Regular Article

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Water hammer phenomenon in pumping stations: A stability investigation based on root locus

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Abstract: In this article, a numerical model based on site theory is developed to study the stability of a pipeline system consisting of a valve, pipe, and surge tank. In the study, four parameters were studied to see how they impact the water hammer phenomenon. They are the pressure in the pipelines, the velocity of the flow, diameter of the conduit carrying liquid, and the liquid's density. The equations are programmed, analyzed, and graphed using MATLAB. The stability analysis shows that the force of the water hammer is significant at low frequencies and for large diameters. The high frequency of a particular pipe is affected by the type of material the pipe is made from, the method of installation, and the friction coefficient of the inner surface. High frequencies reduce the impact of water hammer forces. Among the main parameters listed, it is found that the oscillations of liquids of low density are higher in the case of water hammers.

Keywords: water hammer, hydraulic transient, sudden closing of the valves, pipe conveying fluid

1 Introduction

When the discharge suddenly changes, such as when one of the valves on the pipeline carrying liquids is closed or a power outage occurs, the condition of the water hammer (hydraulic transient) materializes. This occurs quickly and causes catastrophic damage to the closed duct system and hydraulic pumping equipment due to the high-pressure change. Considering the importance of maintaining stable hydraulic systems, researchers have studied this phenomenon for decades. By analyzing and studying these hydraulic systems, they were able to determine the amount of pressure changes due to changes in flow and thus set instructions regarding control and operating methods to protect the hydraulic system from collapse. Obtaining an analytical solution to nonlinear governing equations with the translational flow can be difficult. Thus, numerical models of water hammers are used to calculate this phenomenon in most studies. The model must be able to accurately predict the phenomenon of water hammer or transitional flow so that the designer or engineer can evaluate alternative solutions in controlling hydraulic systems with high pressures. Engineers should explore transition hydraulics to be able to simulate real-world conditions that prevent system failure [1,2].

Many researchers in those areas have examined the effect of different flow parameters on the water hammer phenomenon by using various techniques and have calculated various parameters. Weinerowska and Kodura [3] studied the results of water hammer when operating in closed channels. They investigated different pipe diameters, different conditions, leaks in the pipeline, and in another case, no leaks in the pipeline. They found that the maximum pressure generated would not necessarily be the first amplitude. Zukowski's formula for increasing the diameter gives a theoretical value for the pressure that is often below the maximum value. However, the pressure value was found to be the value of the first amplitude to reduce the tube diameter, which can be compared with Zukowski's theoretical formula.

Mansuri et al. [4] used the MATLAB program to simulate water hammers and the numerical method, as this numerical method depends on the characteristic method. They found that the range of fluctuation will be small with an increase in the diameter of the tube, meaning that the range of pressure fluctuation will obviously decrease with the increase in wave transmission when using a short tube. They found that when the velocity

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of the wave increased, the pressure band would decrease in a clear way, and they concluded that the ends of the tube have the minimum pressure and the maximum pressure, and therefore the critical point in the designs is at the ends of the fluid conveying lines. Chen et al. [5] developed a mathematical model that mitigates the phenomenon of the water hammer when a pump is cut off or when the valve is suddenly closed by including partial nonlinear differential equations that describe the flow along the tube. This method combines the method of estimating partial differential equations of the flow with the method of estimating and controlling the limits of the fluctuation range. The simulation results showed an excellent ability to reduce water hammer, and these results showed great ability to decrease flow fluctuation.

Behroozi and Vaghefi [6] simulates the water hammer phenomenon in a pipeline system consisting of a valve, pipe, and surge tank. The model is used to reduce computational costs and increase accuracy. By using Local Multiquadric Based Differential Quadrature and Crank-Nicholson schemes, the spatial and temporal derivatives of water hammers are implicitly discretized. The water hammer's equations are discretized into matroids and solved by applying boundary and initial conditions. It has been found that the accuracy of the model is dependent on the Courant number. Even so, the model holds its stability better in Courant numbers than one. A model is proposed, and two cases are tested to verify it. According to the comparison between obtained results and experimental data reported, the proposed method is in good agreement with the experimental observations. El-Jumaily et al. [7] were among the first to examine the effect of water hammers on the water pipeline in Iraq. He studied water hammers in the Kufa water project in the Najaf governorate, where he used four parallel pipes. He then programed the equations and simulated them in the MATLAB program, taking each pipe as it is in studying this phenomenon, then studying the four pipes at a standard flow, shut off valves suddenly, determining the proper pressure for each case, and recommending operations for that station.

Gubashi and Kubba [8] studied the water hammer using an approximate method using equations of transitional flow and applied it to a pipeline that carries raw water from the drawing station to the payment station for an actual project to pump water to citizens. In summary, the method is intended to simulate the effect of a water hammer by closing the valves along the pipeline from the starting line to the end, where the computer software showed that the minimum and maximum amount of oscillation occurred in a specific controlled place, which is very close to an experimental environment.

In this research, a model for water hammer simulation is presented. With the help of root locus theory, pipelines used in water pumping stations to deliver water to citizens have been modeled. In the study, four parameters affecting the phenomenon of water hammer are studied, and they are pressure in pipes, flow velocity, the diameter of a conduit carrying liquid, and density of the liquid. This is the biggest challenge faced by many of the water production stations. A software program called MATLAB is used to program equations, solve them, and draw graphs.

2 Analytical investigation

Developing mathematical foundations for the water hammer is difficult and complex, mainly when dealing with the center of the water hammer. Therefore, the flow will stratify until a certain point occurs that can be mathematically analyzed. The flow is stable, when no friction exists between the liquid particles and between the liquid particles and the internal surface of the pipe, and pressure is equal at both ends. There are five input parameters: fluid pressure, fluid velocity, fluid mass, fluid density, and tube diameter and pipe length. Detailed results are presented as follows: state of stability of the system, settlement time, water hammer wave height and intensity, and hammer peak. The water hammer can be controlled with lock valves, control valves, and anti-return valves.

Pressure fluctuations at the water hammer using a pipe of length (L), the cause of the rapid change in pressure can be explained with the presence of a valve at the end of the pipe for sudden closure with analysis of an initial state V_0, is given as [2],

$$\Delta h = -\frac{a}{g} V_0, \tag{1}$$

where g is the gravitational acceleration, and a is the speed of the pressure wave. The speed of the pressure wave can be found from the conduit material properties and the fluid, and is given as,

$$a = \sqrt{\frac{K_\mathrm{f}}{\rho(1 + c(K_\mathrm{f}D)/eE}}, \tag{2}$$

where ρ is the fluid density, E is the Young's modulus of elasticity of the conduit wall material, K_f is the bulk modulus of elasticity of the fluid, e is the wall thickness, and D is the inside diameter of the conduit (Figure 1).

Therefore, the rate of change in fluid element momentum combined with Darcy–Weisbach equation is given as,

$$\frac{\mathrm{d}Q_t}{\mathrm{d}t} = \frac{gA_t}{L}(-z - (c_f + c_s)Q_t|Q_t|), \tag{3}$$

where Q_t is the continuity equation, which is the flow through the valve Q_v plus the flow into the surge tank Q_s, which is given by $Q_s = A_t\left(\frac{\mathrm{d}z}{\mathrm{d}t}\right)$. Hence the above equation becomes,

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{1}{A_s}(Q_t - Q_v), \tag{4}$$

These equations have often been integrated into numerical methods. A first-order ordinary differential equation can be seen in this way,

$$y' = \lambda y + \alpha_1 + \alpha_2 t, \tag{5}$$

where $\lambda, \alpha_1,$ and α_2 are constants. To find parameter variations and root locus representations, although the roots s_1 and s_2 appear as complex conjugates, consider only the roots in the upper half of the s-plane, as shown in Figure 2. Thus, the roots lying on the circle of radius ω_n correspond to the same natural frequency ω_n of the system,

$$s_{1,2} = \pm\frac{\sqrt{-4\,mk}}{2\,m}, \tag{6}$$

where k is the spring stiffness of pipe, and m is the mass of pipe. The relation between damped natural frequency ω_d, natural frequency ω_n, and damping ratio ξ is given as,

$$\omega_d = \omega_n\sqrt{1 - \xi^2}, \tag{7}$$

where

$$\sin\theta = \frac{\xi\,\omega_n}{\omega_n} = \xi, \tag{8}$$

Thus, radial lines passing through the origin correspond to different damping ratios as in the figure below. Therefore, when the radial lines = 0, have no damping ($\theta = 0$), and the damped natural frequency will reduce to the undamped natural frequency; and same steps as above when $\xi = 1$.

It is good to mention here that two roots trace loci or paths in the form of circular arcs as the damping ratio is increased from zero to unity, as shown below. The root with the positive imaginary part moves in the counterclockwise direction, while the root with the negative imaginary part moves in the clockwise direction. When the damping ratio (ξ) is equal to one, the two loci meet, denoting that the two roots coincide, that is, the characteristic equation has repeated roots. Figure 3 shows some representative root locations in the s-plane and the responses they elicit. System response characteristics include oscillatory nature, frequency of oscillation, and response time. This is an inherent characteristic of the system [9–12].

3 Results and discussions

The root locus theory was used to determine the system's stability after the occurrence of the water hammer phenomenon. Additionally, the theory shows the paths and roots of the characteristic equation governing the hydraulic system. This theory illustrates the oscillations

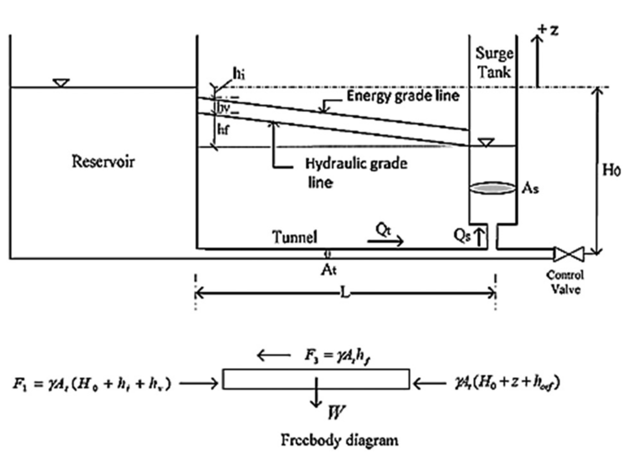

Figure 1: Schematic diagram of the system [2].

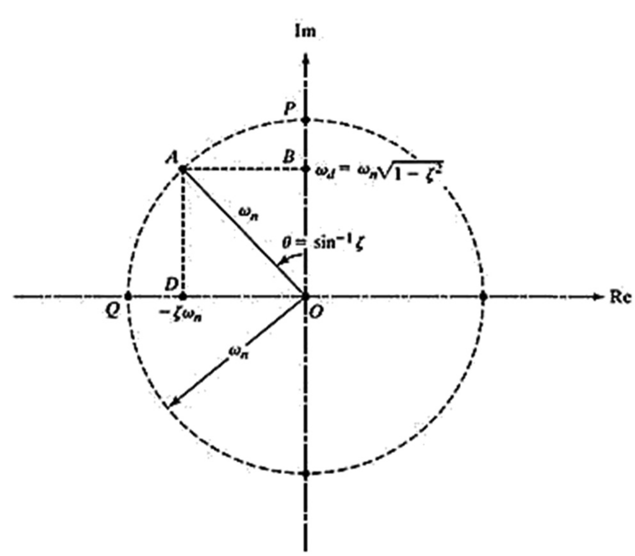

Figure 2: Roots in the upper half of the s-plane.

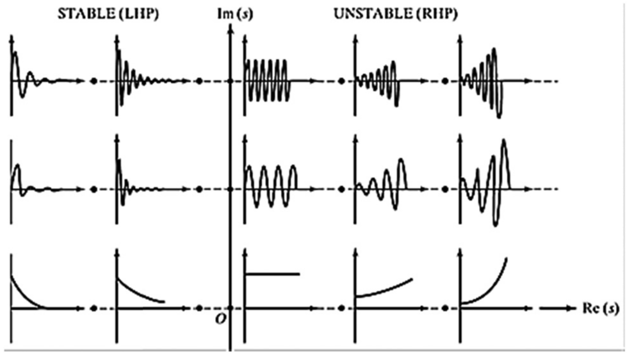

Figure 3: Locations of characteristic roots (•) and the corresponding responses of the system.

of water hammer waves, the overshoot, and feedback defined by the amount and power of pipeline locks. It also shows the amount of damping that should be applied in order to avoid hydraulic breakdown. The four cases studied were common occurrences in water pumping stations, except the fourth case, which involved changing the liquid, as it is known that water pumping stations use only water. The developed equation was solved in MATLAB, which is a high-performance language. Several powerful routines are built into it, which it uses to perform many types of calculations. This makes MATLAB an outstanding tool for this type of research.

3.1 Impact of pressure on hydraulic systems

Figure 4 illustrates the stability, the zeros, the poles, the roots, the transient oscillations at each stage and the whole hydraulic system. A case of pressure change has been assessed under the following conditions: 1.5 m/s fluid flow velocity, 300 mm pipe diameter, and water with a density of 1,000 kg/m^3. This graph shows the highest frequency at 12 bars of pressure and the lowest frequency at 4 bar of pressure. It is high in the stability regions when it comes to overshoot the upper and lower bounds of the oscillation of the function, as in Figure 4, which is the left side of the diagram, and it becomes zero at the right, which is the breakdown region. When it comes to the stability edge of the system, it is at 21.8 for almost all pressure pressures.

In the stability region, the damping rate of the water hammer wave is high, resulting in speedy wave fading. Note the gain or energy required to dampen the impact of the water hammer wave in the left area of the diagram, and find that it reaches infinity at a pressure of 12 bar when the frequency reaches 170 Hz. According to the equation, the roots lie at pressures of 4 and 8 bar, which implies that the system remains stable and the water hammer does not affect the system but causes vibrations in the liquid conveying tube caused by vibrations transmitted from the liquid to the inner

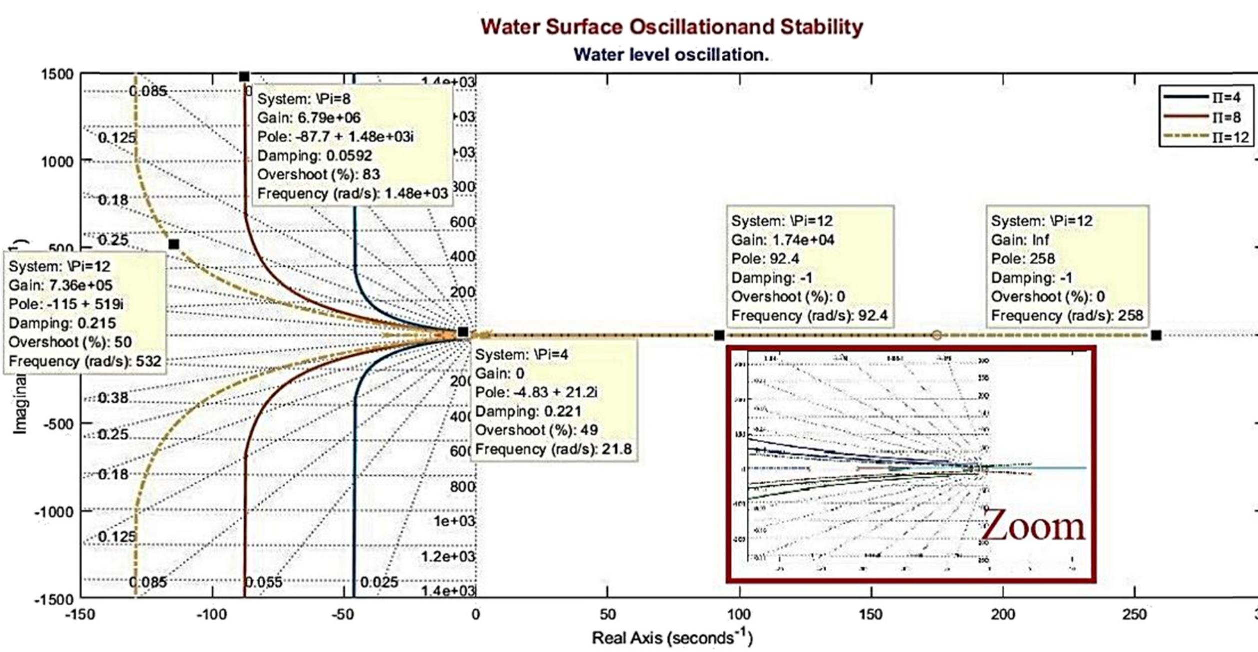

Figure 4: Stability of the system with different pressure effects.

pipe wall. Even so, the roots are far from the edge or threshold of stability; at pressure of 4 bar, the frequency becomes 21.8 Hz, damping power is 0.221%, and the gain ratio equals zero, while with a pressure of 8 bar, the stability edge is at 14.3 and the wave is 74.9% of its total amplitude.

3.2 Impact of fluid velocity on hydraulic systems

As shown in Figure 5, water hammer occurs at a speed of 2.5 m/s higher than that of the rest of the velocity and at a lower frequency. There is an overshoot the upper and lower bounds of the oscillation of the function in the stability regions, at the left side of the diagram, which becomes zero at the right side, as in the pressure chart, the breakdown region or the instability region, while the stability edge is at the stability edge 5.68. In almost all velocities, the damping rate of water hammer waves is high in the area of stability, which leads to the wave fading speed. In the left area of the diagram, note that the energy required to dampen the water hammer wave reaches 0.458 when the frequency reaches 5.43 Hz. Therefore, all the roots of this equation are at the same velocity, 1, 2, and 2.5 m/s. As a result, the system remains stable, but the water hammer still causes vibrations in the tube, transferring from the liquid to the inner wall, and the roots remain far from the edge of stability.

3.3 Impact of the diameter of the hydraulic system

For the third case, which represents the impact of the diameter of the hydraulic system as shown in Figure 6, the force of the water hammer is enormous at low frequencies and large diameters, for example, at 900 mm at 3 Hz with 1.5 m/s of velocity. At 600 mm in diameter, the overshoot is significant. There is no destructive effect of water hammer in all pipe diameters. The ideal case for the diameters as mentioned earlier is 300 mm at constant velocity and density.

3.4 Impact of fluid type on the hydraulic system

Each type of fluid has its properties, such as viscosity or density. Figure 7 shows that low-density liquids such as alcohol and petrol exhibit more significant oscillation when subjected to a water hammer, yet less energy is required to dampen this phenomenon. The water reaches

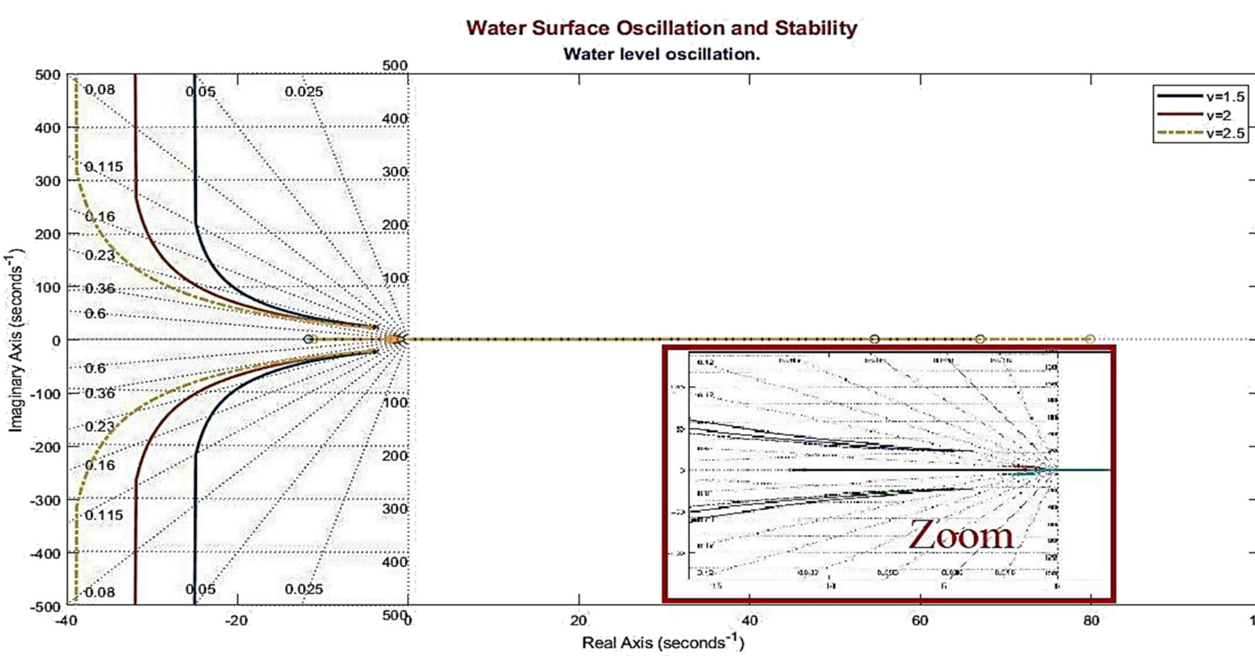

Figure 5: Stability of the system with different flow rate effects.

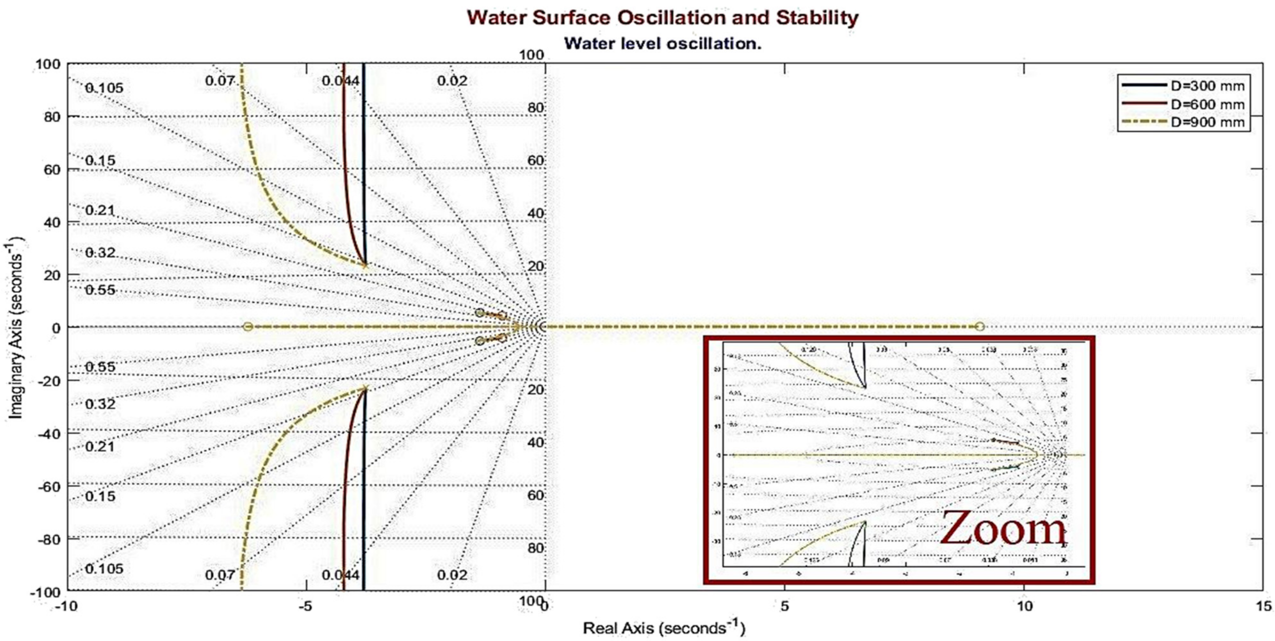

Figure 6: Stability of the system with different diameter effects.

a critical state of stability when the roots of the governing equation approach the center of the diagram. In contrast, less dense liquids move away from the center of the scheme, meaning the system is more stable, and the phenomenon of the water hammer does not collapse it.

The best results obtained the best pressure to be generated for fluid transfer is 4 bar, which is accompanied by a suitable high frequency, low damping force, and zero system gain. As much as possible, the speed limit should be avoided at 2.5 m/s, as the frequency at this speed becomes as low as possible and therefore, the system is as close as possible to sudden collapse. The force of the water hammer is large at large diameters where at these diameters the frequencies are low, and the ideal case is to use the diameter of 300 mm at a constant speed and density. Low-density fluids have a weak water hammer effect compared to high-density fluids, meaning that the water hammer effect is less when transporting fuel (gasoline) or alcohol than when transporting water.

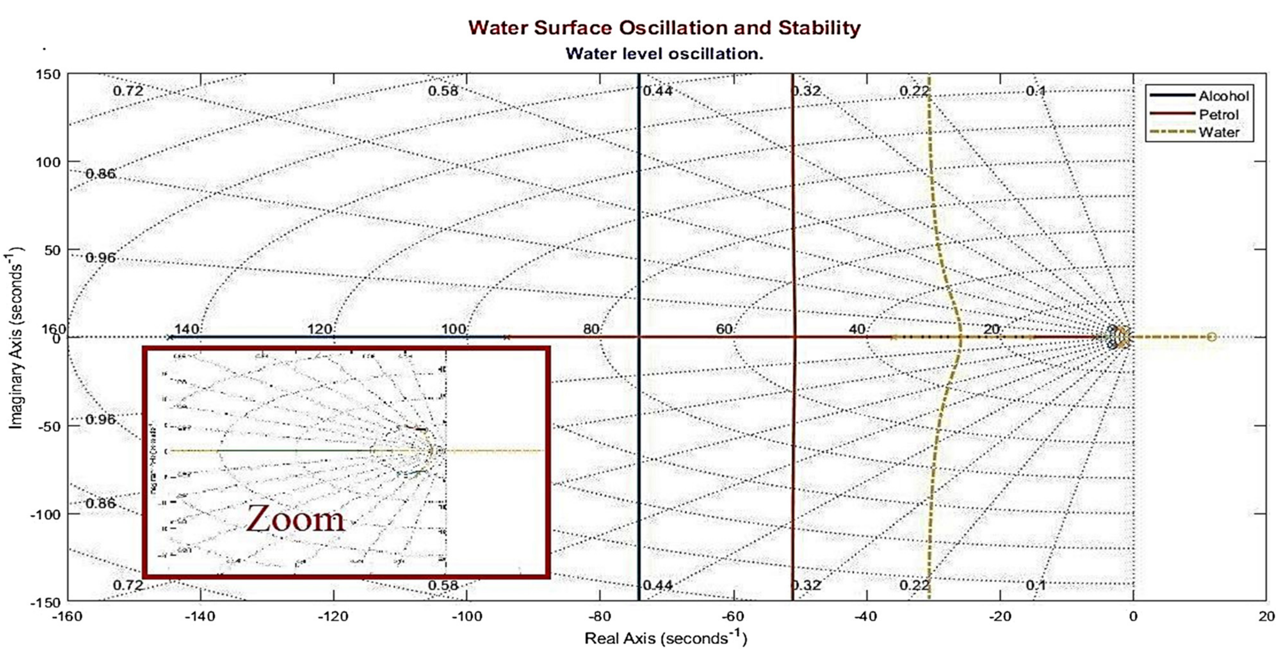

Figure 7: Stability of the system with different fluid type effects.

(a)

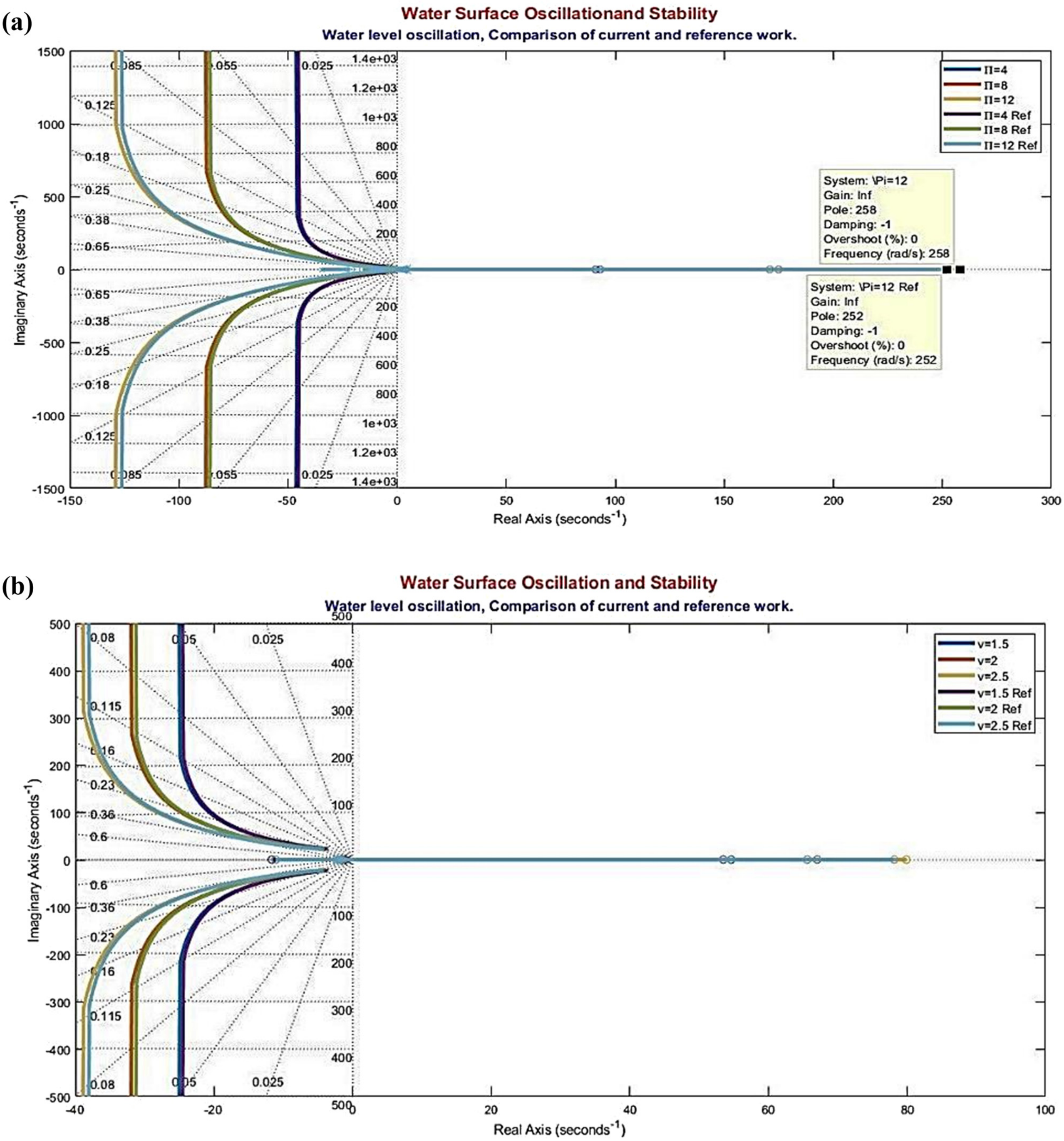

Figure 8: Validation of current work results and ref. [2] at (a) different pressure effects and (b) different flow rate effects.

3.5 Verification case study

Validation of current and reference work shows great convergence between the current work and the reference as shown in Figure 8, as the location of the poles, the location of zeros, the paths of roots, stability, and the hydraulic behavior of the system are very close. The difference may be non-existent when the numerical method was used [13–25], the fourth-order Runge-Kutta method with the root locus method. A comparison was applied when changing the pipe pressure and changing the water flow velocity, as in the figures below, respectively. The verification study was required to give the agreement for technique used to calculate the required results [26–45].

The results of the current research were compared with ref. [2] as follows, different pressure effects as shown in Figure 8(a) and different flow rate effects as shown in Figure 8(b), where a large and acceptable convergence of these results was found.

4 Conclusion

The main factors in order to verify the performance of the water hammer under several design parameters mainly: (1) pressure, (2) velocity, (3) diameter, and (4) density. The following conclusions are drawn from this work:

1. The ideal case is at a pressure of 4 bar compared to other pressures at the same hydraulic system parameters.
2. The velocity of the water in the closed pipes should not exceed 2.5 m/s as the wave of water hammer is large and destructive at speeds higher than the mentioned speed.
3. The force of the water hammer is significant at low frequencies and large diameters.
4. The high frequencies of a particular pipe depend on the type of material the pipe is made of, the installation method, and the friction coefficient of the pipe's inner surface. The higher the frequencies, the less the impact of the water hammer force.
5. The oscillation of the low-density liquids was higher in the case of water hammers for the same main parameters listed.

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