香港科技大學
THE HONG KONG
UNIVERSITY OF SCIENCE
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Workshop on Smart Urban Water Systems (Smart UWSS) – Defects Localization and Acoustic Communication in Water Pipes

Frequency- and Time- Domain Methods of Defect Detection in Water Pipeline Systems

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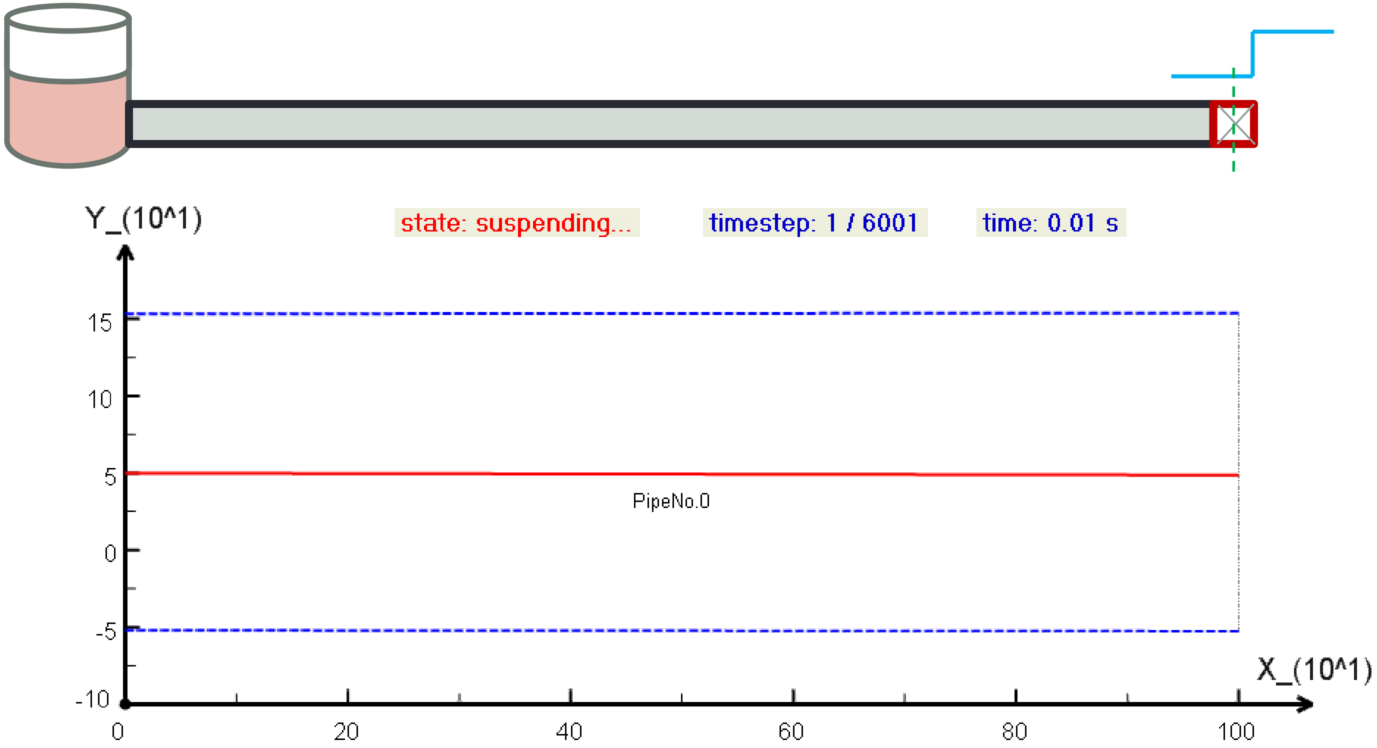
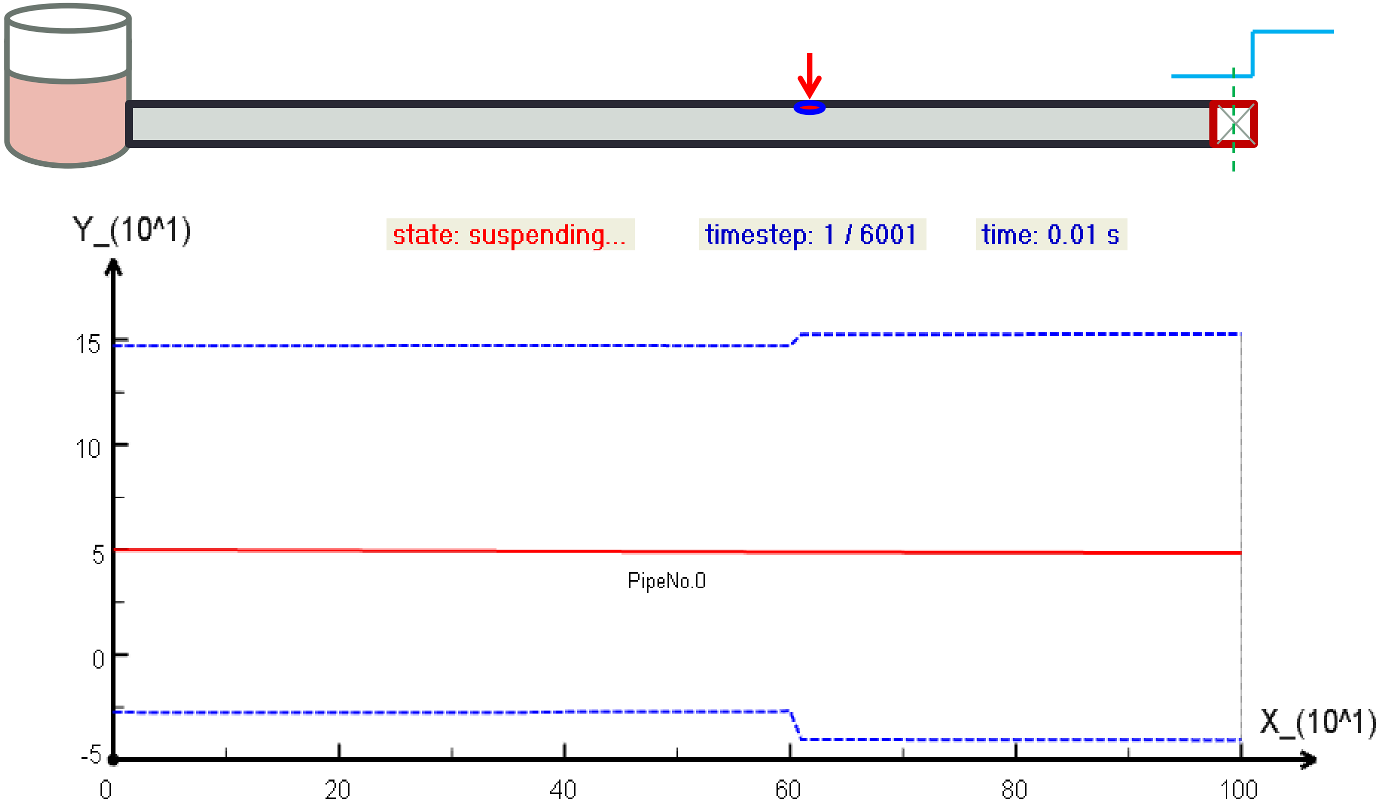
Transient Waves in Pressurized Pipelines

- Wave propagation in an “intact” pipeline system (defect-free)



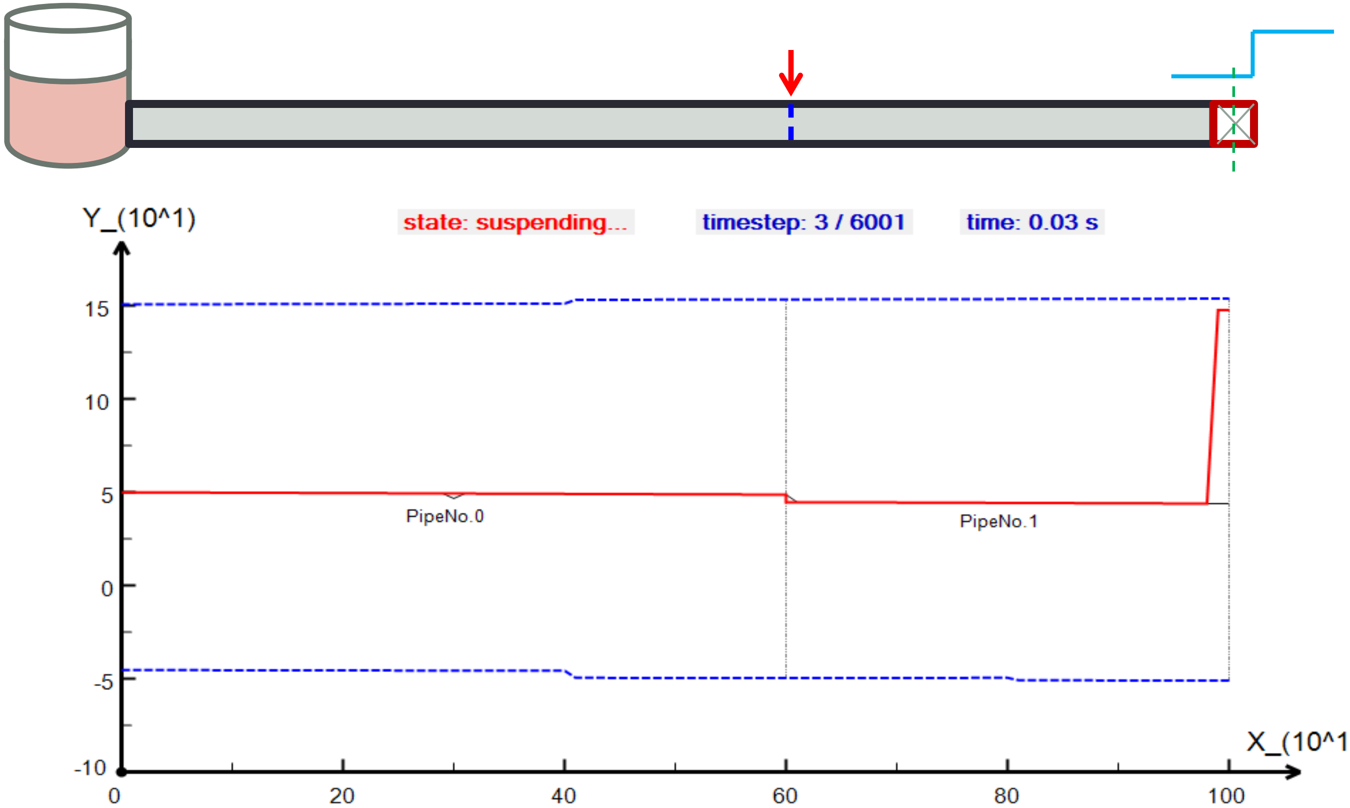
Transient Waves in Pressurized Pipelines

- Wave propagation in the pipeline with a leakage (e.g., crack/hole)



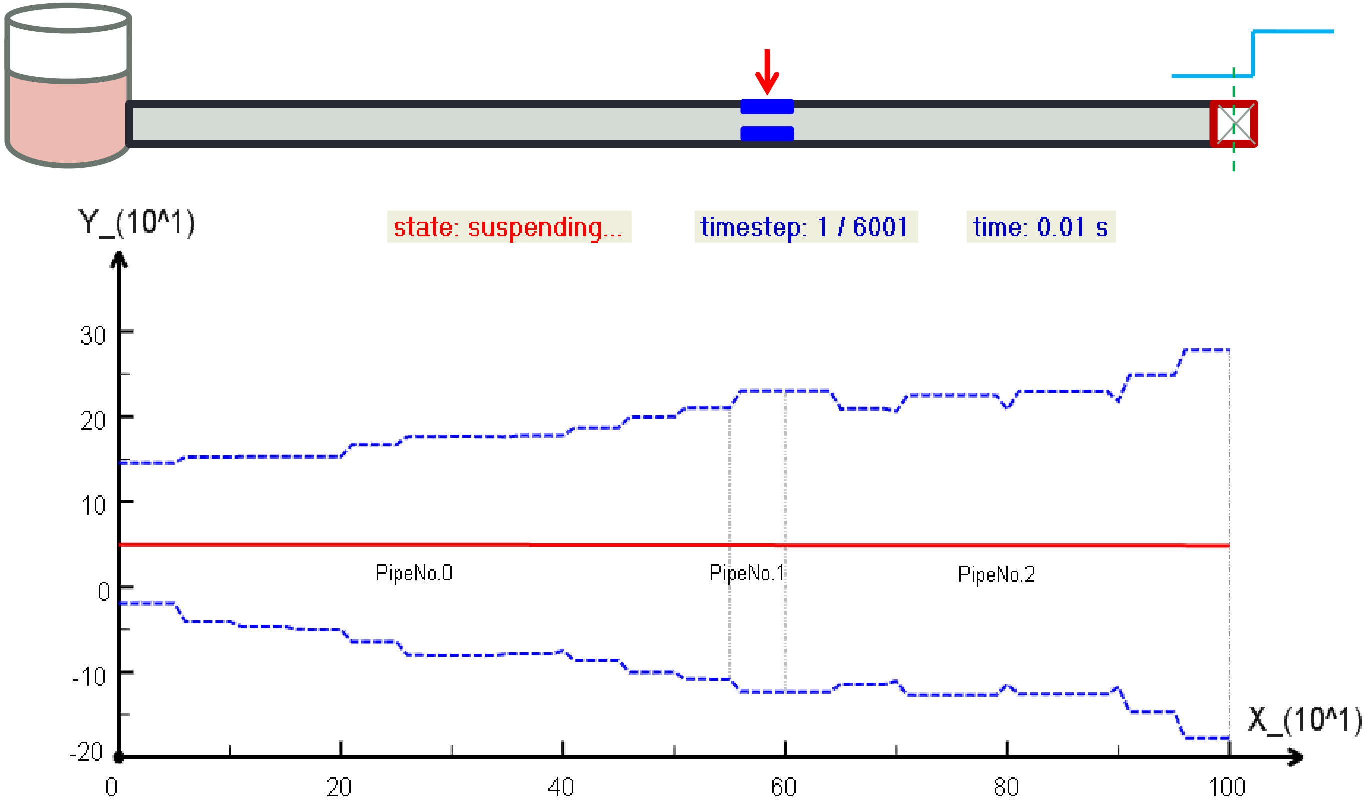
Transient Waves in Pressurized Pipelines

- Wave propagation in the pipeline with a discrete blockage (e.g., partially-closed inline valves)



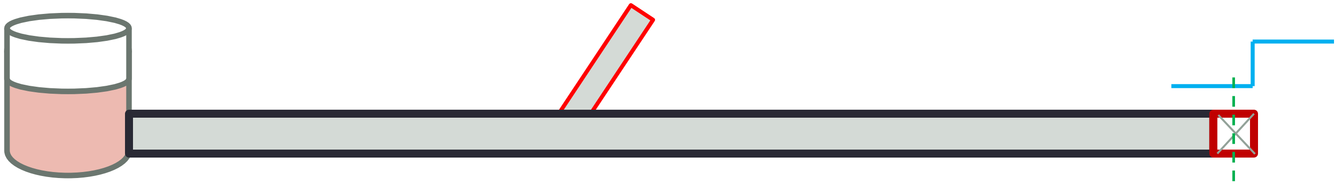
Transient Waves in Pressurized Pipelines

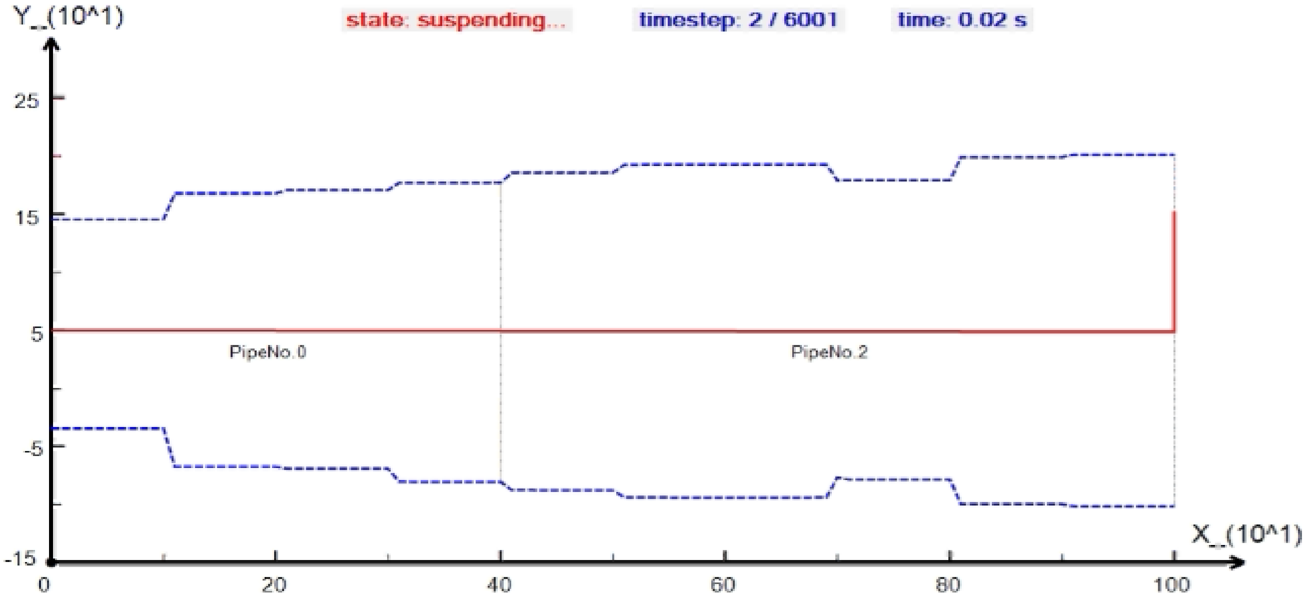
- Wave propagation in the pipeline with an extended blockage (e.g., corrosion/sediment)



Transient Waves in Pressurized Pipelines

- Wave propagation in the pipeline with a dead-end side-branch (e.g., illegal/unknown sections)





Information of Defects in Waves

- Reflections (oscillations)
  - Local inhomogeneities due to defects
  - Wave reflection / transmission / superposition

- Attenuation (damping)
  - Local head loss (turbulence/friction at defects)
  - Local mass loss (e.g., leaking/side-branch cases)

Wave Reflections & Damping – Essential Information for TBM

(Duan et al. 2010, etc.)

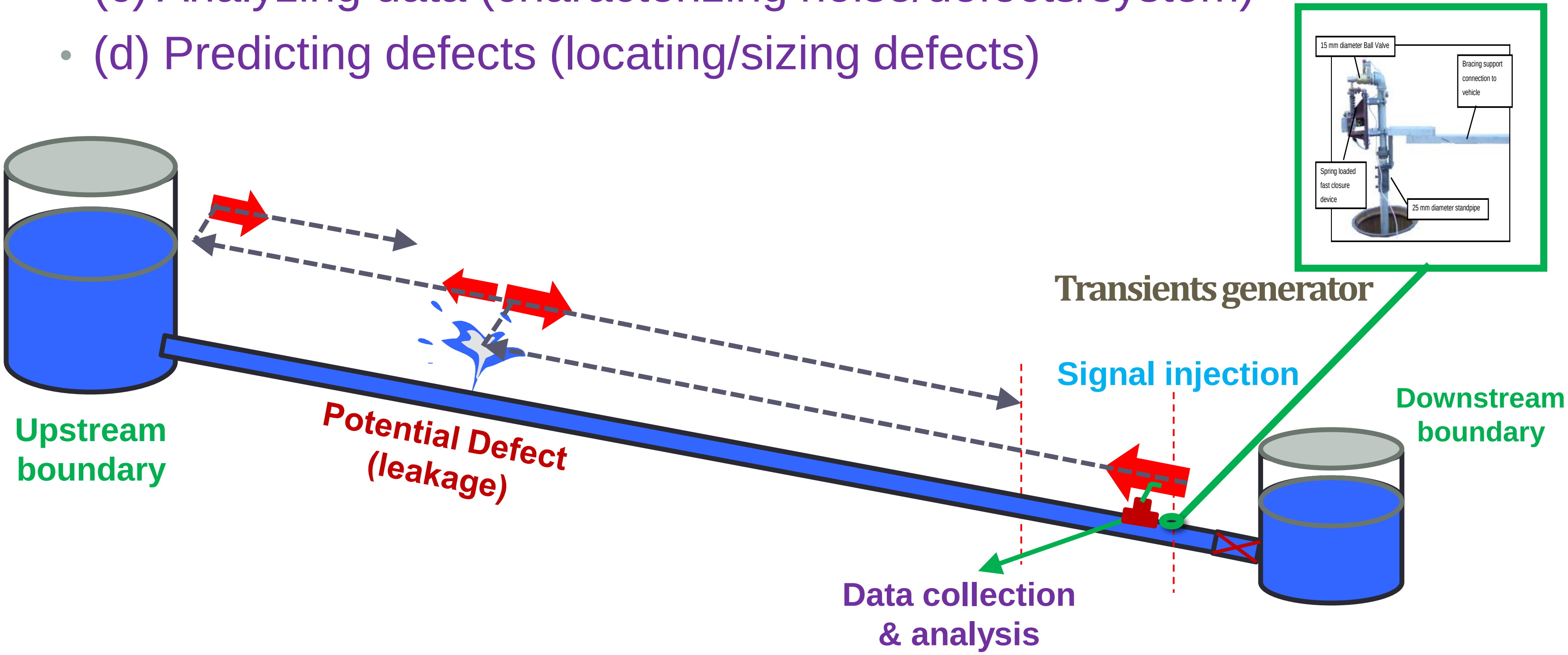
How to Utilize Wave Information in TBM?

- Long-period wave methods (“whole” signal)
  - Direct calibration and analysis
    - Time-domain signal fitting
    - Frequency-domain signal fitting
    - Time consuming and data dependent
    - easily contaminated (turbulence, noises, low-flow stabilities)

- Short-period wave methods (partial signal):
  - Inverse analysis of analytical “pattern” (pre-derived)
    - Time-domain “pattern”
    - Frequency-domain “pattern”

Transient-Based Methods (TBM)

- Procedure of TBM for Defect Detection:
  - (a) Sending waves (input signals)
  - (b) Measuring signals at accessible locations (response signals)
  - (c) Analyzing data (characterizing noise/defects/system)
  - (d) Predicting defects (locating/sizing defects)



Transients generator

Signal injection

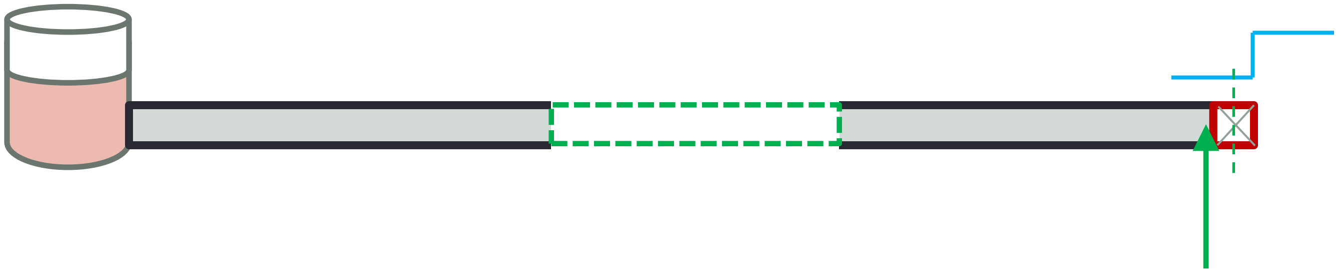
Downstream boundary

Upstream boundary

Potential Defect (leakage)

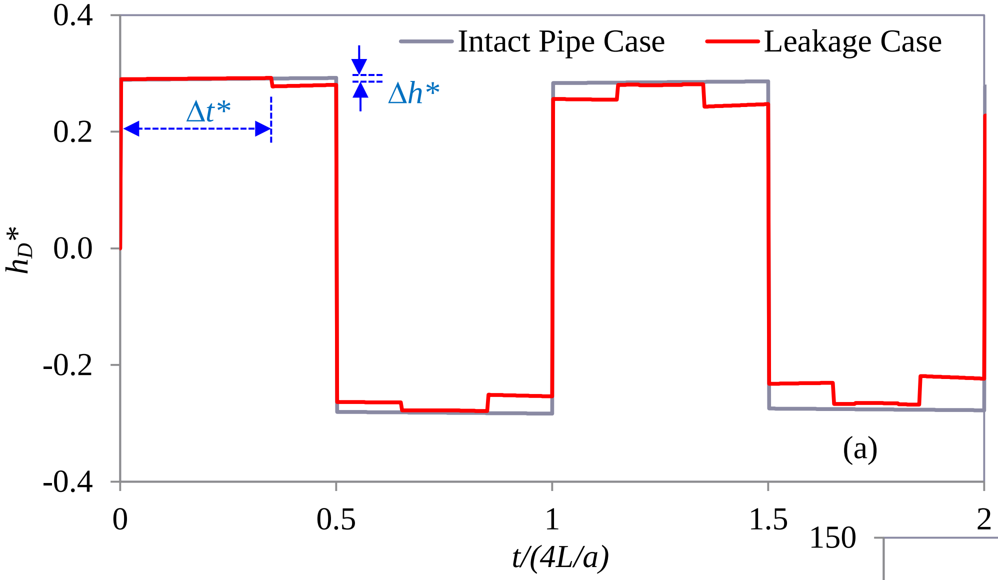
Data collection & analysis

Part – 1:
TBM for Single/Simple Pipe Systems



Data collection location

Transient Signature: Leakage



Time-domain:

$$x_L^* = 2\Delta t^*$$

$$A_L^* \approx \phi \Delta h^* (1 - \Delta h^*)^{-0.5}$$

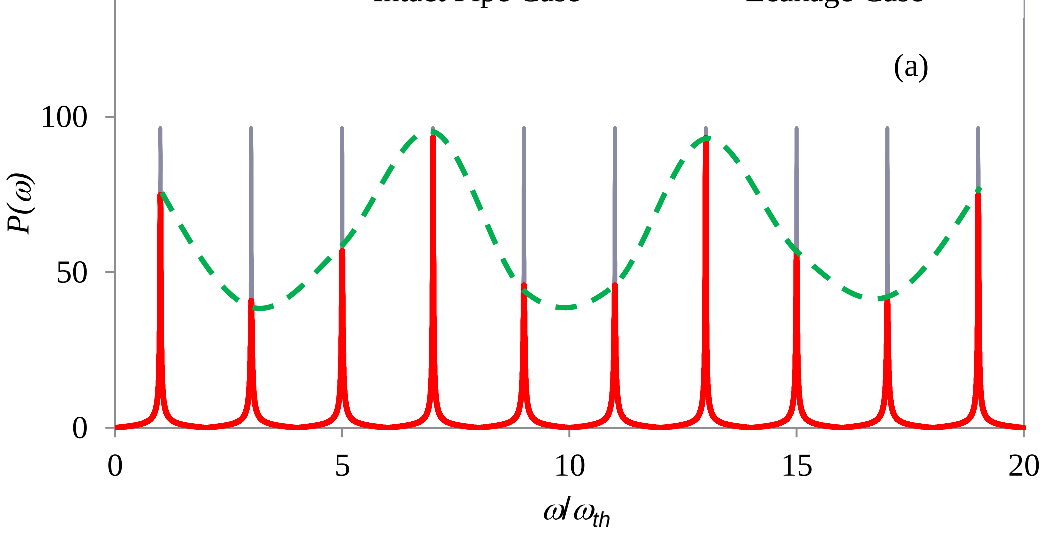
(Brunone 1999, etc.)

Frequency-domain:

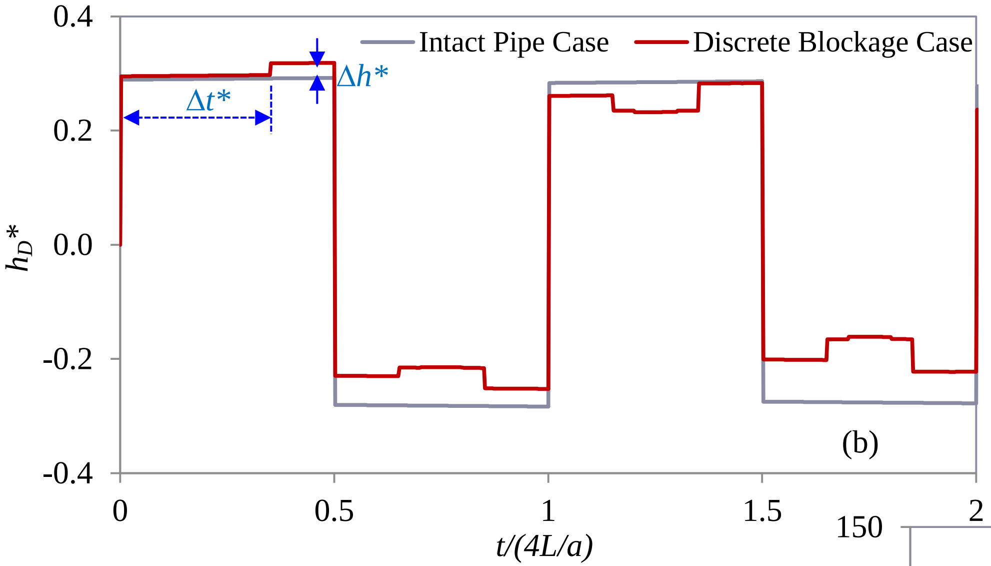
$$\boxed{\hat{P} = \alpha \cos\left(2\pi k x_L^* - \theta\right) + \beta}$$

x_L^* = leak location; α = leak size;
k = number of resonant peaks;
θ, β = coefficients

(Lee et al. 2006, etc.)



Transient Signature: Discrete Blockage



Time-domain:

$$x_L^* = 2\Delta t^*$$
$$\xi_{d0}^* \approx \Delta h^*$$

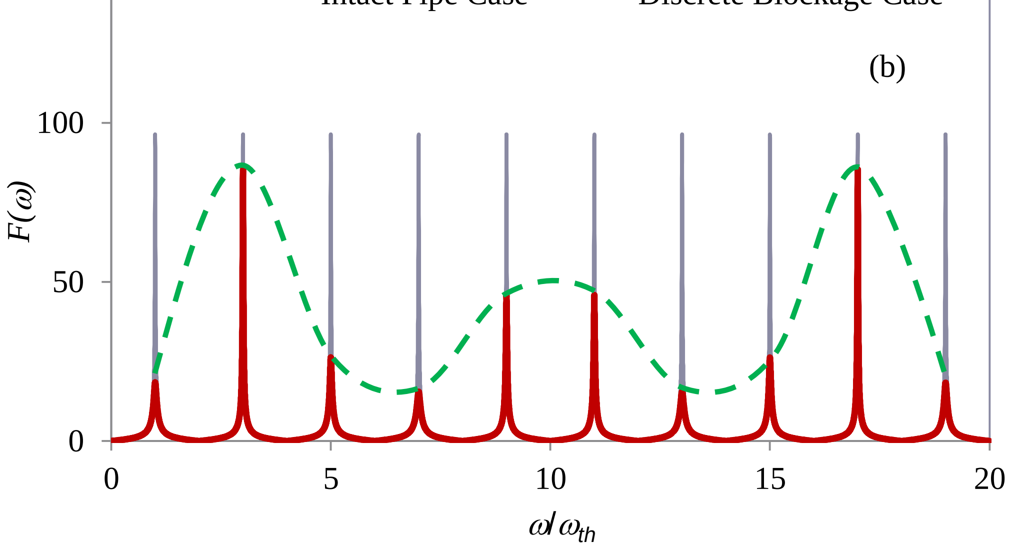
(Contractor 1965, Meniconi et al. 2011a, etc.)

Frequency-domain:

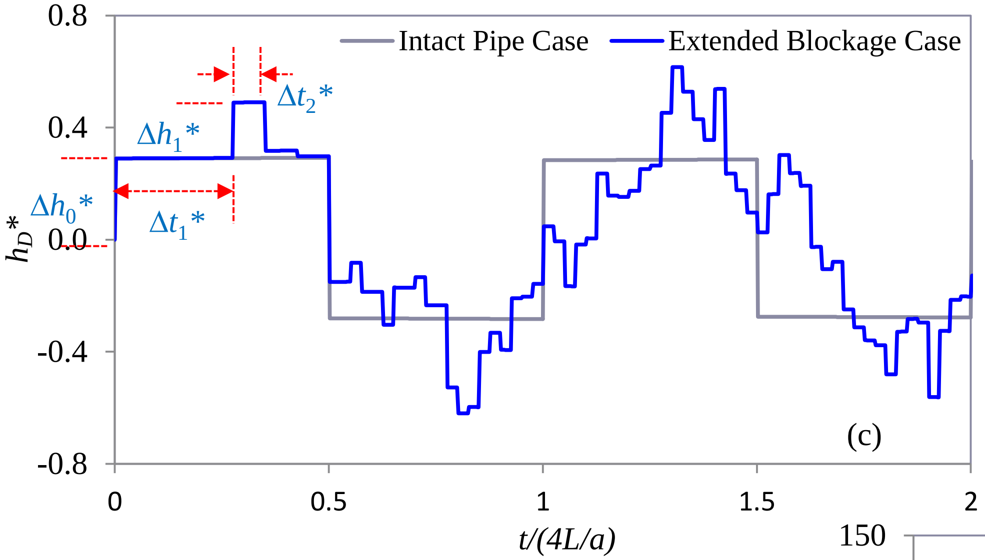
$$\boxed{F^*(m) = I_B^*\left(1+\cos\left(2\pi m x_B^* - \theta\right)\right)+\beta}$$

x_B^* = discrete blockage location; I_B^* = discrete blockage impedance; m = number of resonant peaks; θ, β = coefficients

(Lee et al. 2008, etc.)



Transient Signature: Extended Blockage



Time-domain:

$$x_{bD}^* = 2\Delta t_1^*$$

$$L_b^* = 2\Delta t_2^*$$

$$A_b^* = \frac{A_b/a_b}{A_0/a_0} = \frac{\Delta h_0^* - \Delta h_1^*}{\Delta h_0^* + \Delta h_1^*}$$

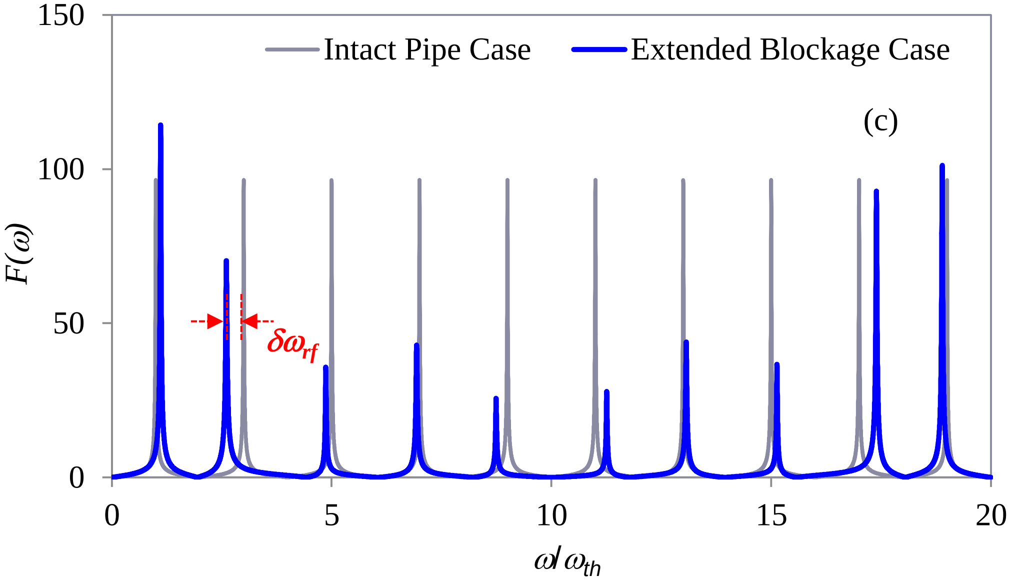
(Meniconi et al. 2013)

Frequency-domain:

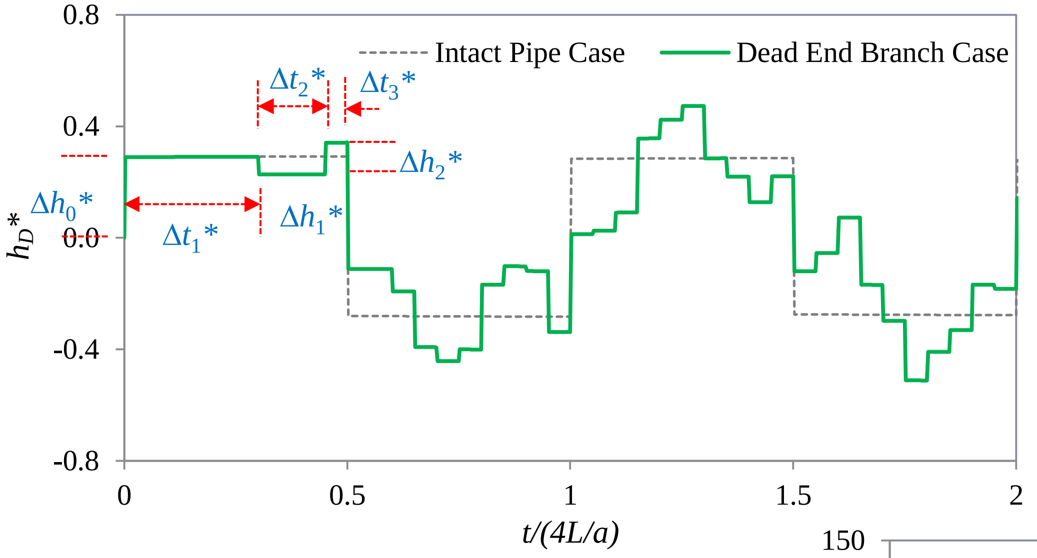
$$\delta\omega_{rf}^* \approx (-1)^{k+1}\frac{\varepsilon}{\pi}\sin\left[\lambda_2\omega_{rf0}\right]\sin\left[(\lambda_1-\lambda_3)\omega_{rf0}\right]$$

$\delta\omega_{rf}^*$ = peak frequency shift; ω_{rf0} = system fundamental frequency; ε = relative blockage size; k = number of resonant peaks; $\lambda_i = L_i/a_i$ = wave propagation coefficients.

(Duan et al. 2012, 2013, etc.)



Transient Signature: Dead-End Side-Branch



Time-domain:

$$x_{SB}^* = 2\Delta t_1^*$$

$$L_{SB}^* = 2\Delta t_2^* \text{ or } 2|\Delta t_2^* \pm \Delta t_3^*|$$

$$A_{SB}^* = \frac{A_{SB}/a_b}{A_0/a_0} = f(\Delta h_0^*, \Delta h_1^*, \Delta h_2^*)$$

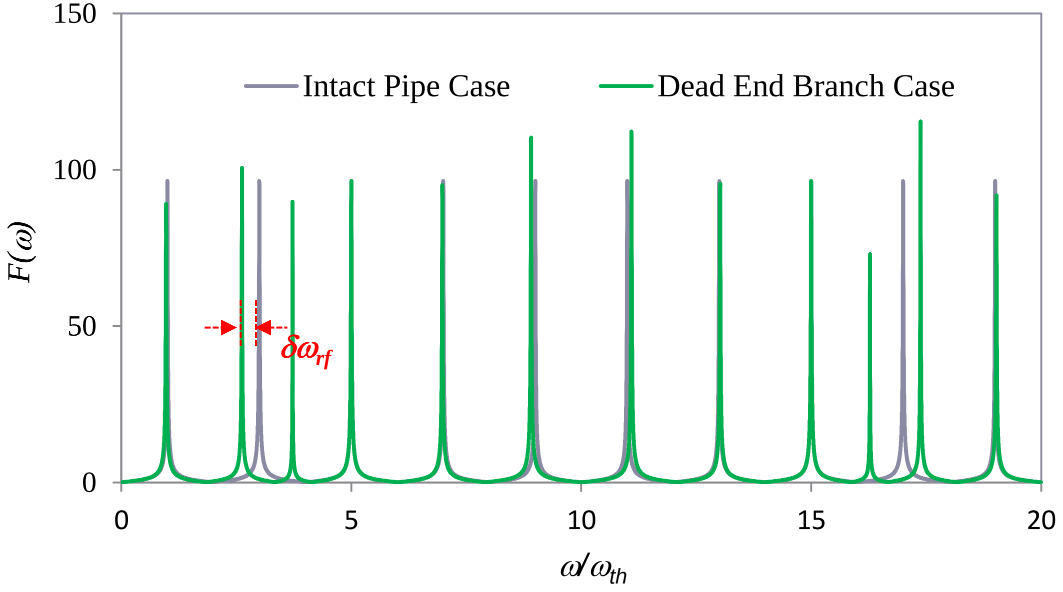
(Meniconi et al. 2011b)

Frequency-domain:

$$\delta\omega_{rf}^* = -\frac{2\varepsilon}{\pi}\frac{\sin[\lambda_3\omega_{rf0}]\cos^2[\lambda_2\omega_{rf0}]}{\cos[\lambda_3\omega_{rf0}]}$$

$\delta\omega_{rf}^*$ = peak frequency shift; ω_{rf0} = system fundamental frequency; ε = relative branch size; $\lambda_i = L_i/a_i$ = propagation coefficients.

(Duan and Lee 2015)



Applications and Accuracy of TBM

- Numerical Applications (“Ideal” tests)
  - TDM:
    - Ferrante and Brunone (2003, 2004); Ferrante et al. (2007); Tuck et al. (2013, 2014);
    - Liggett and Chen (1994); Beck et al. (2005); AL-Khomairi (2008); etc.
  - FDM:
    - Lee et al. (2008, 2013, 2014); Duan et al. (2010, 2011, 2012a, 2012b, 2014, 2015);
    - Mpesha et al. (2001); Kim (2005); Mohapatra et al. (2006), Sattar et al. (2008); etc.
- Experimental Applications (Lab/Field tests)
  - TDM:
    - Brunone et al. (1999, 2001); Meniconi et al. (2009, 2011, 2012, 2013);
    - Stephens et al. (2004, 2008); Vıtkovsky et al. (2007); etc.
  - FDM:
    - Lee et al. (2006, 2014); Duan et al. (2013, 2014); Meniconi et al. (2013);
    - Wang et al. (2002, 2005); Covas et al. (2005); etc.

Results: more accurate to <u>locating defects</u> than to <u>sizing defects!</u>

Comparison of TDM & FDM

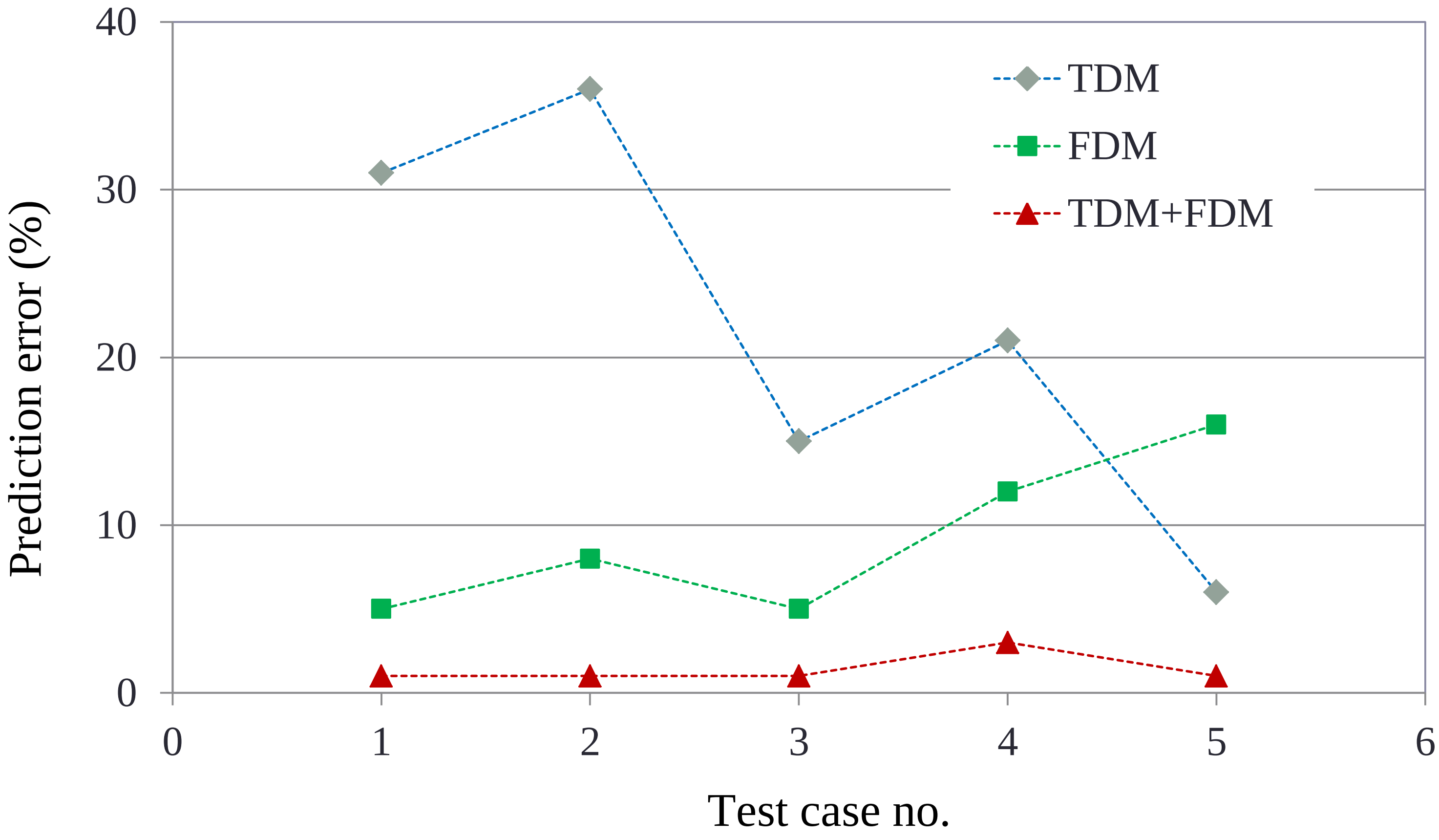
(For simple pipe systems)

- Theoretically, both TDM & FDM are capable of detecting (locating and sizing) these four types of defects by the pre-derived “patterns”;

- But in applications,
  - FDM is more comprehensive and accurate than TDM, because some common complex factors such as friction and local dissipation effects are excluded in TDM;
  - TDM is more efficient and more simple to use than FDM in practical case studies.

Combination of TDM & FDM

- Meniconi et al. (2014) – Lab experiment tests
  - Pipe test system in New Zealand



Prediction for the length of extended blockage

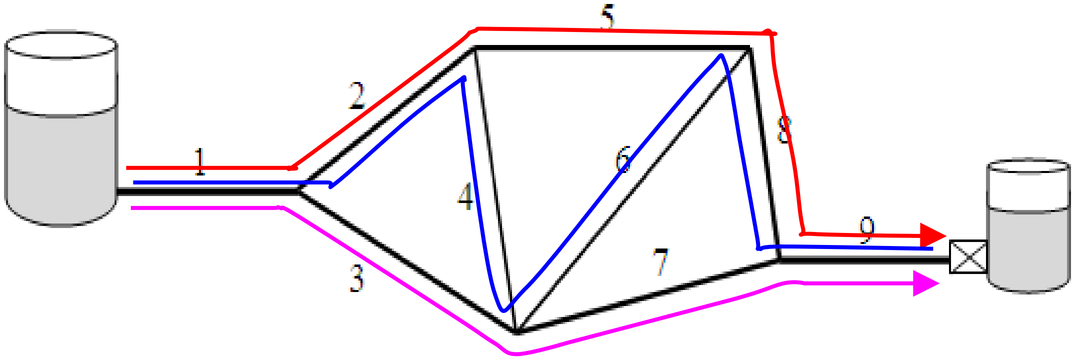
Part – 2:
TBM for More Complex Pipe Systems
(Using FDM for Illustration)

(2.1) Multiple-Pipe Systems

- Leakage in series pipes (Duan et al. 2011)

FDM – Pattern: $$h_L^* = A_L^*\left[1 - \cos\left(2x_L^* \frac{\omega_{rf}}{a} L + \phi\right)\right]$$

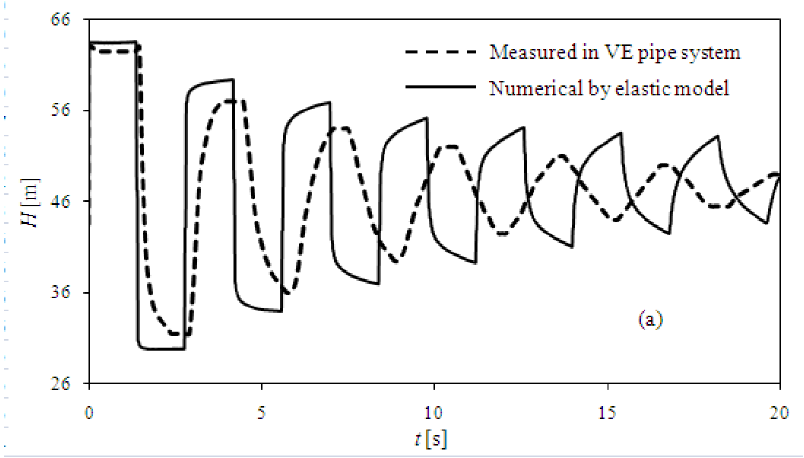
Leak information is independent of junctions

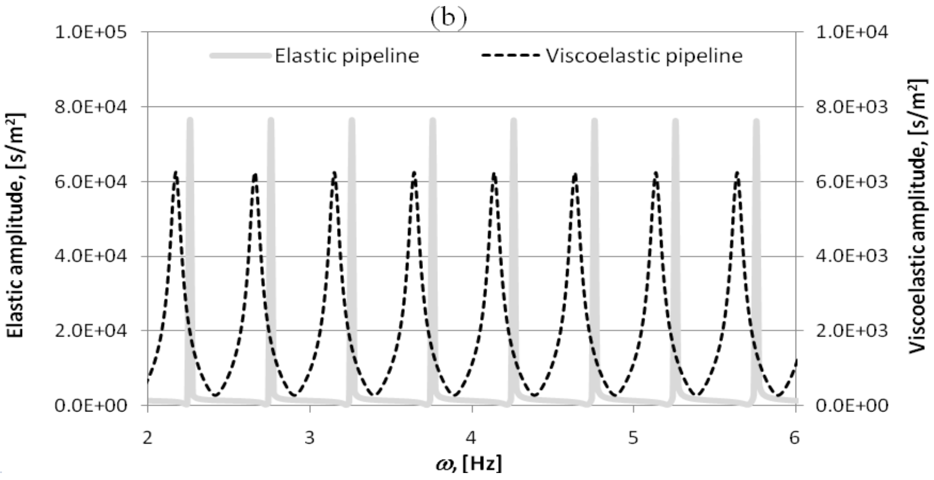


only 1/3 of original test work for this are needed!!!

(2.2) Viscoelastic Pipe Systems

- Plastic pipelines (Duan et al. 2012)





FDM – Pattern:

$$h^*_{leak\text{-}as} = A^*_{leak\text{-}as}\left(1-\cos\left(2x^*_L \frac{\omega_{rf-VE}}{a} L\right)\right)$$

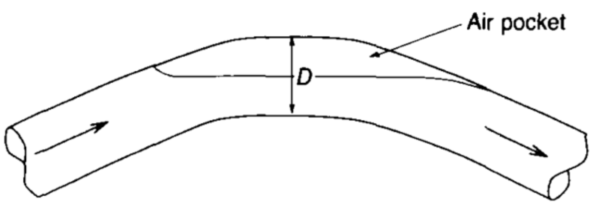
$$\omega_{rf-VE} = \frac{\omega_{rf-Elastic}}{\sqrt{W}}$$

W: visco-elastic parameter

The existing method can be extended to visco-elastic pipelines as long as the W is known!

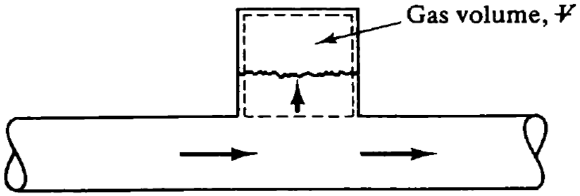
(2.3) Pipeline with Ends / Elbows

- Air-pocket detection (Duan & Lee &…, 2015)



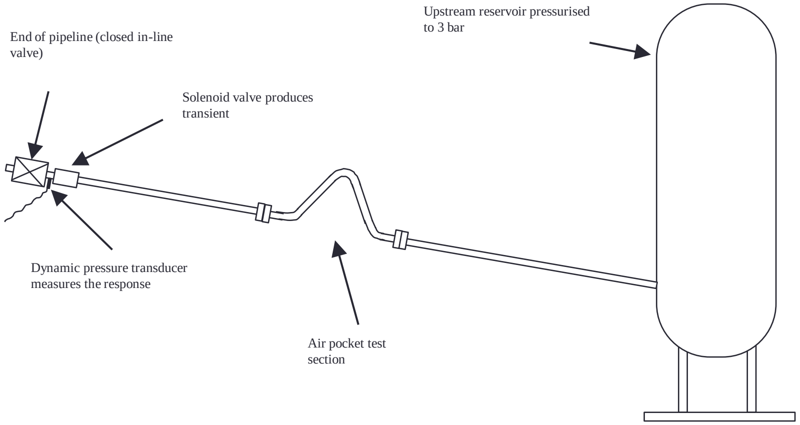
Inline air-pocket

(Burrows and Qiu 1995)



Offline air-pocket

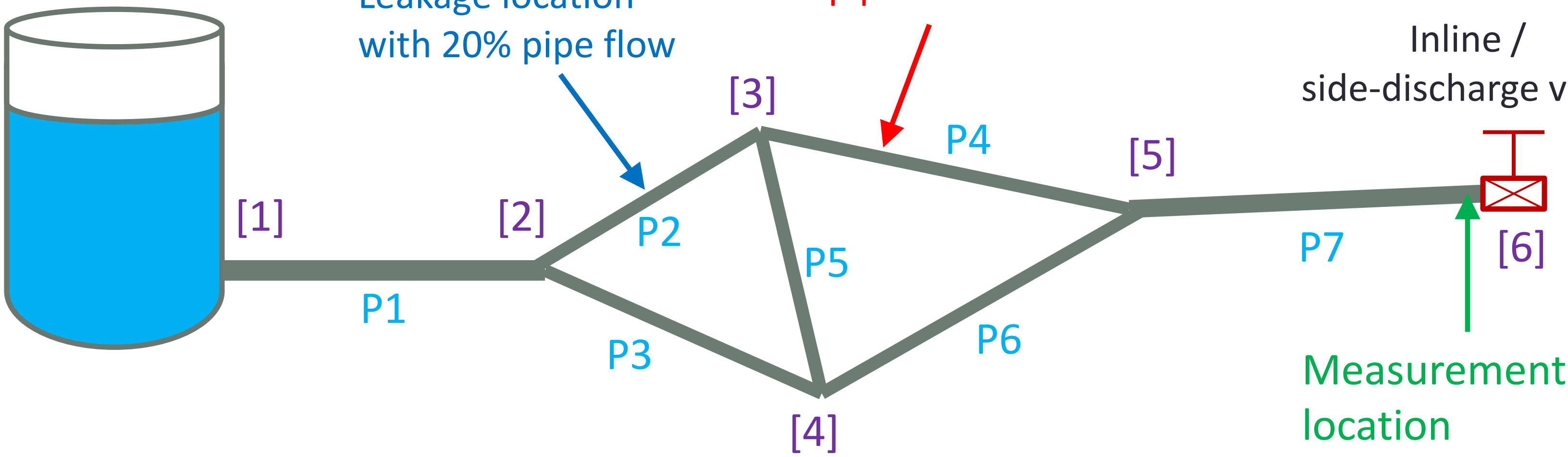
Streeter and Wylie (1993)



Experiment Test System (NZ)

(2.4) Pipe Networks

Numerical Test Case



Reservoir, with available head, e.g., H_a=50m

Leakage location with 20% pipe flow

Blockage location with 30% pipe area

Inline / side-discharge valve

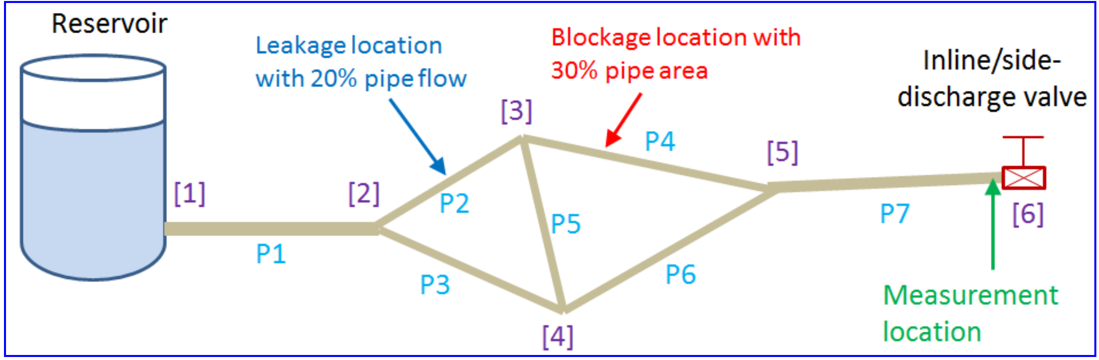
Measurement location

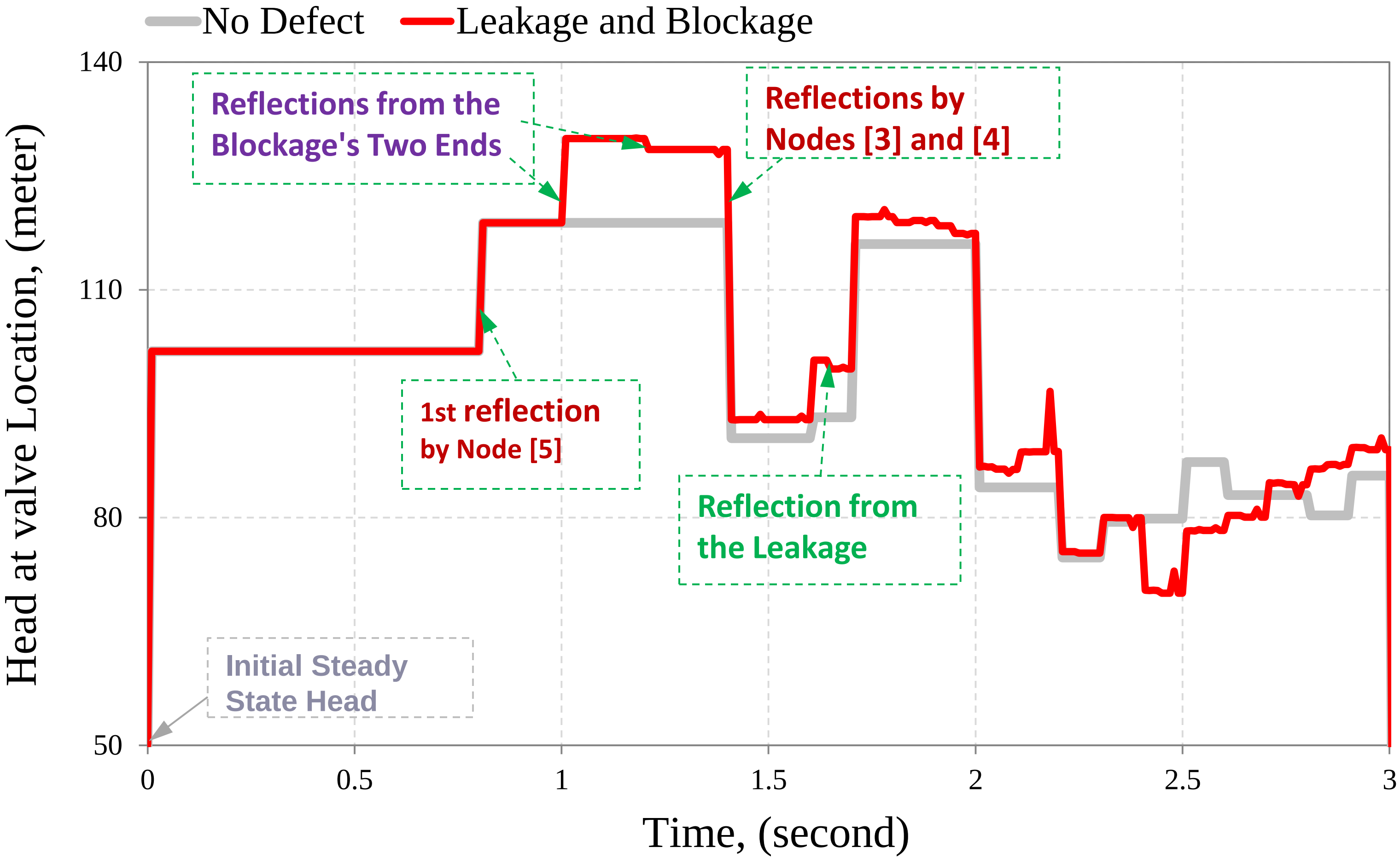
Notations:

[1] = nodal number
P1 = pipe number

Transient Responses at Valve

Numerical Results





Practical Influence Factors

- Input Signals (Lee et al. 2015)
  - Bandwidth
  - Amplitude

- System Complexities (Duan et al. 2011, 2015, etc.)
  - Pipe configurations
  - Defect characteristics (types, inhomogeneities)
  - Noises & uncertainties
  - …

Future Development of TBM

(on the basis of current achievements)

- TDM & FDM (& Combination)
  - For complex pipe systems (e.g., networks)
  - Characterization of different types of defects
- LFW & HFW (& Combination)
  - Range vs. Resolution
  - Efficiency vs. Accuracy

Key References (by the Project Team Members)

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- Duan, H.F., Lee, P.J., Ghidaoui, M.S., Tung, Y.K. (2010b). Essential system response information for transient-based leak detection methods. *J. of Hydraulic Research*, IAHR, 48(5), 650-657.
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- etc……….

Thank you !