On Wave-Defect Interaction in Pressurized Conduits

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Abstract: Pressurized conduits transporting liquids such as freshwater, storm-water, wastewater, oil and gas often experience partial blockages or leakages during their life time due to physical and/or chemical processes. In water supply, these anomalies result in about 30% of water loss and more than 30% of energy waste. Transient-based defect detection methods are highly promising, but require in-depth understanding of wave-defect-turbulence interaction in conduits. This paper develops a two-dimensional compressible flow model, based on the axial symmetry assumption, to investigate the interaction between transient waves and the flow structure in the vicinity of a leak or a blockage. An explicit Finite Volume Scheme (FVS) based on Riemann solvers is used to solve the hyperbolic part of the 2D axi-symmetric compressible Navier-Stokes equations for transient flow in a pipe. The parabolic (viscous and turbulence) part are modeled by a central differential scheme. Several boundary conditions are studied including (i) sudden closure of a valve, (ii) pulse wave and (iii) strong shock waves. Preliminary tests show that the scheme has good accuracy, efficiency and convergence characteristics. Detailed study of the scheme are ongoing and will entail comparisons with other schemes such as implicit factorized scheme and Lax-Wendroff schemes as well as experimental data. Thus far, the focus has been on laminar flows, but the physics of turbulence will be added in the near future and will involve the use of Bardina Large Eddy Simulation model.

Keywords: *transient flow, 2D model, FVS, water hammer, hydraulic waves, waves, turbulence interaction, blockage/leakage*

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Introduction

Pressurized Pipelines

- Very Important transportation method.
- In the U.S., around 19,000 km of new water distribution pipelines are installed annually.
- Many pipelines are over 100 years old and are poorly maintained, resulting in increased occurrences of **leaks** and **blockages**.

Introduction

Leakages

- Around **40%** of water losses in the ***world***
- ***Hong Kong*** alone is investing about **$22 billion HK** to replace **3000 km** of aged water pipes with the aim to curb the water losses from about **30% to just below 20%.**
- For the years **2012 to 2014**, Hong Kong will pay, respectively, **$3.5 billion HK**, **$3.7 billion HK** and about **$4 billion HK** to secure 820 million cubic meters of water.

Ref.:
HK Magazine (27 October 2012). "A New Desalination Plant in Hong Kong". Retrieved 12 August 2012.
CK FUNG, M LEUNG, G ZHAI. *'Pipe Condition Survey and Design for Territory-wide Replacement and Rehabilitation of Large Diameter Water Mains in Hong Kong'. HKIUS, (*2009*).*

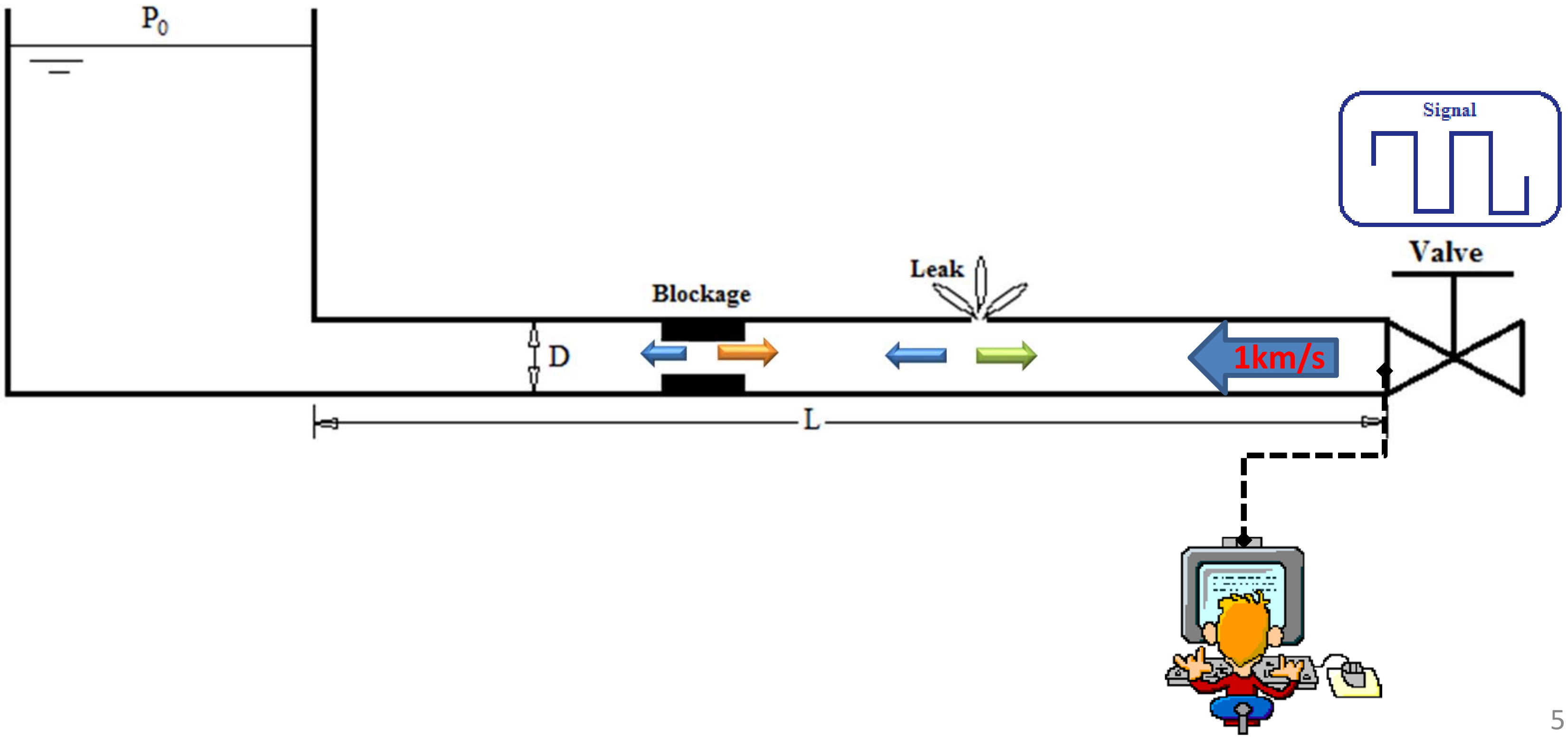
Introduction

Blockages

- Corrosion
- Air blockages
- Bio-fouling (sea water system)
- Pressure increase
- Flow reduction
- Energy losses : friction, pumping

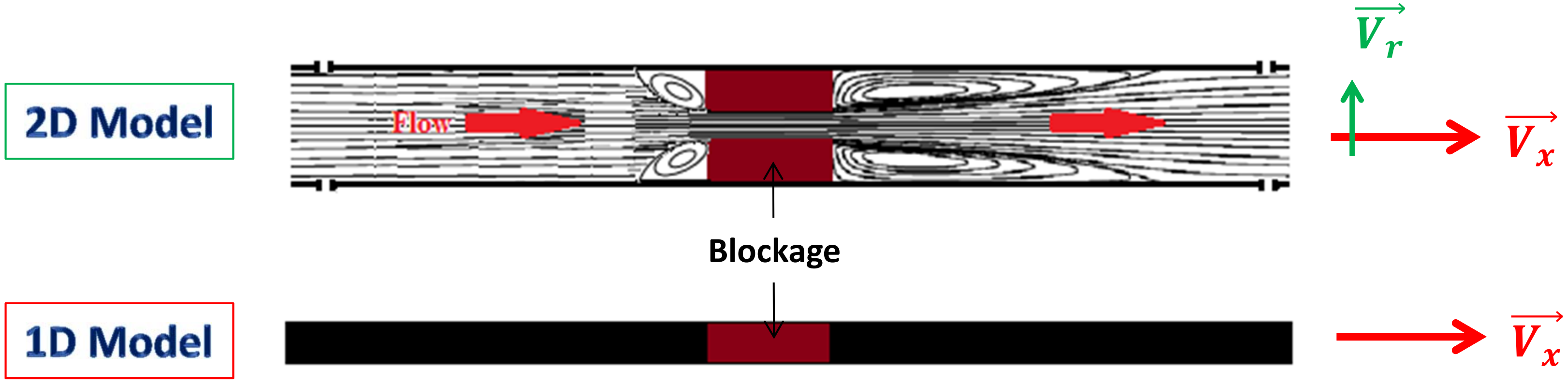
Introduction

Principle of Transient-based methods



Introduction

Flow Separation



$\overrightarrow{V_r}$

2D Model $\overrightarrow{V_x}$

Blockage

1D Model $\overrightarrow{V_x}$

Wave-Turbulence Interaction → **Multi-dimensional Model**

Equations and Numerical scheme

2D compressible Navier-Stokes Equations

$$\underbrace{\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{F}}{\partial r}+\frac{\partial \boldsymbol{G}}{\partial x}}=\underbrace{\boldsymbol{S}\left(\boldsymbol{U},\frac{\partial \boldsymbol{U}}{\partial r},\frac{\partial \boldsymbol{U}}{\partial x}\right)}$$

2nd order Finite Volume Scheme based on Riemann Solver

2nd order Finite Difference Scheme based on Central Discretization

$$\boldsymbol{U}=\begin{pmatrix}\rho\\ \rho V_r\\ \rho V_x\end{pmatrix}=\begin{pmatrix}U_1\\ U_2\\ U_3\end{pmatrix};\quad \boldsymbol{F}=\begin{pmatrix}\rho V_r\\ \rho {V_r}^2+P\\ \rho V_r V_x\end{pmatrix}=\begin{pmatrix}U_2\\ \dfrac{{U_2}^2}{U_1}+P\\ \dfrac{U_2U_3}{U_1}\end{pmatrix};\quad \boldsymbol{G}=\begin{pmatrix}\rho V_x\\ \rho V_r V_x\\ \rho {V_x}^2+P\end{pmatrix}=\begin{pmatrix}U_3\\ \dfrac{U_2U_3}{U_1}\\ \dfrac{{U_3}^2}{U_1}+P\end{pmatrix};$$

$$\boldsymbol{S}\left(\boldsymbol{U},\frac{\partial \boldsymbol{U}}{\partial r},\frac{\partial \boldsymbol{U}}{\partial x}\right)=\begin{pmatrix}S_1\\ S_2\\ S_3\end{pmatrix}=\begin{pmatrix}-\dfrac{U_2}{r}\\ \dfrac{\partial \tau_{rr}}{\partial r}+\dfrac{\partial \tau_{rx}}{\partial x}+\dfrac{1}{r}\left(\tau_{rr}-\tau_{\theta\theta}-\dfrac{{U_2}^2}{U_1}\right)\\ \dfrac{\partial \tau_{rx}}{\partial r}+\dfrac{\partial \tau_{xx}}{\partial x}+\dfrac{1}{r}\left(\tau_{rx}-\dfrac{U_2U_3}{U_1}\right)\end{pmatrix}$$

Numerical scheme

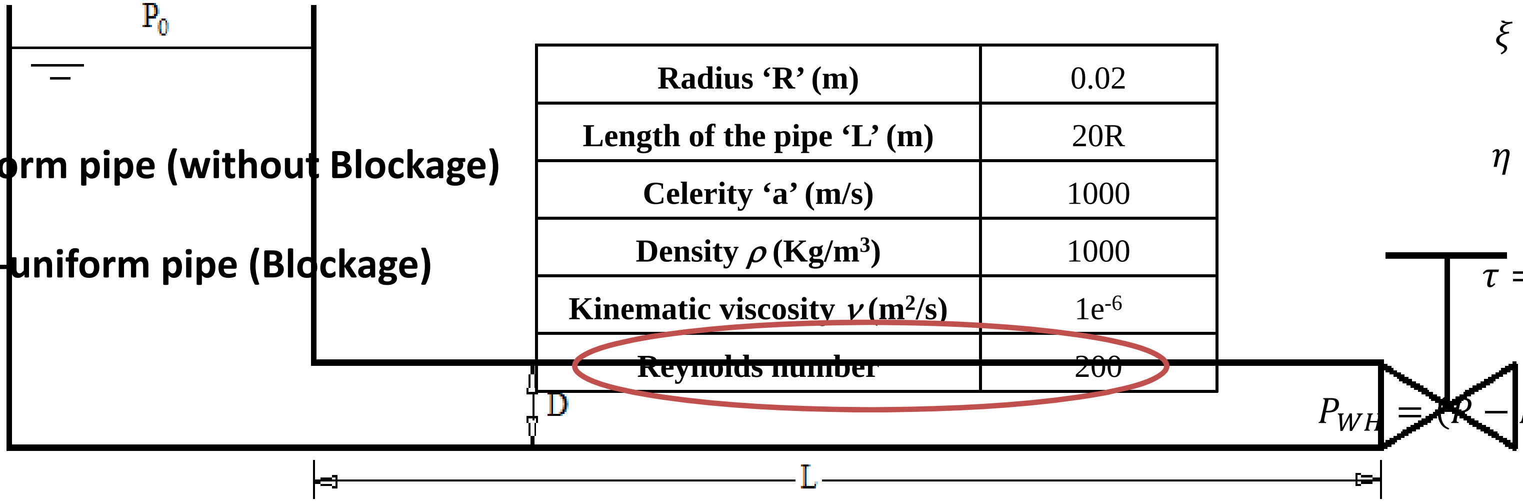
- ✓ **Comparison with 1st order scheme**
- ✓ **Comparison with 2nd order Finite Difference scheme**
- ✓ **Convergence Test**
- ✓ **Order of the scheme : 1.5**
- ✓ **Boundary Conditions**

Test case and Initial Conditions

Test case descriptions

1. **Uniform pipe (without Blockage)**
2. **Non-uniform pipe (Blockage)**

Radius ‘R’ (m)	0.02
Length of the pipe ‘L’ (m)	20R
Celerity ‘a’ (m/s)	1000
Density ρ (Kg/m^3)	1000
Kinematic viscosity ν (m^2/s)	1e^{-6}
Reynolds number	200



$\xi = x/R$

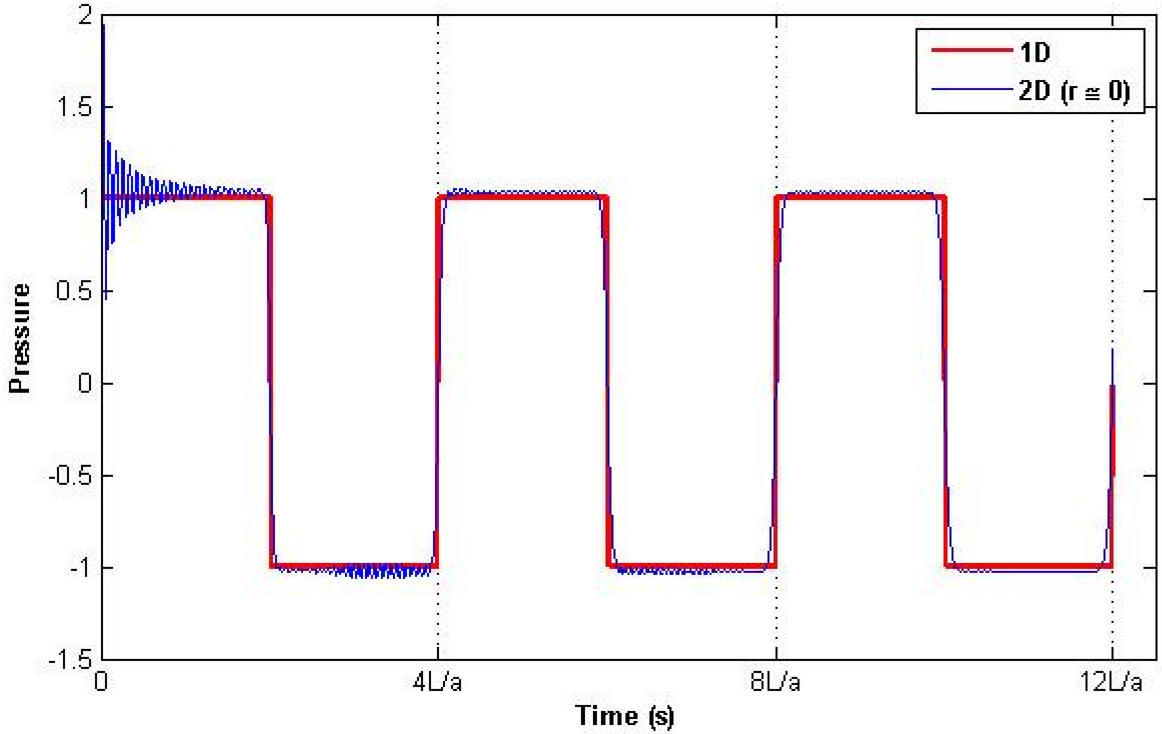
$\eta = r/R$

$\tau = at/R$

$P_{WH} = (P - P_{at})/(\rho V_x a)$

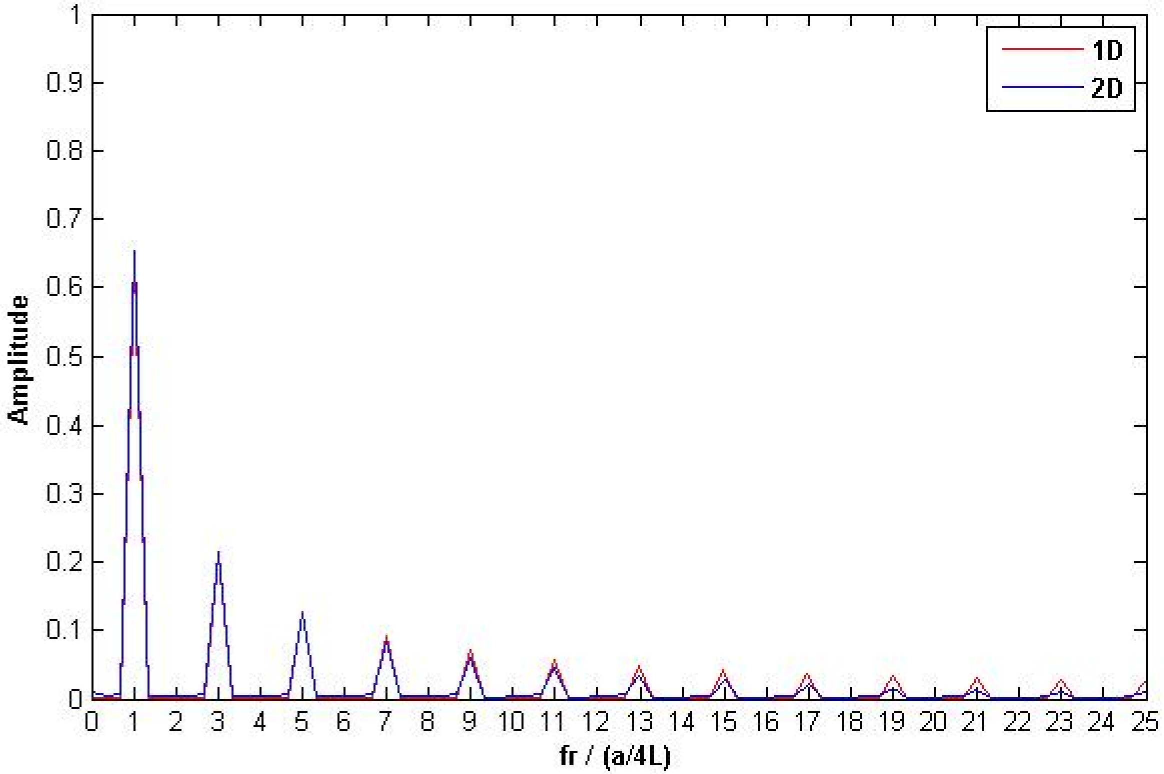
Laminar Flow

Uniform pipe



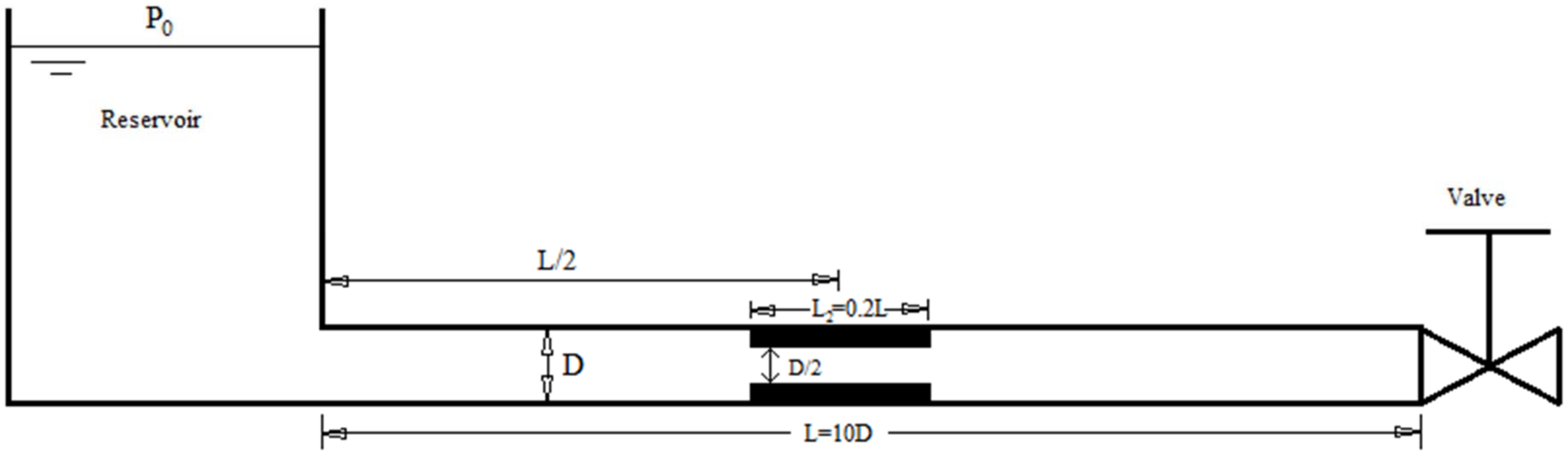
Pressure at the valve

Uniform pipe

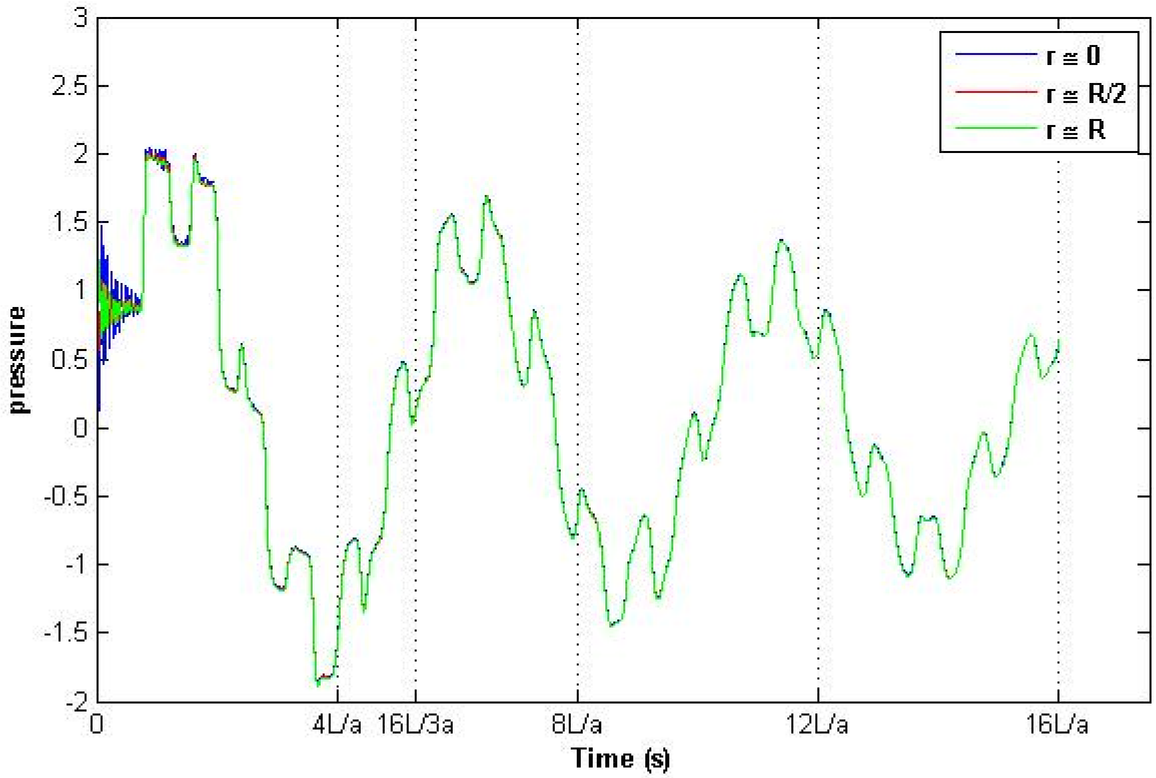


Frequency domain

Blockage

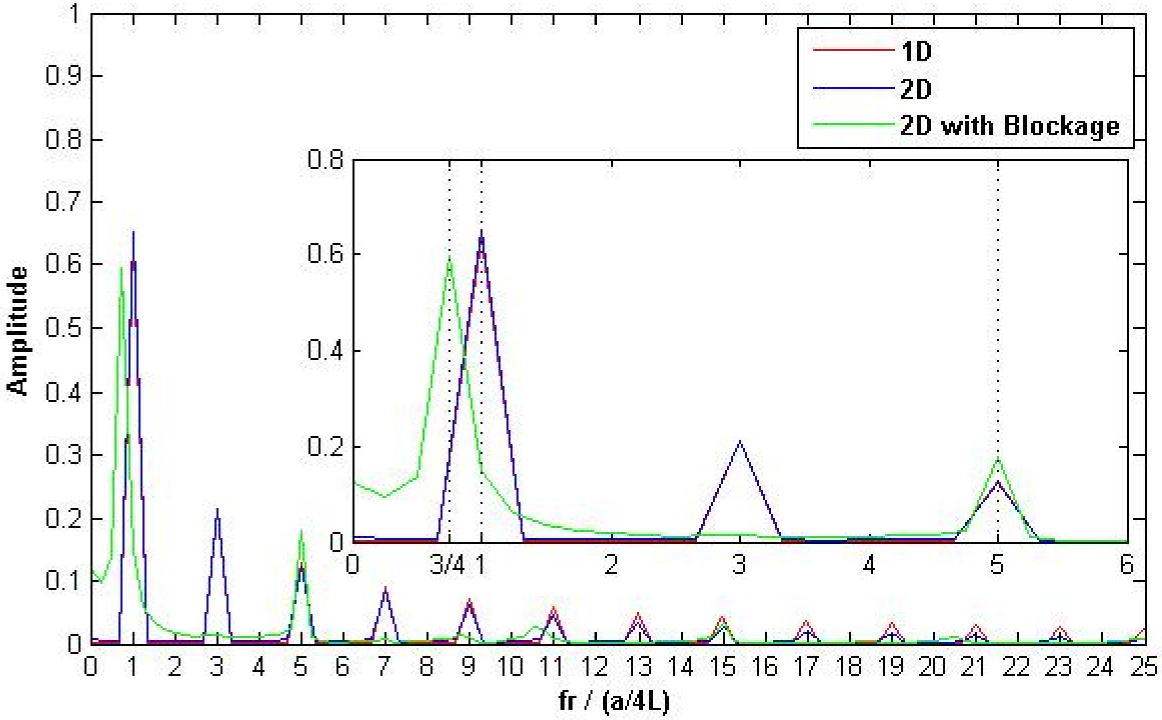


Blockage



Pressure at the valve

Blockage



Frequency domain

Blockage

Water Hammer Equation

Without Blockage

$$\frac{\partial^2 P}{\partial t^2} - a^2 \frac{\partial^2 P}{\partial x^2} = 0$$

With Blockage

$$\frac{\partial^2 P}{\partial t^2} - a^2 \frac{\partial^2 P}{\partial x^2} = \frac{a^2}{A} \frac{\partial A}{\partial x} \frac{\partial P}{\partial x}$$

Fourier Transform

$$\underbrace{\sum A_n e^{ik_n x} \quad \otimes \quad \sum P_m e^{ik_m x}}_{\boxed{C e^{i(k_n + k_m)x}}}$$

Blockage

Animation:

- 3D pressure

Future Work

- ☐ **Turbulence Model (Large Eddy Simulation model)**
- ☐ **Compare with experiment**
- ☐ **Wave-Turbulence Interaction**
- ☐ **3D model**

Thank You