Water Transients in Pipes Due to Value Oscillation

S. Elgassier
Misurata University/Faculty of engineering, Misurata, Libya
s_legsayer@yahoo.co.uk

Abstract — **Pressure transients in pipeline due to valve vibration during closing stroke have been studied. The presumed oscillatory motion of valve actuating element is quiet depends on both the valve mechanical and hydrodynamic designs in one hand and to the controller in the other hand. Since, in almost, practical valve design and control the oscillatory of valve closing is unavoidable. In this computational investigation, a two-equations model with appropriate boundary conditions have been implemented to study the effect of valve element vibrations. The effect of valve vibration on various flow transients has shown quiet pronounced difference than that of the vibration free closing process which normally assumed in-computational. It can be withdrawn from the present study that the pressure peaks with oscillatory valve closing stroke are as much as twice that of oscillation free valve closing stroke.**

Index Terms: **water hammer, water transient, valve closing, valve oscillations, valve vibrations.**

I. INTRODUCTION

Many of water hammer problems facing the process industry today can be linked directly to the control valves which used in the systems [1,2] and it is believed that the valve performance has the key effects on the water hammer [3]. valves are selected and sized normally to perform a specific functions within a process system, failure in perform that given function, whatever if it is controlling a process variables or simple on/off services may produce a higher process costs, so the functions of these valves becomes a critical step in successful process operation [4]. In first part of this paper we will address the valve characteristics that are typically ignored when selecting the control valve, while in the second part we will speak on the dynamic performance of the control valve and how it may impact the pipeline, and it will be included with studies that will illustrate the dramatic impact of that control valve can have on the line.

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II. NOMENCLATURE

Latin symbols

a	water hammer wave speed, *m/s*
E	modulus of elasticity, N/m^2
f	frequency, *Hz*
H	source head, m_w
K	Bulk's modulus, N/m^2
L	pipe length, *m*
P	pressure head, *m*
t	time, *s*ec
T_c	Valve closing time, *s*ec
V	flow velocity, m/s
V_{op}	Valve opening

Greek symbols

δ	Oscillation amplitude

III. WATER HAMMER MODEL

In this investigation the water hammer transient in piping systems is computationally investigated by the method of characteristics, [5]. The equations governing the fluid flow transient in the drive pipe are derived based on the dynamic equilibrium during the transient. The system of equations constitutes two hyperbolic partial differential equations of first order [6]. The method of characteristics was used to transform the two equations into ordinary differential equations. The characteristic values were calculated and the corresponding characteristic functions were solved numerically over the characteristic grid. The pipe downstream end boundary condition constitutes an algebraic second order equation, while the upstream boundary condition is of constant reservoir head.

Governing Equations. As in [6, 7] the following two-equation model for fluid variables: *P*, pressure *V*, fluid flow velocity.

$$\frac{\partial P}{\partial t}+K'\frac{\partial V}{\partial x}=0 \qquad (1)$$

$$\frac{\partial V}{\partial t}+\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\tau_w}{A}\frac{\pi D}{\rho}=0 \qquad (2)$$

Where: the wall shear stress is

$$\tau_w=\frac{f}{4}\rho\frac{V^2}{2} \qquad (3)$$

And the modified bulk modulus is

$$K^{'} = \frac{K}{1 + \left[\left(\frac{K}{E} \right) \left(\frac{D}{t} \right) \right] \left(1 - \nu^2 \right)} \tag{4}$$

The two partial differential equations (1, 2) are transformed along the characteristics to an ordinary differential equation as

$$\left. \begin{aligned} & \pm \frac{1}{\rho a} \frac{dp}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 \\ & \frac{dx}{dt} = \pm a \end{aligned} \right\} \tag{5}$$

Where *+ve* sign for the positive characteristics and *–ve* sign for the negative characteristics and *a* is water hammer wave speed

$$a = \sqrt{\frac{K^{'}}{\rho}} \tag{6}$$

The upstream boundary condition is given by:

$$P_t = P + \rho \frac{V^2}{2} \tag{7}$$

The downstream boundary condition is given by the valve oscillatory part superimposed on linear motion, which describe the valve opening ratio V_{op} at any given time t.

$$V_{op} = \left(1 - \frac{t}{T_c} \right) + \delta(t) \sin\left[2\pi f(t) t \right] \tag{8}$$

The oscillatory amplitude [8], $\delta(t)$ is expressed as a linearly increasing function of time.

$$\delta(t) = \delta_{\max} \left(\frac{t}{T_c} \right) \tag{9}$$

Where δmax is maximum oscillatory amplitude.

And the oscillation frequency, *f(t)* is expressed as a linearly decreasing function of time.

$$f(t) = f_{\max} \left(1 - \frac{t}{T_c} \right) \tag{10}$$

Where f_{max} is maximum oscillatory frequency.

The valve discharge coefficient as a function of valve opening, V_{op}, has been best fitted from the manufacturer data [9].

For globe valve an exponential function has been used as:

$$C_d(t) = a \times b^{\left(c^{V_{op}}\right)} - a \times b \tag{11}$$

In which the best fit constants are; ***a = 0.5226260928, b = 0.01652205336, and c = 0.9706719746***

For butterfly valve a third order polynomials has been used as:

$$C_d(t) = aV_{op} + bV_{op}^{\ 2} + cV_{op}^{\ 3} \tag{12}$$

In which the best fit constants are; ***a = 0.004289002366, b = 2.478851533 x*** $\boldsymbol{10^{-5}}$***, and c = 1.057440809 x*** $\boldsymbol{10^{-7}}$

The valve head loss across the valve is used as :

$$h_{lv} = \frac{1}{C_d^{\ 2}} \tag{13}$$

The valve head loss along with the *+ve* characteristics are used to determine the instantaneous pressure and flow rate at the valve boundary.

IV. FOURIER ANALYSIS

The computed pressure wave form has been analyzed by Fourier transform to obtain the frequencies content of pressure oscillatory part. The obtained pressure spectrums are used to demonstrate the contribution of both valve oscillating frequencies and the water hammer frequency. The well-known Fourier series is used as:

$$P(t) = \frac{a_o}{2} + \sum_{n=1}^{N} a_n \cos(2\pi f_n t) + \sum_{n=1}^{N} b_n \sin(2\pi f_n t) \tag{14}$$

$$f_n = \frac{n}{4L/a} \quad , n = 1, 2, 3, ... \tag{15}$$

V. INPUT DATA

Pipe parameters used in this investigation:

Upstream reservoir head= 100 *m*, downstream reservoir head= 10 *m*, pipe diameter = 2 *m* , Length of pipeline = 100 *m*, friction factor = 0.02, wave speed, *a* = 1000 *m/sec*. Closure time, T_c = 0.8 *sec*. The valve vibration amplitude, *(δ)* is in percentage of valve open as; 0, 5, 10, 15, 20, 25, and 30. The imposed valve frequencies (*Hz*) are; 0, 2.5, 5, 10, 15, 20, 30, 50, 60, 70, 90, 100

VI. RESULTS AND DISCUSSIONS

Figure 1 displays the non-vibrating linear valve closing stroke with its associated valve discharge coefficient (C_d) and the dynamic coupling parameter *(τ)* between the head drop across valve and the amount of flow through the valve. A sample of valve vibration pattern is shown in Figure 2, which displays the effect of valve vibratory closure on both (C_d) and *(τ)* parameters. These parameters are used as a boundary condition at valve location.

Figure 3 displays the time history of pressure at the valve for non-vibrating closure. The pressure trace could be divided as two parts. The first part during the closing time is named as the transient pressure and the second part begins just after the valve closing and is named oscillatory pressure. It is seen from the figure that the pressure in the two parts is clean from any high harmonics. The transient part attains peak value almost just before the end of closing. The oscillatory part attains a cyclic peak with the single water hammer wave frequency. The attenuation of the oscillatory part is in part due to the dissipative viscous friction and the other contribution to the dissipative boundary condition when the flow reverses to the reservoir. Figure 4 on the other side displays the time history of the pressure in case of vibrating valve element. It is seen that the valve vibration during valve closure strongly affects both the transient and oscillatory pressures. Not only the magnitude of both parts has increased, but also the higher harmonics is clearly seen. That is the valve vibration increase remarkably the magnitude of the peak pressures and higher harmonics in the oscillatory part. This may have a pronounced effects when the dynamic or fatigue analysis of the pipe under consideration is in question. It is seen from these figures that as the values of valve vibration frequency increases the pressure peaks increase. Practically small amplitude at high frequency vibration is unavoidable, this emphasis the dynamic design of valve and controller are important issues when the water hammer has to be alleviated.

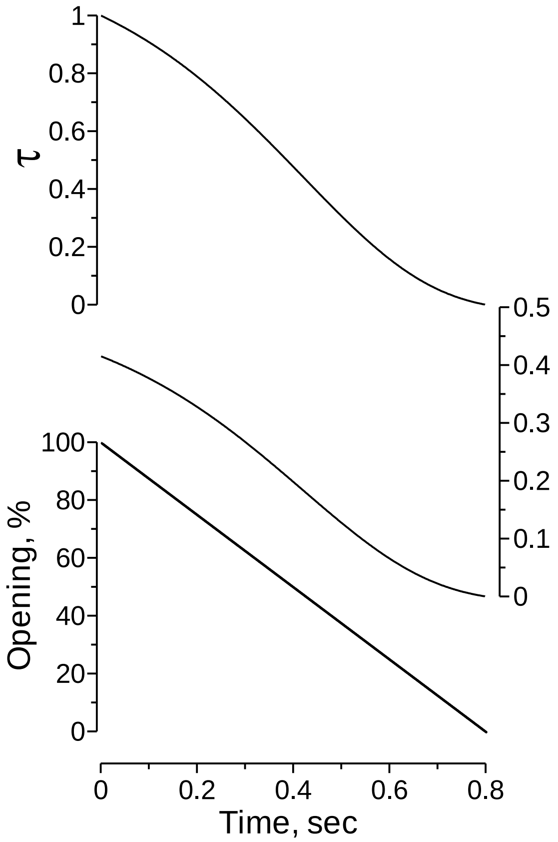

Figure 1. Valve Closing Characteristics Without Oscillatory

Figures (5 and 6) display the pressure history for vibrating valve closure at the same vibrational frequency but at different amplitudes. It is seen that the increase of vibration amplitude increase both the transient and oscillatory pressure peaks.

Figures (7 and 8) display the pressure spectrums (Fourier transform) of the oscillatory part of pressure wave form for both vibration free and vibrating valve closures. The vibration free spectrum displays only one peak at the traditional water hammer frequency *(4L/a)*. On the other hand, the vibrating valve closure spectrum results in multi peaks at higher frequencies. It is seen that the peak of higher harmonics is larger than that of water hammer frequency. That is emphasize the effect of valve vibration during valve closure that has significant effect on pressure oscillatory peaks

Figure 9 displays the transient peak pressure against the valve vibrating frequency at different vibration amplitude. The peak pressure increases as the vibration frequency increase, furthermore, the peak increases remarkably as the amplitude increases and it tends asymptotic value for all frequencies and amplitudes. Figure (10) has the same withdrawn behavior for the oscillatory peaks as figure (9). In all cases the oscillatory peaks is less than the transient peak, and both peaks are much greater than vibration free valve closing process.

The asymptotic trend of pressure peaks with respect to valve amplitude is seen in figure 9. That is in the limit, at high frequency and high vibration amplitude,

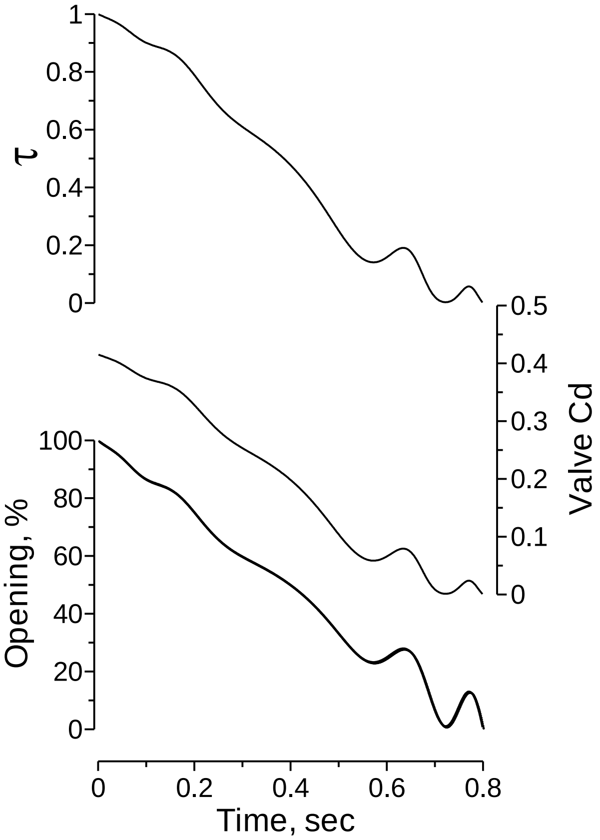

Figure 2. Valve Closing Characteristics $\delta=10^o$, f= 10 Hz

The pressure peaks reaches fixed values as much as twice the values of both transient and oscillatory peaks for non-vibrating case

VII. CONCLUSIONS AND RECOMMENDATIONS

In this analysis, the valve vibration is assumed to attain linearly decreasing frequencies, whilst, the vibrating amplitude is linearly decreasing functions of time. This assumption is considered to simulate the actual valve vibrating behavior of its mechanical components due to both flow hydrodynamic forces and valve structural elasticity. Also the controller driven valve can suffice an additional valve vibration due to the controller step inputs and/or controller instabilities. In this work, the effect of valve vibration during closing stroke is computationally investigated. It is found that the valve vibration greatly affect the pressure transient in the pipe systems. Not only the pressure peaks have increased but also the dynamic characteristics such as the frequency contents of the pressure wave forms have completely changed. The contribution of higher harmonics is quiet pronounced and may cause fatigue failure to the pipeline. It may be concluded that the dynamic characteristic of valve closure should be implemented in water hammer analysis to completely describe the transient pressure in pipelines.

It can be concluded that the pressure peaks with oscillatory valve closing stroke have as much as twice that of oscillation free valve closing stroke.

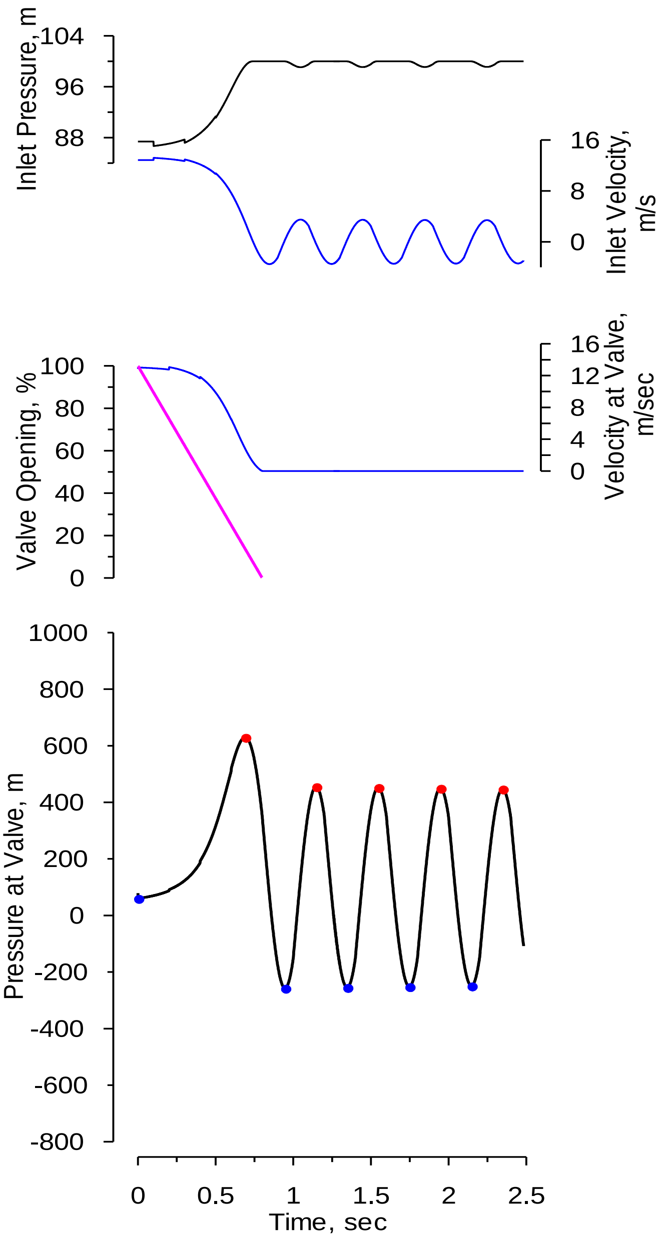

Figure 3. Pressure Transient Without Valve Oscillatory

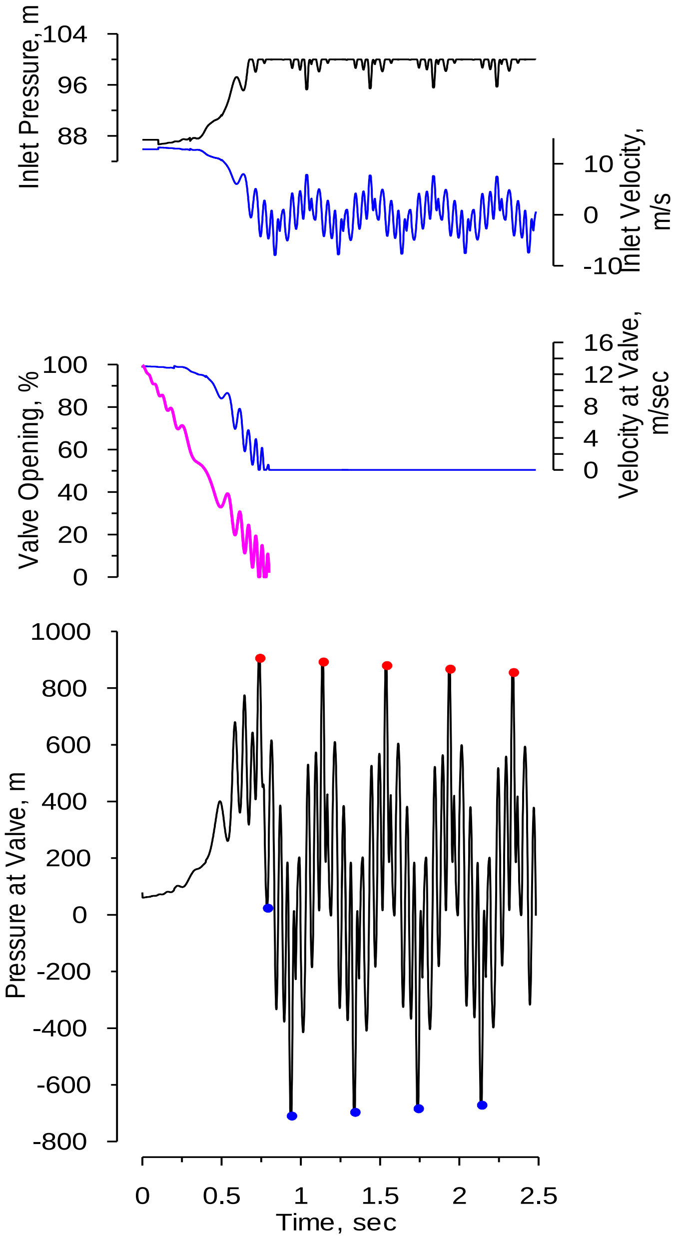

Figure 4. Pressure Transient $\delta=10^o$, f= 30 Hz

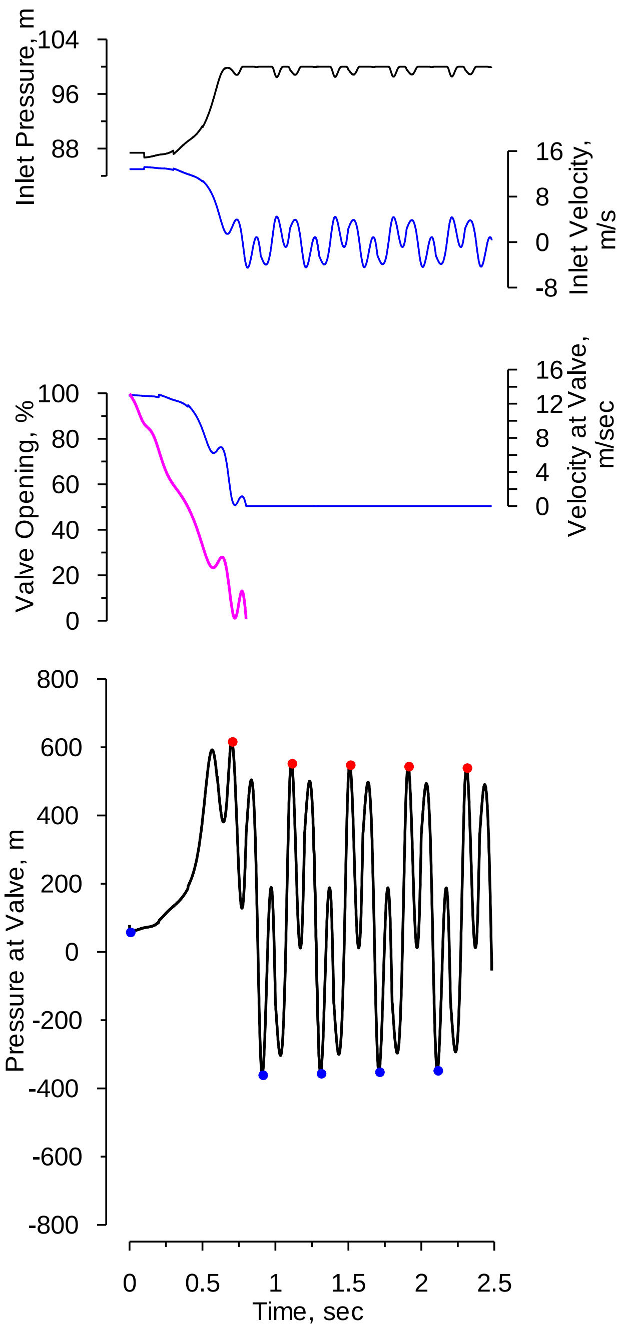

Figure 5. Pressure Transient δ=10°, f= 10 Hz

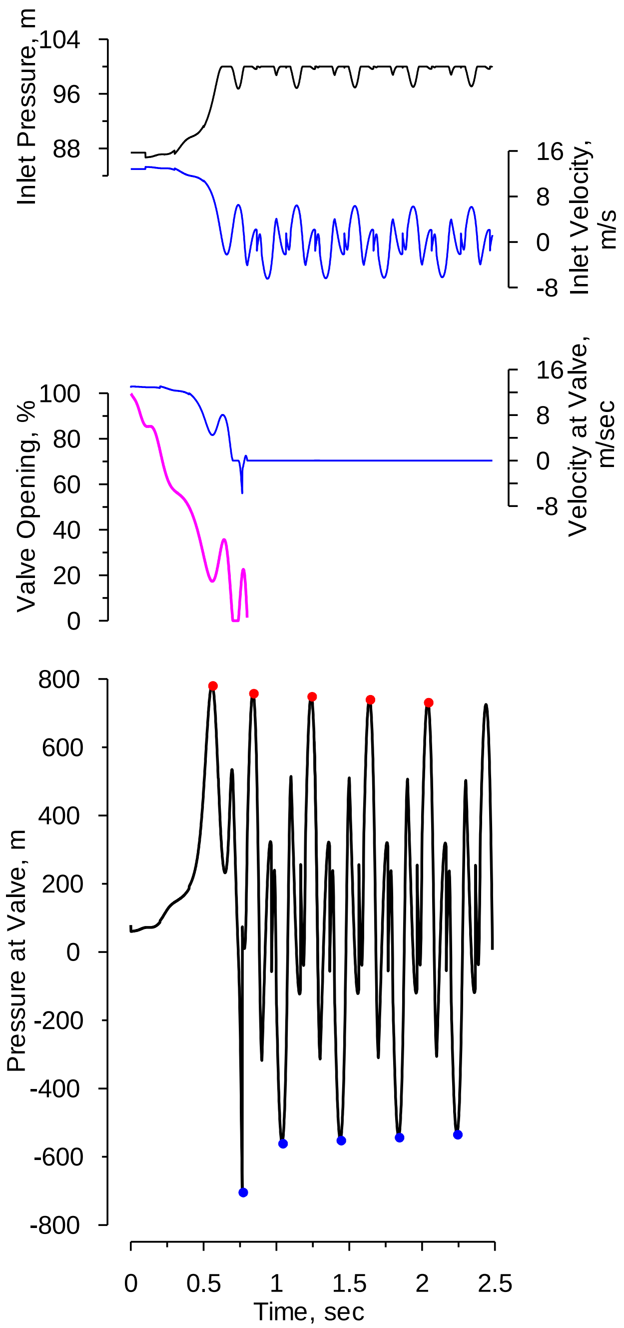

Figure 6. Pressure Transientδ=20°, f= 10 Hz

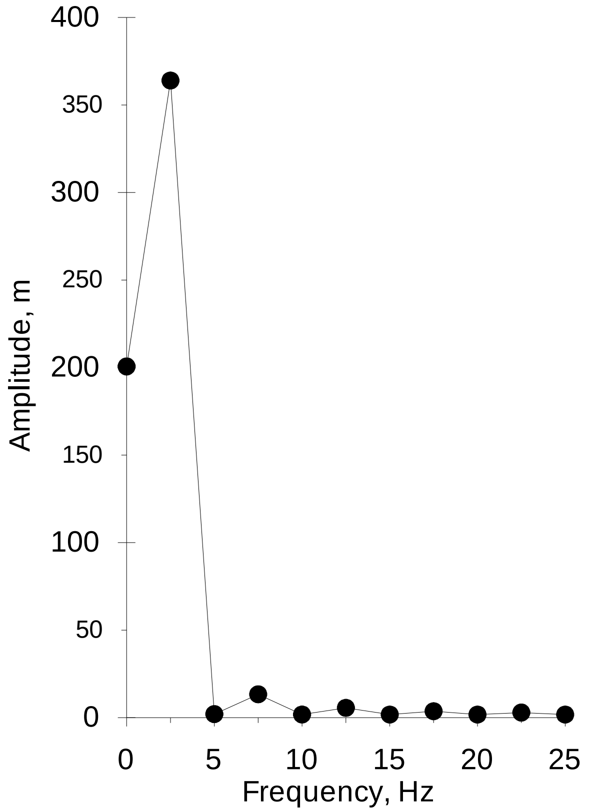

Figure 7. Pressure Spectrum Without Valve Oscillation

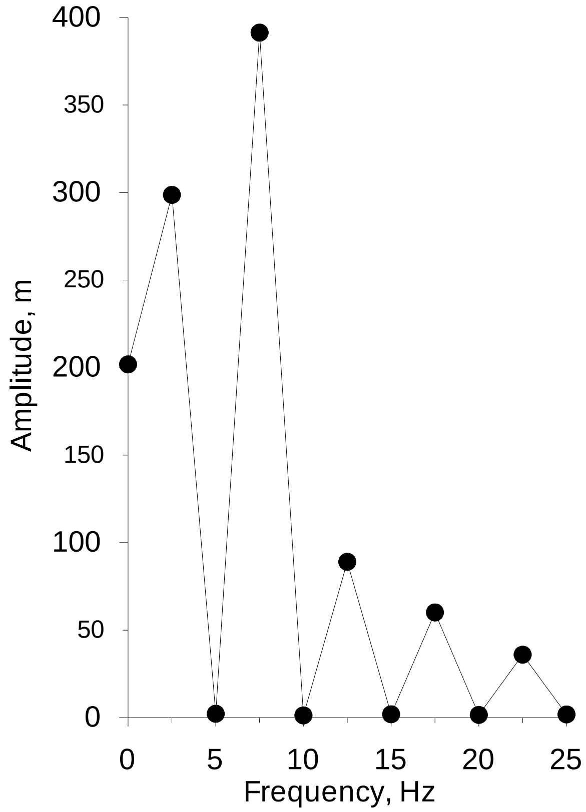

Figure 8. Pressure Spectrum with Valve Oscillation δ=10^{o}, *f= 10* Hz

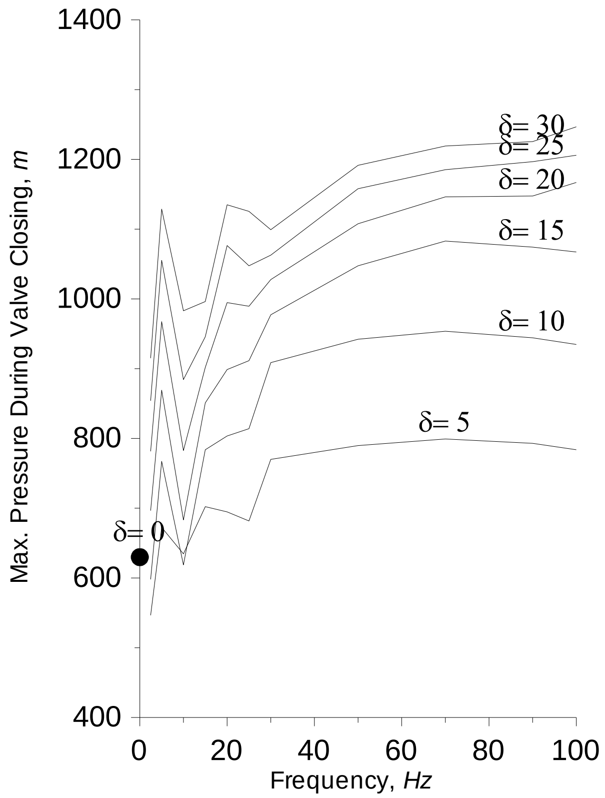

Figure 9. Transient Max. Pressure for Different Altitude and Frequency

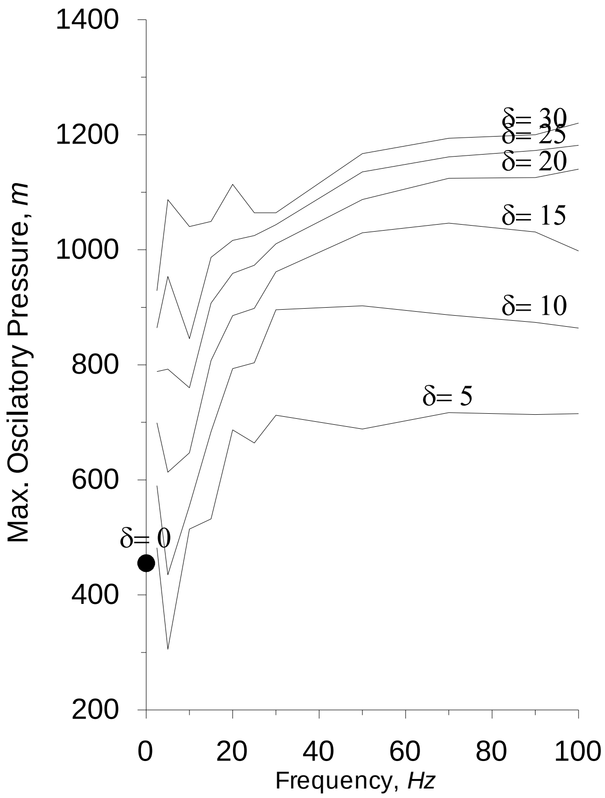

Figure 10. Oscillatory Max. Pressure for Different Altitude and Frequency

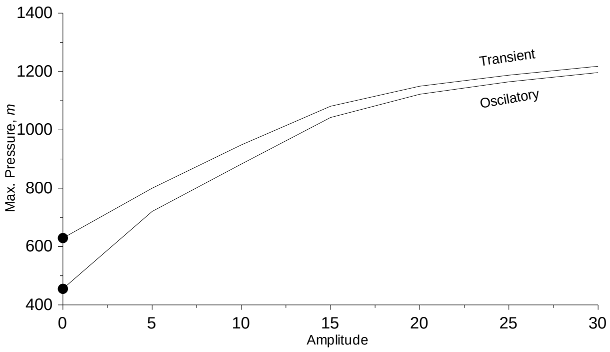

Figure 11. Asymptotic Oscillatory and Transient Maximum Pressures at Different Amplitude

It is recommended for future work to investigate the hydrodynamics of valve in junction with the valve structural elasticity. Deep understanding of the hydrodynamic forces associated with flow pattern around the valve elements is needed to further develop the dynamic valve characteristics. It is of the same importance is the elastic behavior of the valve structure and its controller. The coupling of both hydrodynamics and structure elasticity the so called hydrodynamic elasticity will result in big step toward the actual modeling of fluid transients due to valve controlling processes.

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BIOGRAPHIES

Sami AboBaker ELGASSIER was born in Misurata /Libya, on June 7th, 1971. He received BSc degree in Mechanical Engineering from Benghazi University in 1993. He got MSc degree in mechanical engineering from Misurata University / in 2007. Moreover, he has worked in the General Company for Construction of Administrative Centers as Projects Manager in different projects and carried different tasks for a period of more than 20 years, currently he established his own company "DICES" and working in the field of consultancy and engineering services, and lecturer cooperative in Department of Mechanical engineering at Misurata University/Libya. His research field is hydraulics and fluid mechanics engineering.