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# Numerical methods for hydraulic transients in visco-elastic pipes

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ABSTRACT

In technical applications involving transient fluid flows in pipes, the convective terms of the corresponding governing equations are generally negligible. Typically, under this condition, these governing equations are efficiently discretized by the Method of Characteristics. Only in the last years the availability of very efficient and robust numerical schemes for the complete system of equations, such as recent Finite Volume Methods, has encouraged the simulation of transient fluid flows with numerical schemes different from the Method of Characteristics, allowing a better representation of the physics of the phenomena.

In this work, a wide and critical comparison of the capability of Method of Characteristics, Explicit Path-Conservative (DOT solver) Finite Volume Method and Semi-Implicit Staggered Finite Volume Method is presented and discussed, in terms of accuracy and efficiency. To perform the analysis in a framework that properly represents real-world engineering applications, the visco-elastic behaviour of the pipe wall, the effects of the unsteadiness of the flow on the friction losses, cavitation and cross-sectional changes are taken into account. Analyses are performed comparing numerical solutions obtained using the three models against experimental data and analytical solutions. In particular, water hammer studies in high density polyethylene pipes, for which laboratory data have been provided, are used as test cases. Considering the visco-elastic mechanical behaviour of plastic materials, 3-parameter and multi-parameter linear visco-elastic rheological models are adopted and implemented in each numerical scheme. Original extensions of existing techniques for the numerical treatment of such visco-elastic models are introduced in this work for the first time. After a focused calibration of the visco-elastic parameters, the different performance of the numerical models is investigated. A comparison of the results is presented taking into account the unsteady wall-shear stress, with a new approach proposed for turbulent flows, or simply considering a quasi-steady friction model. A predominance of the damping effect due to visco-elasticity with respect to the damping effect related to the unsteady friction is confirmed in these contexts. Moreover, all the numerical methods show a good agreement with the experimental data and a high efficiency of the Method of Characteristics in standard configuration is observed. Finally, three Riemann Problems are chosen and run to stress the numerical methods, taking into account cross-sectional changes, more flexible materials and cavitation cases. In these demanding scenarios, the weak spots of the Method of Characteristics are depicted.



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## 1. Introduction

Flexible plastic pipes in polyvinyl chloride (PVC), polyethylene (PE) and in particular high density polyethylene (HDPE) are gaining an increasingly important role in pressurized and not pressurized hydraulic systems, being often preferred to other materials (i.e. steel and concrete) for water distribution networks, irrigation plants and sewage systems. This trend is a consequence of the excellent mechanical and chemical properties of polymeric materials, even more considering the easy and rapid process of installation required and the cheaper prices. Almost without exception, polymers belong to a class of substances that show visco-elastic properties, responding to external forces in an intermediate manner between the behaviour of an elastic solid and a viscous liquid (Shaw and MacKnight, 2005), attributing to the material an elastic instantaneous strain together with a retarded damping effect. This aspect is particularly visible in case of hydraulic transients, for which it has already been demonstrated that the classical Allievi–Joukowsky theory for water hammer, based on the assumption of a linear elastic wall behaviour and quasi-steady friction losses (Chaudhry, 1979), fails in the prediction of the real pressure trend in flexible tubes (Covas et al., 2004, 2005). From the experimental point of view, a recent thorough work has been done by Ferràs et al. (2016) for the distinction of the main effects of damping during hydraulic transients in PE pipes. Ramos et al. (2004) discussed the importance of the implementation of a visco-elastic constitutive law for plastic pipes and also the relevance of the unsteady friction with respect to the steady one. Their results show that the pressure wave dissipation is more sensitive to the visco-elastic damping effects than to the unsteady friction losses. Furthermore, Duan et al. (2010) demonstrated that the visco-elastic effects are deeply more significant when the retardation time is less than the wave travel time along the entire pipeline length. Other researches regarding the unsteady friction losses had already been done by Zielke (1968) and Franke and Seyler (1983), while recently Ioriatti et al. (2017) proposed a new more efficient approach for evaluating the convolution integral of the unsteady wall shear stress.

In many industrial applications involving the design of hydraulic networks, accurate computational models able to correctly a priori evaluate the behaviour of the systems are required. The mathematical model has to properly describe the hydraulic system also in terms of resistance and deformation of the pipe wall, especially in the event of water hammers which could seriously damage the whole network. Moreover, considering the increase in complexity of these systems, numerical simulations have to be more and more efficient and robust (Leibinger et al., 2016). The main numerical method used for studies concerning hydraulic transients has always been the Method of Characteristics (MOC) (Ghidaoui et al., 2005). Among these studies, a lot of research has been done for the plastic single-pipe system by Covas et al. (2004, 2005), Soares et al. (2008) and Apollonio et al. (2014). There are applications carried out also with a 2D axially symmetric model by Duan et al. (2010) and Pezzinga (2014). Meniconi et al. (2012, 2014) analysed the effect of water hammer pressure waves in case of a sudden contraction or expansion of the cross-sectional area or with an in-line valve in the pipeline. Evangelista et al. (2015) also investigated the behaviour of more complex hydraulic systems, with a Y-shaped configuration.

Other techniques are only seldom applied for the resolution of transient pipe flows and especially include Finite Volume Methods (FVM) (Seck et al., 2017). Starting from this consideration, in the present work we test the Path-Conservative Osher-type Explicit Finite Volume Method (so-called DOT, Dumbser–Osher–Toro, Riemann solver (Dumbser and Toro, 2011b, a)) and the Semi-Implicit Staggered Finite Volume Method (further simply called SI) presented by Dumbser et al. (2015) with two water hammer problems in single HDPE pipelines. Then we compare the results, in terms of accuracy and efficiency, to those obtained with the classical MOC. It has to be mentioned that the DOT solver had never been used before for this type of applications, only for frequency analysis in Leibinger et al. (2016), while the SI method had already been tested with hydraulic transients, but only considering an elastic tube-wall behaviour (Ioriatti et al., 2017). In the present research, water hammer test cases are carried out taking into account different linear visco-elastic rheological models: the Standard Linear Solid Model (SLSM) and the generalized Kelvin–Voigt (KV) chain, with the aim to evaluate if a more complex model is worth to be chosen for achieving a better agreement with experimental data. To the authors' knowledge, this work is the first one extending the applicability of the generalized Kelvin–Voigt model both to the Explicit and the Semi-Implicit numerical schemes. Furthermore, we made a comparison of the results obtained implementing a quasi-steady friction model and an unsteady friction model, with the approach proposed by Ioriatti et al. (2017), applied in case of turbulent flow for the first time in literature. To stress more these numerical schemes to reveal their weaknesses, tests have been executed also with three demanding Riemann problems, i.e. initial value problems governed by conservation laws with piece-wise constant initial data having a single discontinuity (Toro, 2009), adopting an elastic rheological behaviour of the tube wall. The aim of the Riemann problems here presented is to evaluate the robustness of each scheme, pointing out the performance of every method in case of cross-sectional changes, when more flexible materials are considered and when cavitation occurs.

The paper is structured as follows: in Section 2 the mathematical model is presented, with the specific characterization made for each numerical scheme and for each constitutive tube law and friction model chosen. In Section 3 the three numerical models, MOC, DOT and SI, are described. Section 4 is entirely dedicated to the analysis of the relevance of the unsteady friction effects and to the validation of the ODE Model, for the first time applied for turbulent flow cases. In Section 5 the procedure followed for the calibration of the visco-elastic parameters is briefly illustrated. All the numerical results are presented and discussed in Section 6. Finally, in Section 7, some comments about the novel comparison of the numerical schemes and their modelling are reported, taking into account the numerical results.