Controlling of Steel-Pipe-Based Hydraulic Systems Using Dual In-Series Polymeric Short-Sections

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Abstract. The in-series design measure, also known as the inline measure, was identified as being an efficient alternative water-hammer control tool into existing steel pipes-based hydraulic systems. Specifically, this design tool attenuated markedly the extent of pressure-wave surges. However, further evaluation revealed that such a measure was limited by an expansion effect of the period value of pressure-wave oscillations. Alternatively, this work addressed a dual-technique–based in-series control measure, in order to address the foregoing drawback of the conventional-technique-based in-series measure. Basically, the reported technique was devised upon the splitting of the single in-series section, used in the conventional technique, into two subsections placed upstream each of the steel-pipe connections to the hydraulic system parts. The one-dimensional unconventional water-hammer model, including the Vitkovsky and Kelvin-Voigt formulations, was discretized using the Method of Characteristics, for numerical solution. Application assessed the efficiency of the dual technique for a reservoir-pipe-valve system. Two plastic material types were demonstrated in this study and including high- and low-density polyethylene (HDPE and LDPE). Results evidenced that the dual technique devised upon an (HDPE-steel-LDPE) configuration provided the best compromise between the attenuation and expansion effects of pressure-wave oscillations. It was also found that the last two effects are sensitive to the employed dual in-series sections.

Keywords: Design · Dual · In-series · HDPE · Kelvin-Voigt · LDPE · Viscoelasticity · Vitkovsky · Water-hammer

1 Introduction

The control of water-hammer surges is a challenging issue pertaining to the design of urban water distribution and industrial hydraulic systems. If this phenomenon was not properly considered, the hydraulic installation may experience service disruption and/or unsafe operations for operators. These surges also referred to as flow shocks,

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induce a series of positive and negative pressure-waves, which may cause, in specific cases, significant damage to the piping system (e.g.: pipe-wall stretch or collapse) and hydraulic devices; and even risks to operators (Chen et al. 2015).

In order to attenuate the extent of these pressure-wave surges, the designers resort to the change of the piping system layout and/or operating procedure parameters, or the installation of surge protection devices (such as pressurized vessels or air-relief valves) (Fig. 1).

Conjointly, the use of plastic materials such as polyethylene has recently increased in hydraulic system networks. These plastic material types are distinguished by their ability to dampen high-pressure load in addition to their flexibility and great resistance to aggressive agents. Physically, this dampening effect is attributed to the mechanical behavior of plastic materials; which is characterized by temperature, time, and pressure gradient dependent deformations. In other words, these materials exhibit a viscous response to pressure-load; in addition to the elastic one, involved in steel materials (Brinson and Brinson 2008). This effect is quite interesting to dissipate gradually the energy caused by pressure-load. Basing on the aforementioned merits of plastic materials, several studies investigated the usefulness of substituting a short-section of existing steel-pipe–based hydraulic systems by another one made of plastic material, in order to improve the capacity level of these hydraulic systems (Triki 2016, 2017, 2018a, b; Ben Iffa and Triki 2019; Trabelsi and Triki 2019, 2020a, b, c; Triki and Fersi 2018; Fersi and Triki 2019a, b, 2020; Triki and Chaker 2019; Chaker and Triki 2020a, b, c, d). In these studies, the authors utilized High- and Low-Density PolyEthylene (HDPE and LDPE) materials for the replaced in-series short-section. These studies highlighted that such plastic materials types helped attenuation of excessive magnitudes of the initiated positive or negative pressure-wave. Although these studies delineated the benefit from such a handling technique of the piping system, hereinafter referred to as in-series design measure, it should be emphasized that the use of in-series plastic section leads to the expansion of pressure-wave oscillation period. Consequently, this design tool may cause an important increase in the duration of operational procedures (such as the critical time value of valve closure setting).

(a) **(b)**

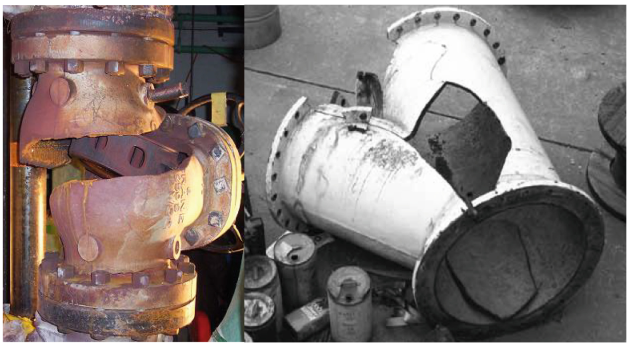

Fig. 1. Illustration of ruptured (a)- check valve; (b)- Cast Iron Strainer (Wayne F. Kirsner Steam Accidents & Forensic Investigations).

Accordingly, it is interesting to re-examine the conventional technique of implementation of the in-series design measure according to the two foregoing effects. Alternatively, we planned in this paper to address a dual technique–based in-series design measure; which is based on the splitting of the single in-series section, used in the conventional technique, into two subsections placed upstream each of the steel-pipe connections to the hydraulic system parts. Such a technique is expected to limit the expansion of the wave-oscillation period involved in the controlled system case based upon the conventional technique; while safeguarding acceptable attenuation of pressure-wave magnitude. Special analyses are reported on the compromise between the two aforementioned effects.

In the following, the method of characteristics (MOC) procedure used for discretizing the extended one-dimensional water-hammer Eqs. (1-D E-WH Eqs) based upon the Vitkovsky et al. and Kelvin-Voigt formulation, is briefly outlined.

2 Theory and Calculations

Referring to Triki (2018a, b), the (1-D) extended water-hammer model incorporating the Vitkovsky et al. and Kelvin-Voigt formulations is given by:

$$\frac{\partial H}{\partial t} + \frac{a_0^2}{gA}\frac{\partial Q}{\partial x} + 2\frac{a_0^2}{g}\frac{d\varepsilon_r}{dt} = 0 \text{ and } \frac{1}{A}\frac{\partial Q}{\partial t} + g\frac{\partial H}{\partial x} + g\left(h_{f_s} + h_{f_u}\right) = 0 \quad (1)$$

wherein, H designates the pressure-head; Q denotes the flow-rate; A is the area of the pipe cross-section; g stands for the acceleration due to gravity; a_0 refers to wave-speed; h_{f_s} corresponds to pressure-head losses; $h_{f_u} = \left(k_v / gA\right)\left(+a_0\, Sgn(Q)\left|\partial Q / \partial x\right|\right)h_{f_u}$ accounts for unsteady friction losses, evaluated according to Vitkovsky, in which, $k_v = 0.004$ designates the Vitkovsky et al. (2000) decay coefficient; ε_r designates the retarded radial-strain of the pipe-wall; and x and t: axial and time coordinates, respectively.

Incidentally, the retarded radial-strain of the pipe-wall may be evaluated according to the generalized Kelvin-Voigt linear-viscoelastic mechanical model sketched in Fig. 2 (Aklonis et al. 2006):

$$J(t) = J_0 + \sum_{k=1}^{n_{kv}} J_k\left(1 - e^{-t/\tau_k}\right) \quad (2)$$

wherein, $J_k = 1/E_k$ and $\tau_k = \mu_k/E_k$ $(k = 0 \cdots n_{kv})$ are associated with creep compliance of the spring and the retardation time of the dashpot, respectively; E_k and μ_k $(k = 1 \cdots n_{kv})$ are the modulus of elasticity of the spring and viscosity of the dashpot of the k^{th} Kelvin-Voigt element, respectively, n_{kv} designates the number of Kelvin-Voigt elements.

The numerical solution of the set of Eqs. (1) using the Method Of Characteristics (MOC) leads to (Triki 2018a, b; Trabelsi and Triki 2019, 2020a, b, c):

$$Q_{i,t}^j = c_p^j \mp c_{a\mp}^j H_{i,t}^j \text{ along } \mathbf{C}^{\pm} : \frac{\Delta x^j}{\Delta t} = \pm\frac{a_0^j}{c_r^j} \quad (3)$$

in which, j: pipe number (np: number of pipes $1 \leq j \leq np$); Δt: time-step increment; c_r: Courant number;n_s^j: number of sections of the j^{th} pipe ($1 \leq i \leq n_s^j$);

$$c_p^j = \left(Q_{i-1,t-1}^j + \left(1/B^j\right)H_{i-1,t-\Delta t}^j + c_{p1}^{\prime\prime j} + c_{p1}^{\prime\prime\prime j}\right)/\left(1 + c_p^{\prime j} + c_{p2}^{\prime\prime j} + c_{p2}^{\prime\prime\prime j}\right) \quad ; \quad B = a_0/(gA) \quad ;$$
$$c_n^j = \left(Q_{i+1,t-1}^j + \left(1/B^j\right)H_{i+1,t-\Delta t}^j + c_{n1}^{\prime\prime} + c_{n1}^{\prime\prime\prime}\right)/\left(1 + c_n^{\prime j} + c_{n2}^{\prime\prime j}\right) \quad ;$$
$$c_{a+}^j = 1 + c_{p2}^{\prime\prime\prime j}/\left(B^j\left(1 + c_{p2}^{\prime j} + c_{p2}^{\prime\prime j}\right)\right) \quad ; \quad c_p^{\prime j} = R^j \Delta t\left|Q_{i-1,t-1}^j\right| \quad ; \quad c_n^{\prime j} = R^j \Delta t\left|Q_{i+1,t-1}^j\right| \quad ;$$
$$c_{p_1}^{\prime\prime j} = k_v \theta Q_{i,t-1}^j - k_v(1-\theta)\left(Q_{i-1,t-1}^j - Q_{i-1,t-2}^j\right) - k_v \mathbf{sgn}\left(q_{i-1,t-1}^j\right)\left(Q_{i,t-1}^j - Q_{i-1,t-1}^j\right) \quad ;$$
$$c_{n_1}^{\prime\prime j} = k_v \theta Q_{i,t-1}^j - k_v(1-\theta)\left(Q_{i+1,t-1}^j - Q_{i+1,t-2}^j\right) - k_v \mathbf{sgn}\left(q_{i+1,t-1}^j\right)\left(Q_{i,t-1}^j - Q_{i+1,t-1}^j\right) \quad ;$$
$$c_{p1}^{\prime\prime\prime j} = -c_{n1}^{\prime\prime\prime j} = -2a_0^j A^j \Delta t \sum_{k=1}^{n_{kv}}\left[\varepsilon_{rk}^j(x,t)/\partial t\right] \quad ; \quad c_{p2}^{\prime\prime\prime j} = c_{n2}^{\prime\prime\prime j} = 2a_0^j A^j c_0 \gamma \sum_{k=1}^{n_{kv}} J_k^j\left(1 - e^{-(\Delta t/\tau_k)}\right) \quad ;$$
$$\varepsilon_{rk,i,t-\Delta t}^j = J_k^j c_0\left\{\left[H_{i,t-\Delta t}^j - H_{i,0}^j\right] - e^{-(\Delta t/\tau_k)}\left[H_{i,t-2\Delta t}^j - H_{i,0}^j\right] - \tau_k\left(1 - e^{-(\Delta t/\tau_k)}\right)\left[H_{i,t-\Delta t}^j - H_{i,t-2\Delta t}^j\right]/\Delta t\right\} + e^{-(\Delta t/\tau_k)}\varepsilon_{rk,i,t-2\Delta t}$$

; $R^j = f^j/2D^jA^j$; $c_0 = \alpha\gamma D^j/2e^j$; and $c_{p2}^{\prime\prime j} = c_{n2}^{\prime\prime j} = k_v\theta$ (wherein, $\theta = 1$ is a relaxation parameter).

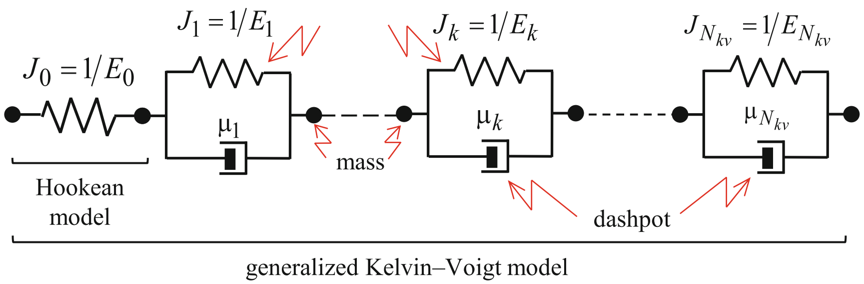

Fig. 2. Sketch of the generalized Kelvin-Voigt model.

For an in-series connection of multi-pipes, common flow-rate and pressure-head values are assumed (Wylie and Streeter 1993; Triki 2016; Ben Iffa and Triki 2019; Trabelsi and Triki 2019, 2020a, b, c):

$$Q_{x=L}^{j-1} = Q_{x=0}^j \text{ and } H_{x=L}^{j-1} = H_{x=0}^j \tag{4}$$

The next section is devoted to exploring the effectiveness of the dual technique-based in-series control measure within upsurge initiated water-hammer waves framework.

3 Case Study

Test case corresponds to a reservoir steel-pipe valve system. The specifications of the steel piping system are: $L = 143.7$ m; $D = 50.6$ mm; $a_0 = 1369.7$ m/s; $e = 3.35$ mm;

and $J_0 = 0.0049$ GPa^{-1}. Initially, the steady-state flow regime corresponds to the values of discharge and pressure-head, at the valve located downstream extremity, equal to: $Q_0 = 0.58\,\mathrm{l}/\mathrm{s}$ and $H_{0|valve} = 45$ m, respectively. The transient regime relates to the abrupt switch-off of the downstream valve; jointly with a constant value condition, set for the water level in the upstream reservoir. Such a scenario may be coded as:

$$Q^{t \succ 0}_{|x=L} = 0 \text{ and } H^{t \succ 0}_{|x=0} = H_{0|\mathrm{reservoir}} \tag{5}$$

In this case, the implementation of the dual technique- based in-series design measure is based on the substitution of an upstream and down-stream in-series subsections of the original steel piping system by other ones build of (HDPE) or (LDPE) plastic materials (Fig. 3). According to Keramat and Haghighi (2014), the coefficients of the linear-viscoelastic model of these materials are: $\{J_k[\mathrm{GPa}^{-1}]\,;\,\tau_k[\mathrm{s}]\}^{\mathrm{HDPE}}_{k=0-5} = \{0.8032;\,-/1.057;\,0.05/1.054;\,0.5/0.905;\,1.5/0.262;\,5/0.746;\,10\}$; or $\{J_k[\mathrm{GPa}^{-1}];\,\tau_k[\mathrm{s}]\}^{\mathrm{LDPE}}_{k=0-3} = \{2.083;\,-/7.54;\,0.00089/10.46;\,0.022/12.37;\,1.864\}$, respectively.

Firstly, the length and diameter values of employed sub-short-sections are equal to: $l^{\mathrm{dual}}_{\mathrm{sub\ short-section}} = 2.5$ m and $d^{\mathrm{dual}}_{\mathrm{sub\ short-section}} = 50.6$ mm, respectively.

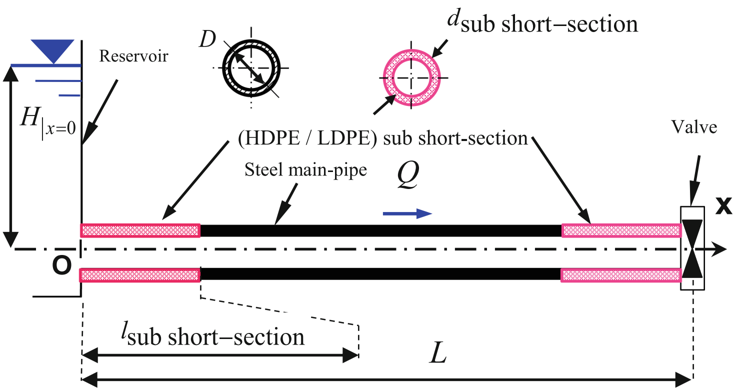

Fig. 3. Definition sketch of the controlled system using the in-series design measure based upon the dual-technique.

Incidentally, the results associated with the conventional technique-based in-series design measure are also addressed, in the following, in order to compare the capacities of the different control techniques. Consequently, for the consistency of comparison, the same plastic material volume is utilized in each technique of implementation of the in-series design measure. In other words, the diameter and length values of the short-section, utilized in the in-series control measure based upon the conventional technique, are equal to: $l^{\mathrm{conventional}}_{\mathrm{short-section}} = 5$ m and $d^{\mathrm{conventional}}_{\mathrm{short-section}} = 50.6$ mm, respectively.

Figure 4 compares the downstream pressure-head associated with the original hydraulic system case, and its counterpart estimated into the controlled system cases based upon the dual or conventional technique of the in-series design measure. Jointly, Table 1 summarizes the main features of pressure-wave traces shown in Fig. 4.

The general trend of the wave curves plotted in Fig. 4 illustrates magnitude attenuation and period expansion of pressure-wave oscillations. In order to address comprehensively the relationship between the two foregoing effects, the magnitude values of positive- and negative surge according to the period value of pressure-wave oscillation are traced in Fig. 5 for the hydraulic systems with and without using the control techniques.

Figures 4 and 5 infer that the dual technique configurations involving an (HDPE-steel-LDPE) or (LDPE-steel-LDPE) in-series connections, illustrate remarkable attenuation of pressure-surge magnitude, as compared with the original system case. In particular, the values of positive-surge magnitudes, involved in the foregoing controlled system cases, are: $\Delta H_{up-surge}^{HDPE-steel-LDPE} = 30.4$ m or $\Delta H_{up-surge}^{LDPE-steel-LDPE} = 30.1$ m, respectively; while the corresponding value estimated in the original system case is equal to: $\Delta H_{up-surge}^{steel-pipe} = 40.6$ m.

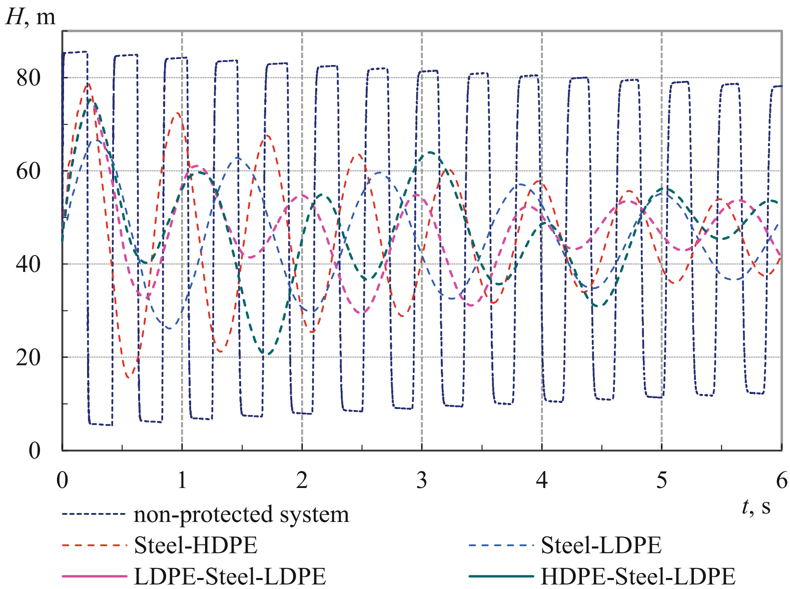

Fig. 4. Pressure-wave time histories in the original and control hydraulic system cases.

Table 1. Main features of pressure-wave signals in Fig. 2.

Parameters:		Original system	(Sub) short-section configurations of the controlled systems			
			HDPE	LDPE	LDPE-LDPE	HDPE-LDPE
H_{max}	(m)	85.6	79.0	66.6	75.1	75.4
H_{min}	(m)	5.4	15.5	26.1	29.5	20.6
T_1	(s)	0.42	0.756	1.18	0.918	0.876

Besides, Figs. 4 and 5 display significant expansion of pressure-wave oscillation period, in the cases involved in the dual- or conventional- technique–based in-series design measure. In particular, the phase-shifts depicted between the pressure-wave signals involved in an (HDPE-steel-LDPE) or (LDPE-steel-LDPE) configuration of the dual-technique and their counterparts involved into original system case are equal to: $T_1^{HDPE-steel-LDPE} - T_1^{steel} = 0.498$ s or $T_1^{LDPE-steel-LDPE} - T_1^{steel} = 0.456$ s, respectively.

Similarly, but less important phase-shifts are induced by the aforementioned configurations of the dual-technique as compared with the (steel-HDPE) configuration of the conventional technique-based in-series design measure: $T_1^{HDPE-steel-LDPE} - T_1^{steel-HDPE} = 0.12$ s or $T_1^{LDPE-steel-LDPE} - T_1^{steel-HDPE} = 0.162$ s. Contrarily, the (HDPE-steel-LDPE) or (LDPE-steel-LDPE) configurations of the dual-technique induce more important spreading of wave oscillation period as compared with the conventional one based on (steel-LDPE) configuration: $T_1^{HDPE-steel-LDPE} - T_1^{steel-LDPE} = 0.304$s or $T_1^{LDPE-steel-LDPE} - T_1^{steel-LDPE} = 0.262$ s, respectively.

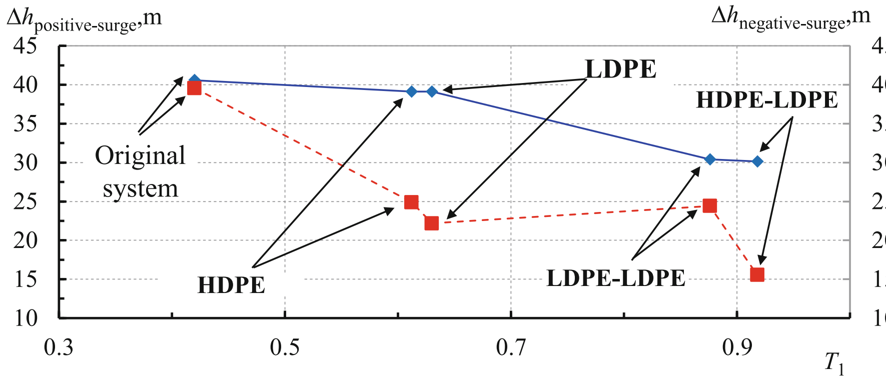

Fig. 5. Variations of up- and down-surge amplitudes as a function of the period, for the first cycle of pressure-wave oscillation.

Basing on the preceding discussion, the (LDPE-steel-LDPE) configuration of the dual technique may be considered as the best configuration; providing a satisfactory compromise between surge attenuation and period spreading of pressure-wave oscillations.

The variations of the first pressure-head peak depending on the diameter and length of utilized in-series LDPE sub-short-sections are illustrated in Figs. 6- a and-b, respectively.

Basing on these curves slopes, it obvious that the first pressure-head values are significantly attenuated when increasing the length of the downstream in-series sub-short-section for the range values within: $1 \le l_{\text{sub short-section}}^{\text{downstream}} \le 2.5$ m; however, no remarkable effects are depicted for the variation of the upstream in-series sub-short-section length and diameter values. In addition, this figure suggests that the first pressure-head values are significantly attenuated when increasing the diameter value of the downstream in-series sub-short-section from 25 mm to the original value (i.e.: 50.6 mm); whereas, no

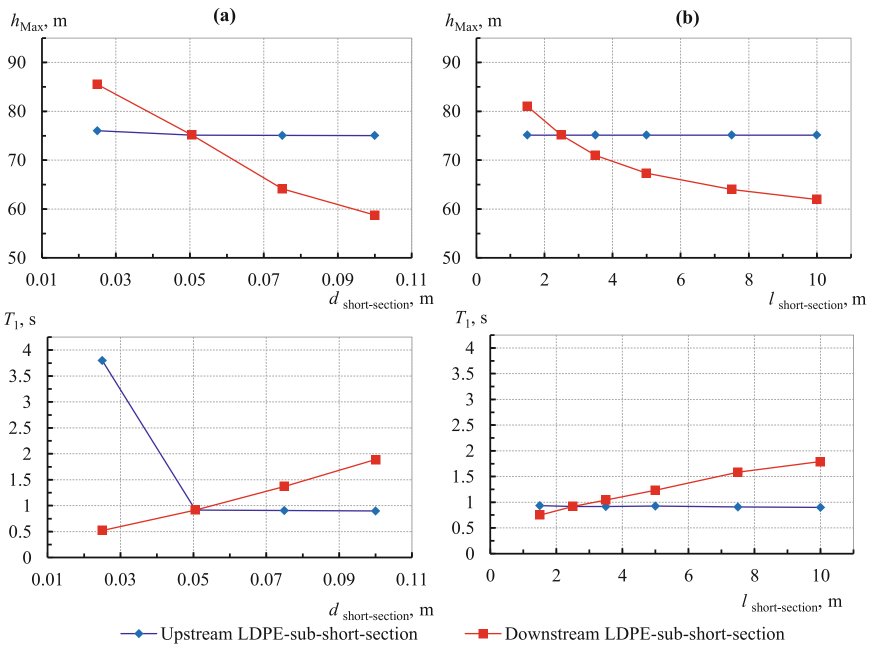

Fig. 6. Dependencies of the first peak and period values, for the 1st cycle of pressure-wave oscillations on the utilized up- and down-stream sub-short-sections: (a)- diameter (for $l_{sub-short-section} = 2.5\,\text{m}$), (b)- length (for $d_{sub-short-section} = 50.6\,\text{mm}$).

remarkable attenuations are depicted for the variation of the length and diameter values of the upstream in-series sub-short-section.

Similar conclusions may be addressed for the period value of pressure-wave oscillations.

4 Conclusion

Overall, this investigation evidenced that the dual technique-based in-series design measure could improve the conventional technique-based one; with regards to the attenuation of surge-magnitude and limitation of period-expansion criteria of pressure-wave oscillations. On this point, the specific configuration of the dual-technique based upon an upstream and downstream in-series LDPE sub-short-section presented a satisfactory compromise between the aforementioned two criteria. Additionally, the examination of the sensitivity of the first pressure-wave peak value according to the dimension of the utilized in-series plastic sub-short-sections, suggests that the pressure surge attenuation increases as the downstream in-series sub-short-section volume increases. Nonetheless, this relationship is not remarkable beyond the primitive diameter and length values of the utilized sub-short-section.

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