# Transient Movement in a Single Looped Water Distribution Network. Pressure Simulation and Experimental Measurement

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*Abstract:* - Transient movement results as a hydraulic system response to sudden valve manoeuvres in a water supply network. Investigation on pressure variation was carried out on a representative loop of a pipe network. Both numerical simulation and experimental laboratory measurements were developed in order to validate the software *Hammer* for looped networks. Theoretical and experimental results reveal the same extreme pressure values, but the recorded oscillations have a lower frequency and an increased damping ratio than the simulated ones.

*Key-Words:* - Hydraulics, Water Distribution Network, Water Hammer, Pressure

## 1 Introduction

Looped pipe configuration is preferred in urban water distribution networks for its reliability [6]. Consumers, placed in the nodes of the network have no regular demand pattern. Any manoeuvre of a valve on the network may be a source of disturbance, generating transient movement along the pipes. Pressure variation might be considerable as the manoeuvres are fast. Valves operation pattern might influence the extreme pressure values reached during a hydraulic shock.

The identification of the most vulnerable consumers, in terms of pressure variation, as early as the engineering design phase, is of great interest for the hydraulic engineers. Numerical simulation is a useful tool for pointing out the extreme pressure variation over time in a specified section of a pipe. Our goal was to investigate if *Hammer*, an automate programme special conceived for hydraulic shock simulation, is reliable in the case of looped networks.

## 2 Transient Movement Analysis in a Looped Network

Investigations on pressure variation over time, in the nodes of a looped network were performed both by:

- numerical simulation;
- experimental measurement.

The pressure oscillation graphs are analyzed in order to find out if the extreme values resulted by numerical simulation cover the ones registered by the transducers; the damping ratio and oscillation frequency are compared, aiming to see how accurate the automate programme is.

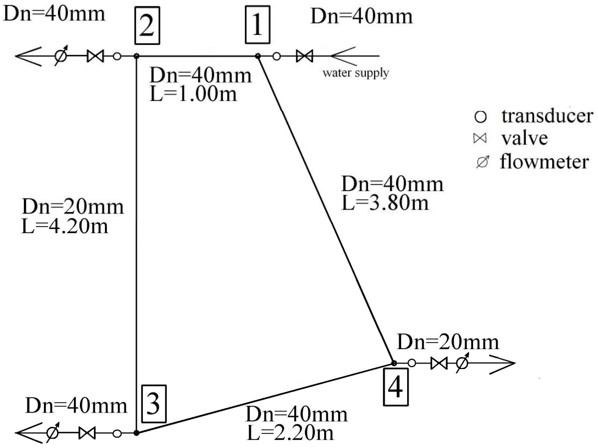

Fig.1 Geometry of the studied single loop network

The single loop network used for simulation and subjected to laboratory experimental measurements is represented in Fig.1. The considered loop is similar from hydraulic view point to a real single loop network. The system is supplied by a reservoir with constant water level of 2m. Each node is equipped with a ball valve that can be opened at different opening angles. The source is placed in node 1. The valves in nodes 2, 3 and 4 are the water consumers. The looped network lies in the same horizontal plane. All the four sides of the loop are HDPE pipes.

In Table 1 there are given the values of the flow rate in the nodes and through the pipes of the loop, in the case of steady state water movement.

Table 1. Flow rate values in steady state water movement, [l/s]

| ***Nodes*** | | | |
|---|---|---|---|
| *1* | *2* | *3* | *4* |
| 0.449 | 0.235 | 0.182 | 0.0321 |
| ***Pipes*** | | | |
| *1-2* | *2-3* | *3-4* | *1-4* |
| 0.255 | 0.020 | 0.162 | 0.194 |

It is investigated the dynamic response of the hydraulic system to the following operation scenario: all the three valves in the consumers nodes 2, 3 and 4 are completely open. Previous calibration of the network showed that the steady state movement is reached after only 2 seconds from the valve opening. After 5 seconds of operation, the valves in node 2 is suddenly closed and after other 5 seconds valves in nodes 3 and 4 are simultaneously and sudden closed. It is only one among the numerous scenarios that could be taken into account with respect to the possibility of operation and consumption in nodes.

### 2.1 Pressure Variation Numerical Simulation

Hammer programme was developed for solving hydraulic shock problems in water branched pipe networks. The programme was adapted to looped networks by the use of fictive nodes that turn a linear system into a looped network.

The mathematical model of the water hammer phenomenon is composed of two main equations: momentum and mass balance equations. They may be transformed and written in finite differences [5], as the velocity (1) and the head (2) equations:

$$v_{i,i+1} = \frac{1}{2}\left[v_{j-1,1} + v_{j+1,i} + \frac{g}{c}\left(H_{j-1,1} - H_{j+1,i}\right) - \frac{\lambda\Delta t}{2D}\left(v_{j-1,1}\left|v_{j-1,1}\right| + v_{j+1,1}\left|v_{j+1,1}\right|\right)\right] \quad (1)$$

$$H_{i,i+1} = \frac{1}{2}\left[H_{j-1,1} + H_{j+1,i} + \frac{c}{g}\left(v_{j-1,1} - v_{j+1,i}\right) - \frac{c\lambda\Delta t}{2gD}\left(v_{j-1,1}\left|v_{j-1,1}\right| + v_{j+1,1}\left|v_{j+1,1}\right|\right)\right] \quad (2)$$

where: index *i* accounts for time, index *j* accounts for node, *v*-velocity, [m/s]; *H*-head, [m]; *c*-celerity, [m/s]; $\Delta t$-step of time, [s]; $D$-pipe's diameter, $[m]$; $\lambda$-Darcy's coefficient; g-gravity acceleration.

The programme uses the method of characteristics for solving water hammer problems, considering one dimension movement of water [4]. The wave celerity is constant along the pipes.

The initial pressure and velocity conditions correspond to the steady state movement of water in the loop. The boundary conditions are implemented according to the above mentioned operation scenario.

Pressure as a time dependant function is graphically represented for each node of the loop.

### 2.2 Pressure Variation Experimental Measurement

The laboratory stand allows accurate and real-time display (graphical and / or tabular) of physical quantities collected from transducers mounted in the network nodes. Each node of the loop is equipped with a MBS 33 pressure transducer that provides a reliable pressure measurement.

The flexible sensor covers an output signal in the range of 4 ÷ 20 mA and a gap measuring pressure from 0 ÷ 1 bar to 0 ÷ 600 bar at operating temperatures of -40 ÷ +85$^{o}$ C. The pressure transducer MBS 33 has a very good vibration stability and a robust construction. Collected data are processed in LabVIEW programming environment;

The valves in the looped network are operated in accordance with the pre-established scenario. Once again, pressure as a time dependant function is graphically represented for each node of the loop.

## 3 Results

The collected data allows us to represent, on the same diagram, pressure variation over time in each node, in both cases: numerical simulation and experimental measurement. This superposition makes it easier to compare the two evolutions of pressure in the hydraulic system.

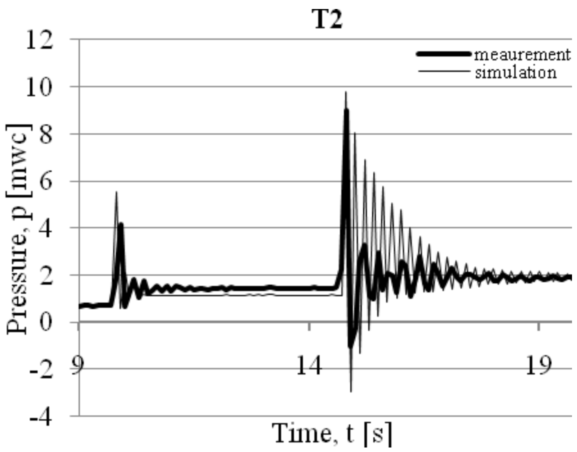

Fig.2.Pressure variation in node 2

In Fig.2 there is represented the pressure variation in the node 2, the closest to the input node 1, and also the node with the greatest withdrawal. Hammer programme indicates extreme pressure values that cover the extreme pressure values recorded by the measure system. But, we may notice that the absolute value of minimal pressure indicated by the numerical simulation is about 30% greater than the measured one.

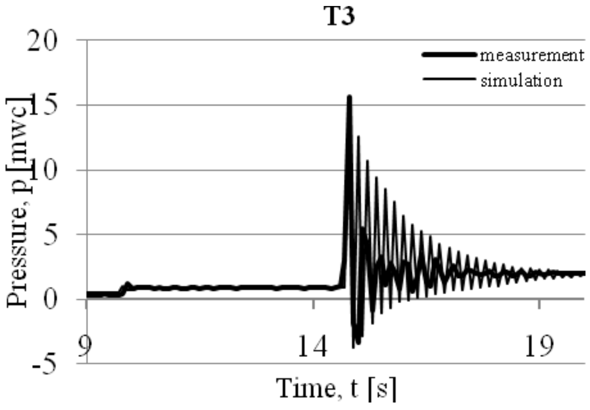

Fig.3.Pressure variation in node 3

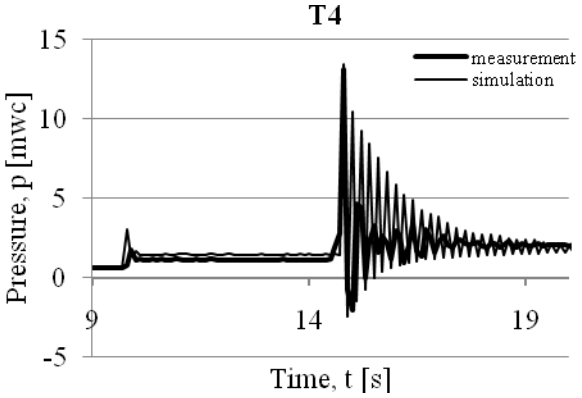

Fig.4.Pressure variation in node 4

The graphs in Fig. 3 and Fig.4 indicate that the extreme pressure values in the nodes 3 and 4 are very well estimated by the automate programme.

The Hammer programme shows the under damped oscillation of pressure in the hydraulic system and calculates with good accuracy the amplitude of the first oscillation. But the pattern of decaying oscillation differs. The envelope of the wave form is represented as a function of time in Fig.5,6 and 7, for the three consumer nodes. In each node, the envelope of the simulated oscillation is of exponential form, but the envelope of the measured one is better approximated by a polynomial of order 3. The real oscillation proves to be amplitude modulated.

The logarithmic decrement, $D$, is given by the relationship:

$$D = \ln \frac{p_{\max\ i}}{p_{\max\ i+1}} \tag{3}$$

where $p_{\max i}, p_{\max i+1}$ maximal pressures at two consecutive oscillations, at the moments $t_i, t_{i+1}$.

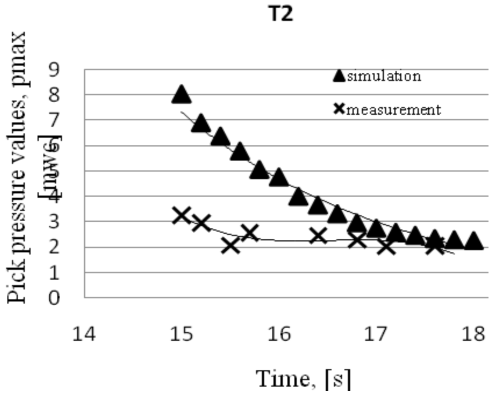

Fig.5.Oscillation envelope, in node 2

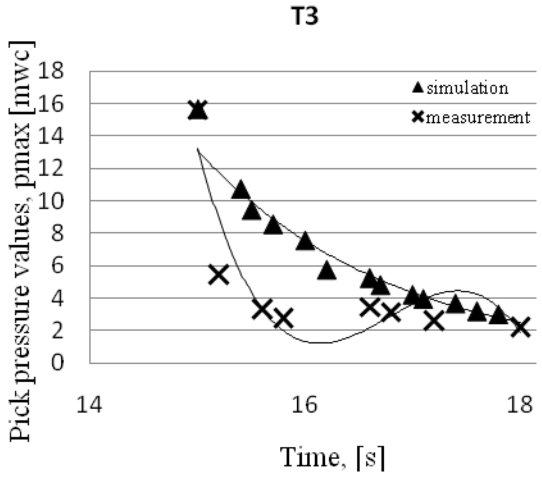

Fig.6. Oscillation envelope, in node 3

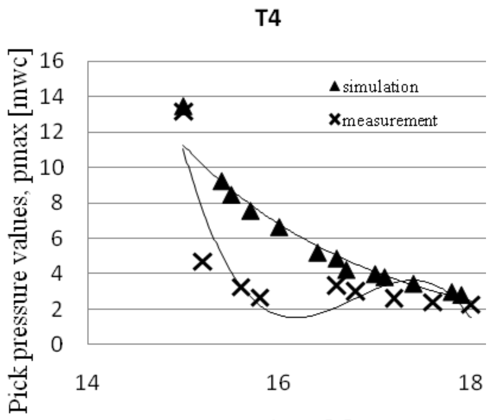

Fig.7. Oscillation envelope, in node 4

In the case of under damped oscillation, the damping ratio is related to the logarithmic decrement by the relationship:

$$\delta = \frac{D}{\sqrt{D^2 + 4\pi^2}} \qquad (4)$$

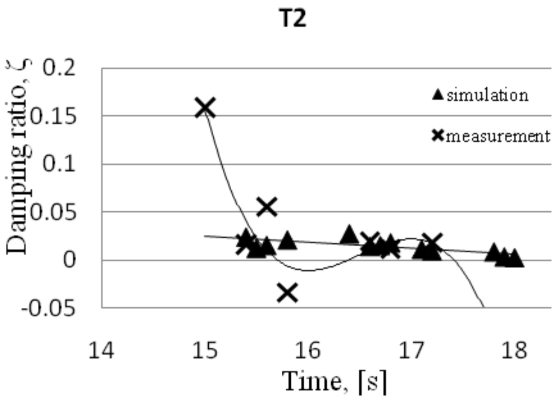

Fig.8.Damping ratio variation in node 2

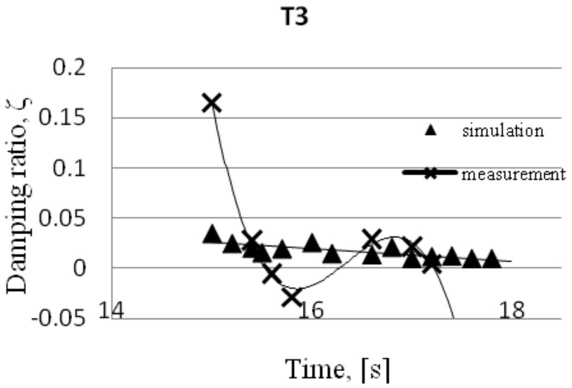

Fig.9.Damping ratio variation in node 3

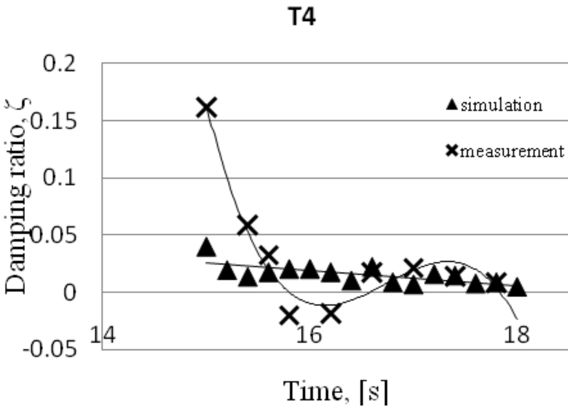

Fig.10.Damping ratio variation in node 4

The graphical representation of the damping ratio, in each node, is given in Fig.8, 9 and 10. The damping ratio is $\delta < 1$ and it takes small values, revealing a slow damping of the oscillation [2].
This is a main consequence of the small friction coefficient of the HDPE pipes [7]. Simulated oscillation exhibits even a smaller damping ratio than the real one.

The natural frequency of pressure simulated oscillation is 5.12 Hz, instead the real one of 3.125 Hz.

## 4 Conclusion

Hammer programme calculates with accuracy the maximal amplitude of pressure variation in the hydraulic system that means the amplitude of the first oscillation. Taking into account that extreme pressure values dictate the pipes size, we may say that this programme is an useful tool in the engineering design.

The simulation reveals the most vulnerable consumer, the one exposed to the extreme pressures in the network.

The disadvantage consists of a poor evaluation of the damping ratio. The real oscillation decays faster than the simulated one. Furthermore, being derived from a variant dedicated to branched networks, the programme doesn't take into account the waves reflected in the nodes. This may be the cause for the amplitude modulated shape of the real oscillation.

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