000, Israel.

[1] *smjz@campus.technion.ac.il*, [2]*ostfeld@technion.ac.il*

Abstract

This study tackles the problem of simulating the head damping effect in transient flows when modeled in the Lagrangian approach rather than Eulerian. The Lagrangian approach normally requires orders of magnitude fewer calculations, which allows very large systems to be solved in an expeditious manner, and it has the additional advantage of using a simple physical model as the basis for its development. Moreover, since it is continuous in both time and space, the method is less sensitive to the structure of the network and the length of the simulation process, resulting in improved computational efficiency. Nevertheless, most recent studies used an Eulerian approach when simulating the systems transient response (e.g., method of characteristics), thus focused on developing and improving different computational routines for modeling and simulating unsteady friction models that are better fixated for Eulerian methods and are not suited for Lagrangian ones. One-dimensional methods of representing unsteady contributions to skin friction based on instantaneous acceleration have a long track record (e.g., Daily et al. 1956). And it is still the most popular method in software used for practical simulations, despite it cannot accurately depict the system's transient responses without additional calibrations and tunings. However, the more accurate models (e.g., Brunone 2000) are not suited for the Lagrangian approach. The lack of a mesh structure in the Lagrangian approach makes it challenging to consider the convective acceleration terms in addition to the local acceleration. Therefore, there is a need for a more accurate friction model that is suited for Lagrangian methods without compromising their performance. Unfortunately, such a model is yet to be published in the literature. This study presents a new friction modeling technique that compensates for both the local and convective acceleration terms for the Lagrangian transient modeling approach, without compromising the computational time. Additionally, fixating only on the Eulerian approach for transient modeling and undermining the Lagrangian based models is concerning since it can provide different perspectives for developing novel solutions and tools that take advantage of transient events.

Keywords
Transient, WCM, Water hammer, Unsteady friction.

1 INTRODUCTION

Water hammer models are becoming more present in the designing and analysing complex pipeline system. In addition, they are more frequently used for the identification of system leakage, closed or partially closed valves, and the assessment of water quality problems. Turbulence models have been developed and used to perform numerical experiments in turbulent water hammer flows for a multitude of research purposes, such as the computation of instantaneous velocity profiles and shear stress fields, the calibration and verification of water hammer models, the evaluation of the parameters of unsteady friction models, and the comparison of various unsteady friction models.

Understanding the governing equations that are in use in water hammer research and practice and their limitations is essential for interpreting the results of the numerical models that are based on these equations, for judging the reliability of the data obtained from these models, and for minimizing misuse of water hammer models. While the most common approaches used to describe transient events in literature are inherently Eulerian, they require a dense mesh to mimic real life transient events and guarantee accurate results. subsequently, significantly increasing the computational capacity, time and resources required. Consequently, deeming these models impractical to use in advanced optimizing algorithms. For instance, stochastic algorithms (e.g., genetic algorithms) are inconvenient to work with when dealing with time extensive simulation, since their efficiency relies on the speed of the simulation parallelly performed.

This work presents a framework for simulating the head damping effect in transient flows when modelled in the Lagrangian approach. The Lagrangian approach normally requires orders of magnitude fewer calculations, which allows very large systems to be solved in an expeditious manner, and it has the additional advantage of using a simple physical model as the basis for its development. Moreover, since it is continuous in both time and space, the method is less sensitive to the structure of the network and the length of the simulation process, resulting in improved computational efficiency. The suggested model relies on the wave characteristics method (WCM) and describes an unsteady wave celerity in addition to unsteady friction factor. The celerity is modelled in such that it decreases while the waves propagate through the pipelines due to energy dissipation.

While advanced sophisticated methods tris to mathematically describe and model the shear stresses and velocity profiles to better mimic transient events in a lab, it can lead to misuse and inaccurate estimation in real life settings. Therefore, the suggested method attempts to “catch” the transient behaviour by introducing a calibrated factor that can accommodate for the unknown uncounted for parameters that exist in real life networks.

2 MODELS

The equations governing unsteady turbulent flows in pipes form a system of hyperbolic-parabolic partial differential equations which cannot, in general, be solved analytically. As a result, numerical solutions are used to approximate them. Extensive research has been devoted to developing theories and models to better describe and manage hydraulic transients in pipeline systems. Previous studies have employed one-dimensional models to analyze the efficiency of systems' transient responses (Wylie et al. 1993; Duan et al. 2010b; Chaudhry 2014). More recent studies have suggested and explored more complex two-dimensional and quasi-two-dimensional models that can contain various factors (e.g., Brunone 1999; Lee et al. 2013; Meniconi et al. 2013; Gong et al. 2014, 2016, 2018; Duan and Lee 2016; Kim 2016, 2020; Wang and Ghidaoui 2018; Che et al. 2018, 2019; Wang et al. 2019; Keramat et al. 2019; Zhao and Ghidaoui 2003; Zouari et al. 2020).

3 MODEL FORMULATION

The model formulation described below is composed of a description of the WDS mapping and modeling process, the transient model simulations, followed by a comparison with the TSNET package (Xing and Sela, 2020).

3.1 Mapping the water distribution system

The network is imported from a database file (INP) and prepared for the transient simulation. The water distribution system is mapped onto an undirected graph G= (V, E), in which the vertices V represent the consumers, sources, and valves, and the edges E represent the connecting pipes. The different types of vertices are defined as different discontinuities with different resistance coefficients. All the transient calculations and simulations were carried out via MATLAB codes and the TSNET Package in Python.

3.2 The wave characteristic method model

The wave characteristic method (WCM) introduced by Wood (1965) is based on the notion that transient pipe flow is caused by the propagating of pressure waves which occurs when a disturbance is introduced into the system. These pressure waves are described as a rapid pressure change that travel at pressure wave speed in the liquid-pipe medium. In pressurized water pipes, the pressure waves travel about 1000 m/s in metallic pipes and around 400 m/s in polymeric pipes (Duan et al. 2020, Wan and Mao 2016). When these waves encounter discontinuities, they are partially reflected and transmitted through the pipe system.

3.3 Pressure magnitude

The magnitude of a pressure wave is calculated using the Joukowsky equation (Eq.1.) while assuming an immediate change in the valve opening. The Joukowsky equation does not only describe the correlation between pressure change ΔP and flow change ΔQ, but also forms the basis for the WCM mathematical model. In order to work with head-pressure units, the ΔP is replaced by the term ρ g ΔH as shown in Eq.1.

$$\Delta P = \rho c \frac{\Delta Q}{A} \xrightarrow{\Delta P = \rho g \Delta H} \Delta H = c \frac{\Delta Q}{gA} \tag{1}$$

Where ΔP represents the pressure, ΔH is the change in head pressure, ΔQ is the change in flow rate, c is the pressure wave's celerity; A represents the flow section area, ρ is the fluid viscosity, and g is the gravitational acceleration constant.

3.4 Unsteady friction attenuation

Previous works have captured the influence of line friction (viscous resistance) on the propagation of pressure waves using the "orifice analogy" (e.g., Jung et al 2009) where (n) imaginary friction orifices are added to the pipe, thus dividing it into (n+1) pipes that are similar in length. The friction orifices are modeled as a square-law orifice with a properly chosen orifice coefficient. This takes the form of a quadratic correlation between the pressure head ΔH and the flow rate Q, as follows:

$$\Delta H = A(t) + B(t)|Q| + C(t)Q|Q| \tag{2}$$

The terms A, B, and C represent the coefficients for a general representation of the characteristic equation. The coefficient may be time-dependent but known at every time step. The absolute values of Q are employed to make the resistance term dependent on the flow direction. The new modification suggests a simple linear damping factor to the wave's celerity (Cel) as follow:

$$Cel = 1000 - \alpha \cdot t \tag{3}$$

where α is a calibrated coefficient and t represent the lifespan of the wave.

The model presented by Brunone et al. 2000 is the most commonly used in conventional transient analyses, However, it does not fit the Lagrangian approach for transients modeling. Consequently, in addition to the Darcy-Weisbach equation, the Daily (1955) empirical correction to the wall shear stress model was adopted here to compute the head-loss and shear stresses along the pipelines. The wall shear stress is expressed as:

$$\tau_{wall} = \frac{\rho f V^2}{8} + \frac{k_u \rho D}{4}\frac{\partial V}{\partial t} \tag{4}$$

where τ_{wall} is the combined steady and unsteady wall shear stresses, ρ is the water density, f is the Darcy-Weisbach coefficient, V is the flow velocity, D is the pipe diameter, $\partial V/\partial t$ is the local instantaneous acceleration, and K_u is Brunone's friction coefficient.

$$K_u = 0.16 + \frac{t}{\beta} \tag{5}$$

where β is a calibrated coefficient and t represent the lifespan of the wave.

The result of including the unsteady shear stress model into the square- law orifice analogy is described by the following equation:

$$\Delta H = [\underbrace{\frac{k}{2gA}}_{A(t)}\frac{\partial Q}{\partial t}] + [\underbrace{\frac{-fL}{2gDA^2}}_{C(t)}]\, Q|Q| \tag{6}$$

4 COMPUTATIONAL RESULTS

4.1 Case study 01:

The first network resembles a simple pipeline system with a valve at the downstream. In this case study the new suggested parameters (α, β) are calibrated and to be further used in the second case study. The desire is to get constant parameters that will fit in other layouts and would be considered constants coefficients in the future.

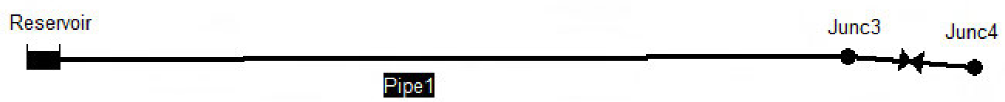


Figure 1. The layout of the first case study, describing a simple pipeline system with a valve downstream

In this section, the performance of the refined WCM model and the other models available at the TSNET package are compared. The main purpose is to find the main differences and refine the WCM accordingly. As seen in figure 2, the WCM, the steady friction model and the quasi-steady model almost align with each other. While the unsteady friction model differs dramatically. The main reason is the Celerity attenuation in the unsteady friction model. hence the main focus in this work will be introducing celerity attenuation into the WCM.

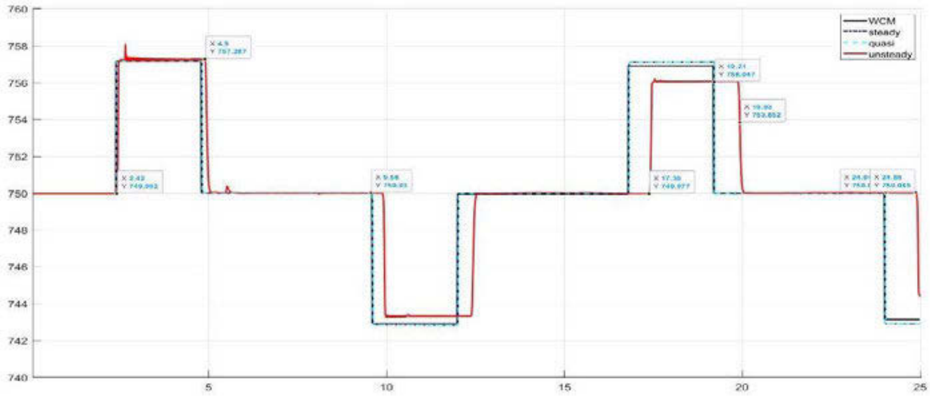


Figure 2. Comparison between the WCM model and the three available models in the TSNET package.

The next step is to introduce the celerity and friction modification to the WCM model and observe the influence of each parameter over the transient response, at node 3 in this case. The transient response presented at Figure 2.a will serve as the baseline for these modifications, since it holds no celerity or friction attenuations. The WCM pulses arrive much faster than their counterparts in the unsteady model, mostly due to different wave celebrities. Therefore, by adjusting the wave celerity to be 960 m/s and the Ku to 0.16, the phase difference is eliminated (Figure 2.b), however, the amplitudes are still different. As shown in Figure 2.c, by introducing the damping effect for the friction factor, the transient response received from both models are similar to a great extent. Lastly, Figure 2.d shows the potential of adjusting both the celerity and friction factor so that the transient responses match to a great extent. The Parameters α and β were calibrated to be 0.5 and 0.15, respectively.

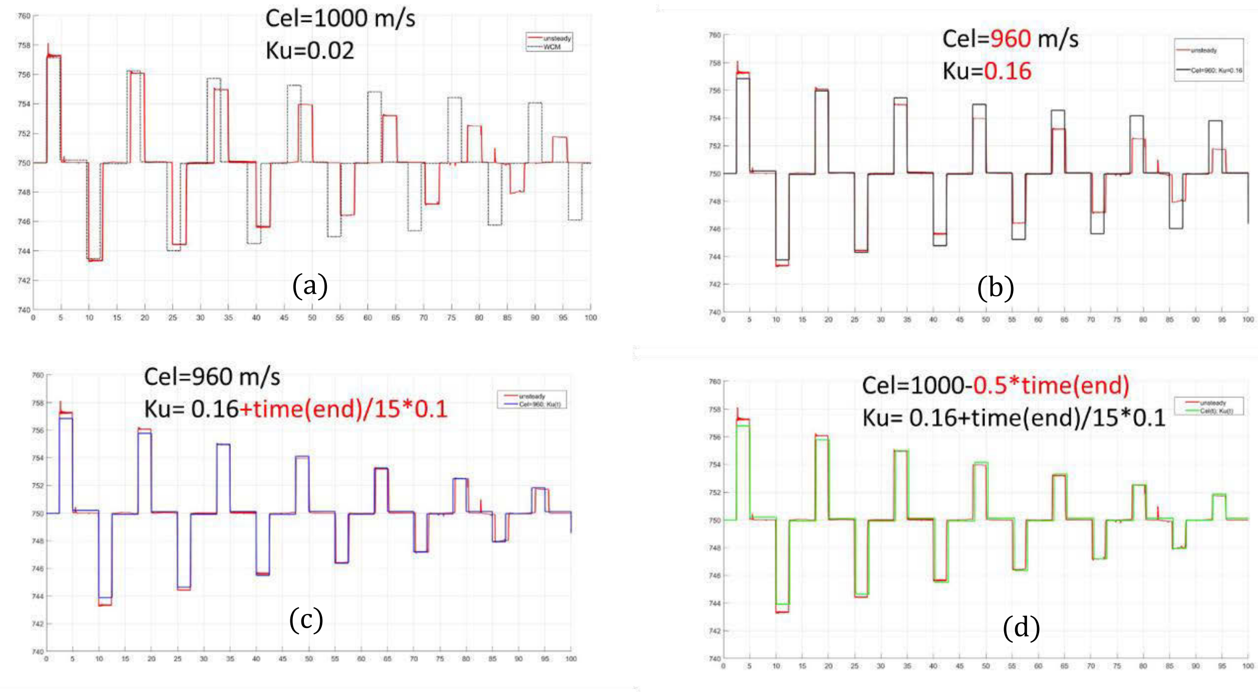
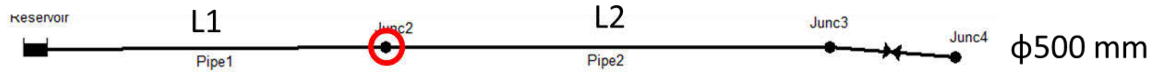


Figure 3: different adjustment to the WCM in comparison to the unsteady model from TSNET.



Case study 02: different adjustment to the WCM in comparison to the unsteady model from TSNET.

Another pipe was added to the first case study layout to better test the calibrated parameters [α=0.5, β=0.15]. the transient respond at Node 2 is observed and compared to the unsteady friction model from the TSNET package. The pipe lengths L1 and L2 are changed to avoid over fitting scenarios. In this first case L1 is 1.5 Km while L2 is 2.0 Km. the transient response of the refined WCM, and the unsteady friction model are presented in Figure 4.

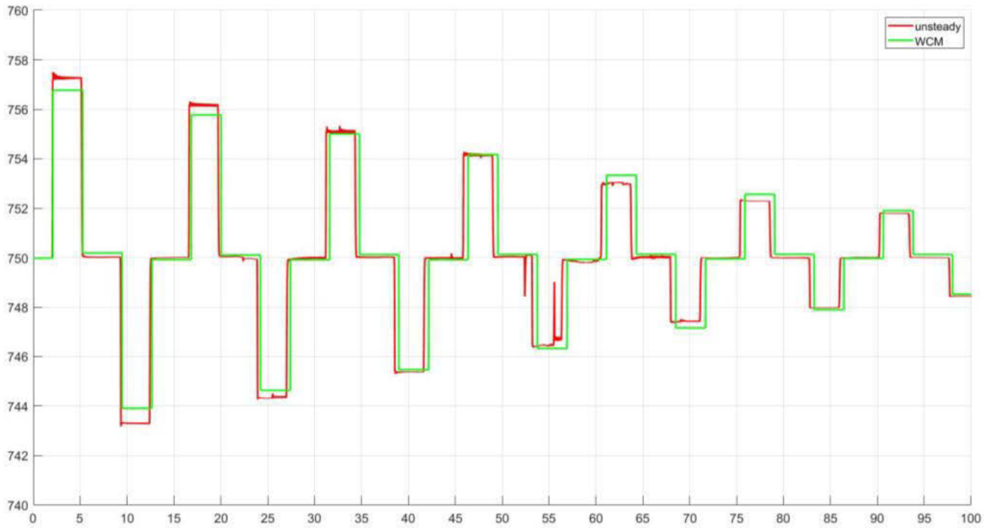


Figure 4: the transient response for the refined WCM and the unsteady TSNET model for second case study.

As seen in Figure 4, the Transient response for the two models are quiet similar, with few anomalies. However, the improvement from the regular WCM is clear in this case. Moreover, these differences are negligible from an engineering standpoint when dealing with unpredicted noise and disturbances. To further check the parameters, the lengths of L1 and L2 are now 3.0 Km each. The results of the transient simulation for both models are presented at Figure 5.

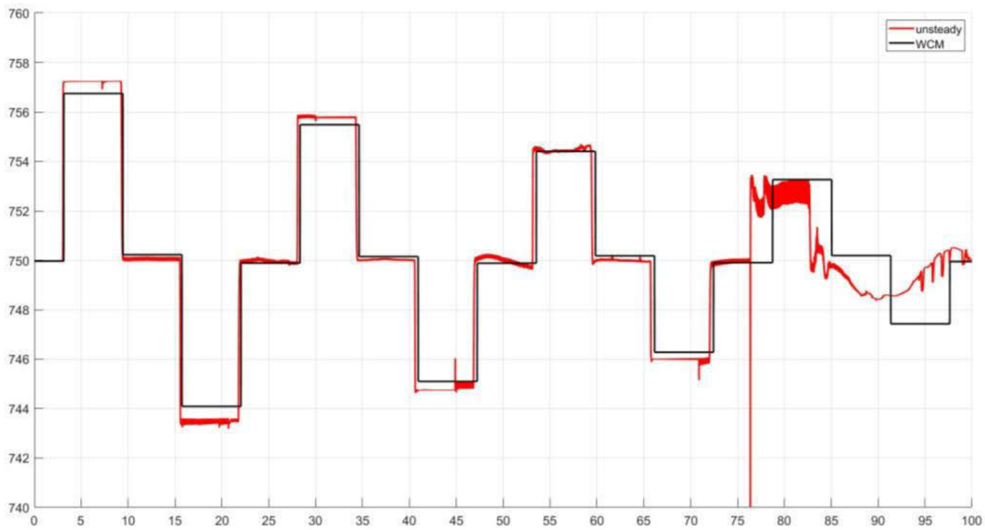


Figure 4: the transient response for the refined WCM and the unsteady TSNET model for the modified second case study.

As seen in Figure 5, the refined WCM can depict a similar transient response to that of the unsteady model, it is important to note that the WCM take less computational resources and therefore less computation time when compared with its counterpart. In addition, the unsteady model faces some instability around 75 seconds from the beginning of the simulation, probably due to mesh sensitivity or other sensitive boundary conditions, when the WCM do not have this problem due to its inherently Lagrangian approach.

5 CONCLUSIONS

Previous works have implemented numerous approaches for accurately simulating transient response and capturing the damping effect that occurs in real life scenarios. Approaches mostly included Eulerian based method, more specifically different variations and modifications of the method of characteristics. However, these approaches require dense mesh to get accurate result, hence increasing the computational capacity needed. This study builds on the wave characteristics method, which is much less computationally intensive and requires no mesh for performing transient analysis. However, it generates less accurate result in general, unless numerous friction orifices are introduced. I this study, we introduced modification for the wave celerity and the friction factor. New suggested parameters (α, β) are introduced to the model and are calibrated in the first case study, and further used in the second case study, generating promising results.

In line with the hypothesis, the introduced Celerity and friction linear attenuation resulted in a better transient response that is, to an extent, similar to the response received by the more complex unsteady model. It is worthy noting that the running time of the refined WCM is significantly lower than the unsteady MOC based model.

6 ACKNOWLEDGMENTS

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