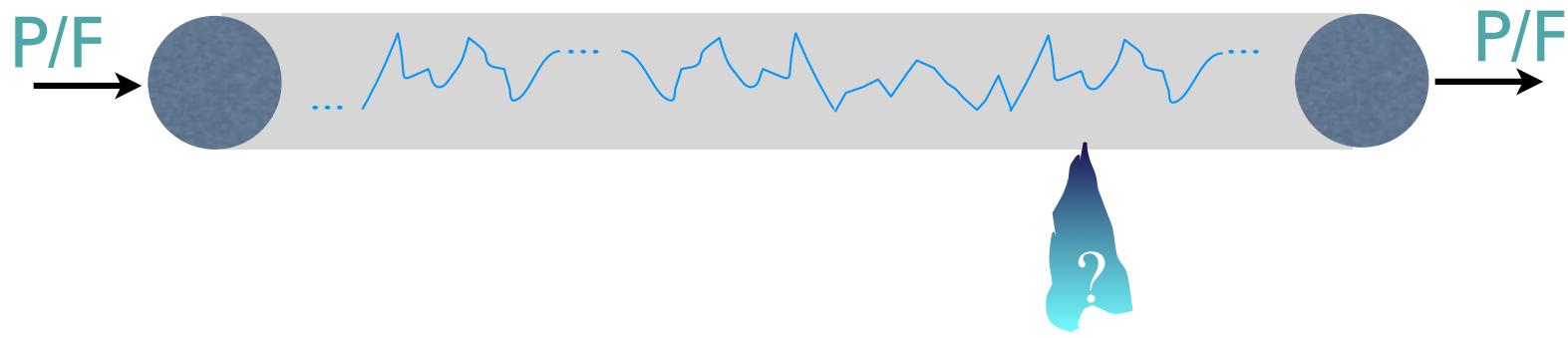


Leak Detection on Liquid Pipelines



George Harriott / Junxiao Wu / Vishrut Garg / Edward O'Reilly / Michael Pingitore

Corporate Technology / Air Products

P2SAC Spring Conference / Purdue University / May 12, 2022

Air Products Overview

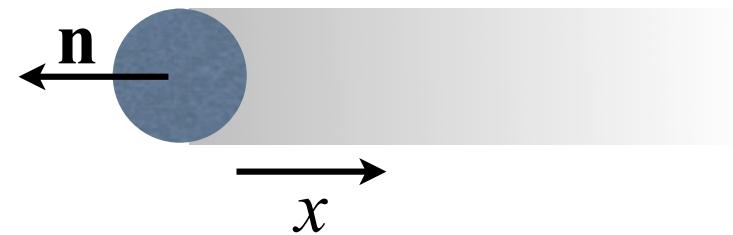
- Industrial gas ...O₂...N₂...Ar...H₂...CO...He...Xe...CO₂...
- Founded in 1940
- 20,000 employees
- \$10.3 billion sales
- Separation & liquefaction equipment
- Hydrocarbon gasification (gas / liquid / solid)
- Ammonia production (hydrogen carrier)



Leak Detection Strategy

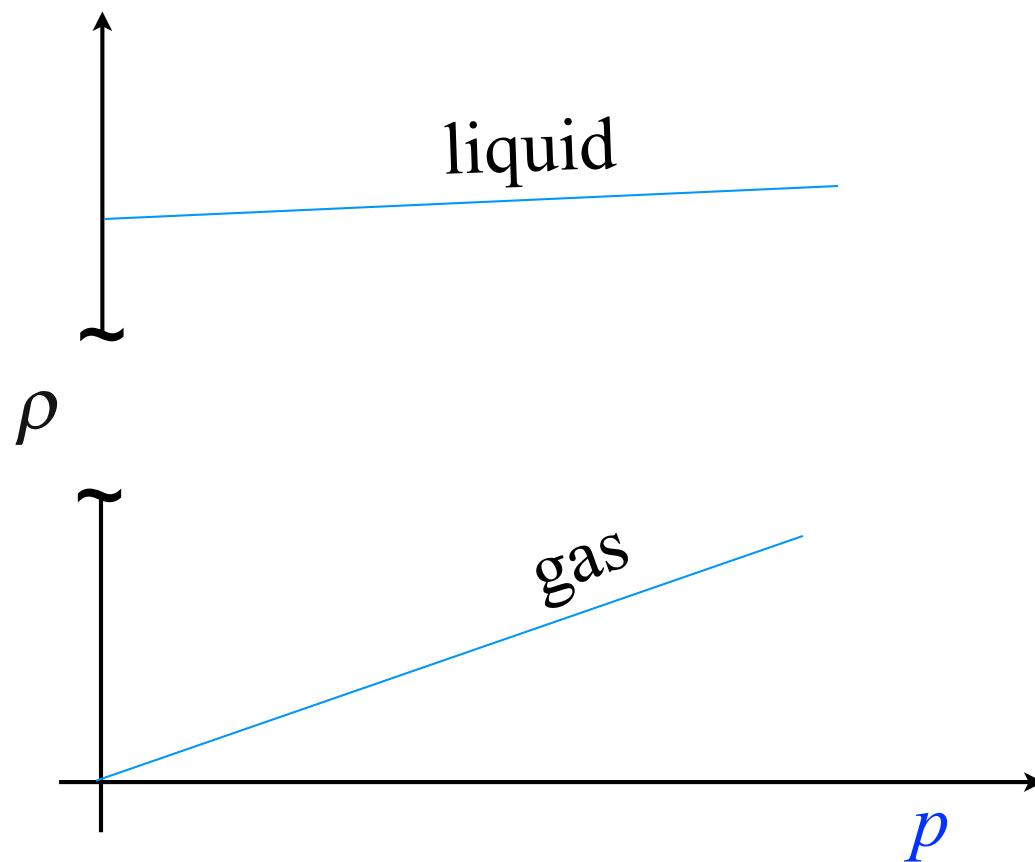
- Measure pressure, flow, temperature at boundaries
- Simulate fluid dynamics (assuming no leak)
- Construct boundary flow residuals...

$$\Delta = \mathbf{n} \cdot (\mathbf{F}_S - \mathbf{F}_D)$$



- ... to identify and locate leaks

Density-Pressure



Conservation Laws

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \textcolor{red}{q} = 0$$

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial \textcolor{blue}{p}}{\partial x} + \frac{f}{R} \rho u |u| = 0$$

(Energy Balance)

Liquid State Equation

$$\rho = \rho_0 + \left(\frac{\textcolor{blue}{p} - p_0}{c^2} \right) \quad \left| \quad \left(\frac{\textcolor{blue}{p} - p_0}{c^2} \right) \ll \rho_0 \right.$$

Pressure-Velocity Dynamics

$$\rho = \rho_0 + \left(\frac{\mathbf{p} - \mathbf{p}_0}{c^2} \right) \Rightarrow \partial \rho = \frac{\partial \mathbf{p}}{c^2}$$

⇓

$$\frac{1}{c^2} \left(\frac{\partial \mathbf{p}}{\partial t} + u \frac{\partial \mathbf{p}}{\partial x} \right) + \rho_0 \frac{\partial u}{\partial x} + \mathbf{q} = 0$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \frac{1}{\rho_0} \frac{\partial \mathbf{p}}{\partial x} + \frac{f}{R} u |u| = 0$$

Scaling

$$\boxed{x \rightarrow L \quad t \rightarrow L/c \quad u \rightarrow U \quad \textcolor{blue}{p} \rightarrow \rho_0 c U}$$

$$U \ll c$$



$$\boxed{\begin{array}{|c|c|} \hline \frac{\partial \textcolor{blue}{p}}{\partial t} + \frac{\partial u}{\partial x} + \textcolor{red}{\mu} = 0 & \textcolor{red}{\mu} = \frac{\textcolor{red}{q}}{\rho_0 U} \\ \hline \frac{\partial u}{\partial t} + \frac{\partial \textcolor{blue}{p}}{\partial x} + \textcolor{green}{\lambda} u |u| = 0 & \textcolor{green}{\lambda} = \frac{fL}{R} \frac{U}{c} \\ \hline \end{array}}$$

Dimensions & Scales

$$L = 2000 \text{ ft}$$

$$R = 1/3 \text{ ft}$$

$$c = 4000 \text{ ft/s}$$

$$U = 10 \text{ ft/s}$$

$$\rho_0 = 0.69 \text{ g/cc}$$

$$R_e \sim O(10^6) \Rightarrow f \sim 1/300$$

$$T \equiv L/c = 0.5 \text{ s}$$

$$P \equiv \rho_0 c U = 372 \text{ psi}$$

$$\lambda \equiv \frac{fL}{R} \frac{U}{c} = 0.05$$

Characteristic Form I

$$\phi \equiv \begin{Bmatrix} p \\ u \end{Bmatrix} \Rightarrow \boxed{\mathbf{A} \cdot \frac{\partial \phi}{\partial t} + \mathbf{B} \cdot \frac{\partial \phi}{\partial x} + \psi = 0} \Leftrightarrow \begin{Bmatrix} \mu \\ \lambda u |u| \end{Bmatrix} \equiv \psi$$

Eigenvalue (σ) / Eigenvector (ξ): $\sigma(\xi \cdot \mathbf{A}) = \xi \cdot \mathbf{B}$

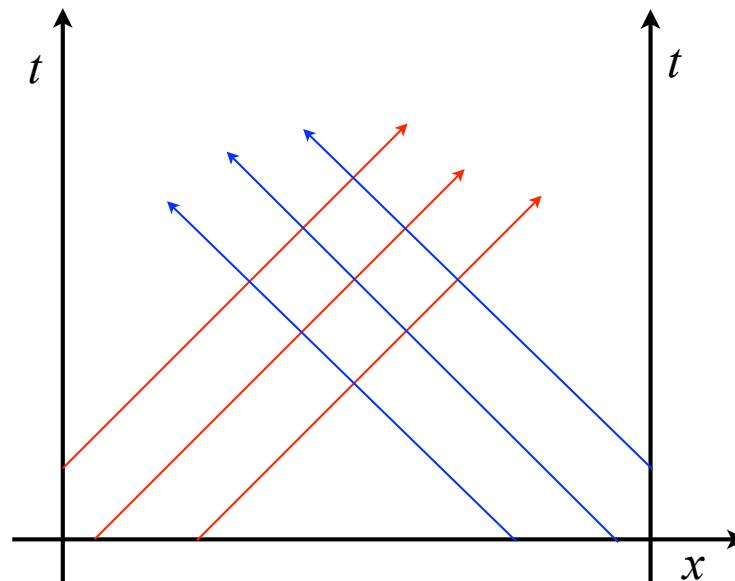
$$(\xi \cdot \mathbf{A}) \left\{ \frac{\partial \phi}{\partial t} + \sigma \frac{\partial \phi}{\partial x} \right\} + \xi \cdot \psi = 0$$

$$\boxed{(\xi \cdot \mathbf{A}) \cdot \frac{d\phi}{dt} + \xi \cdot \psi = 0 \quad : \quad \frac{dx}{dt} = \sigma}$$

Characteristic Form II

$$\frac{d}{dt}(\textcolor{blue}{p} + u) + \textcolor{red}{\mu} + \textcolor{green}{\lambda}u|u| = 0 \quad : \quad \frac{dx}{dt} = +1$$

$$\frac{d}{dt}(\textcolor{blue}{p} - u) + \textcolor{red}{\mu} - \textcolor{green}{\lambda}u|u| = 0 \quad : \quad \frac{dx}{dt} = -1$$



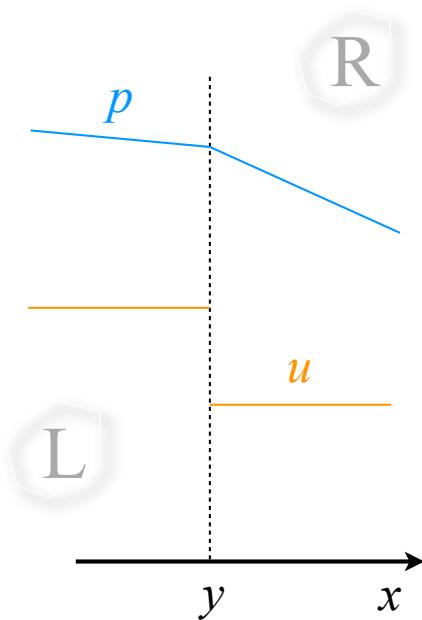
Small Point Leaks

Linear Equations: $p_0 \gg p, u_0 \gg u$

Boundary Conditions: $p = 0$ @ $x = 0, x = 1$

Point Leak: $\mu = \varepsilon \delta[x - y]$

Point Conditions: $p_L = p_R, u_L = u_R + \varepsilon$



$$\frac{d\Gamma^+}{dt} + 2\lambda|u_0|u = 0 : \frac{dx}{dt} = +1 \iff \Gamma^+ = p + u$$

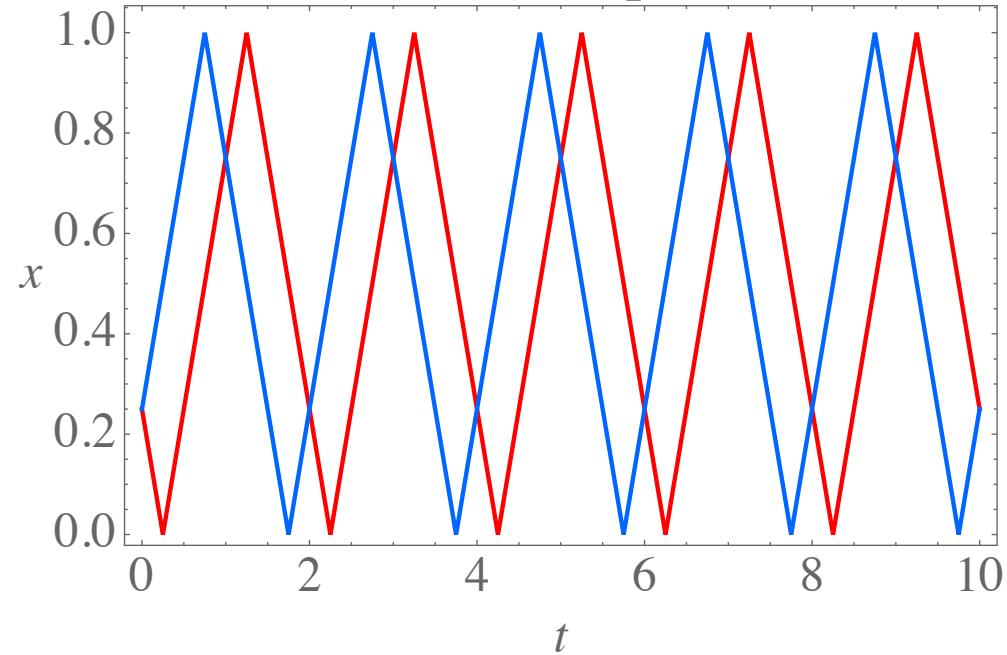
$$\frac{d\Gamma^-}{dt} - 2\lambda|u_0|u = 0 : \frac{dx}{dt} = -1 \iff \Gamma^- = p - u$$

Inviscid Dynamics

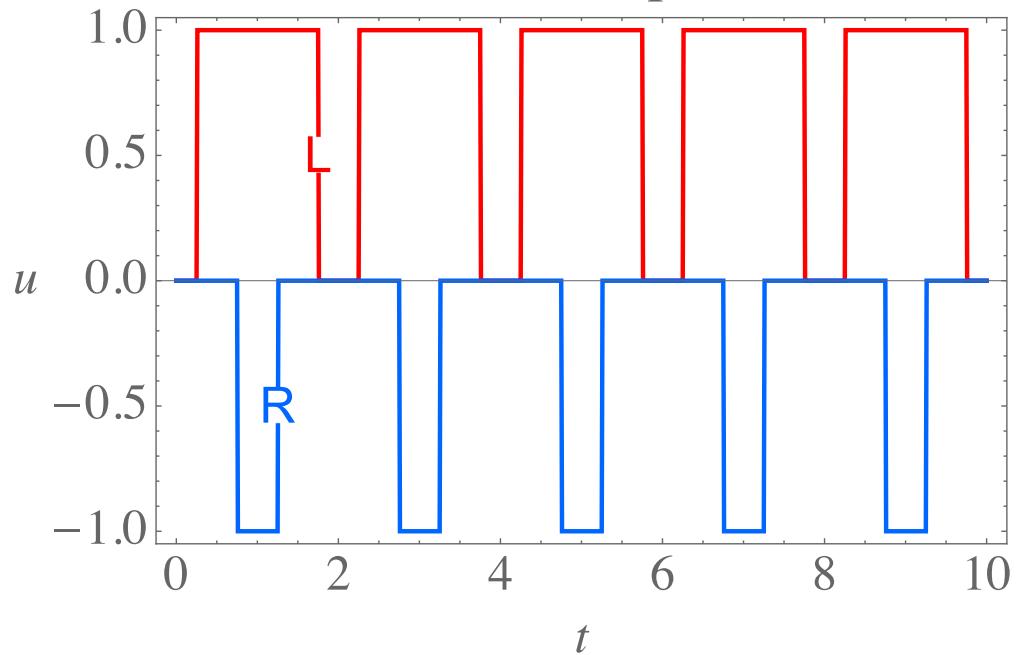
$$\frac{d\Gamma^+}{dt} = 0 : \frac{dx}{dt} = +1 \iff \Gamma^+ = p + u$$

$$\frac{d\Gamma^-}{dt} = 0 : \frac{dx}{dt} = -1 \iff \Gamma^- = p - u$$

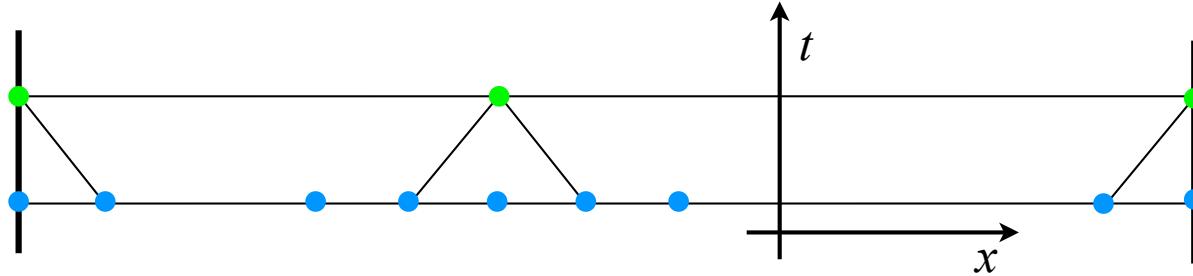
Inviscid Quarterpoint Leak



Inviscid Quarterpoint Leak

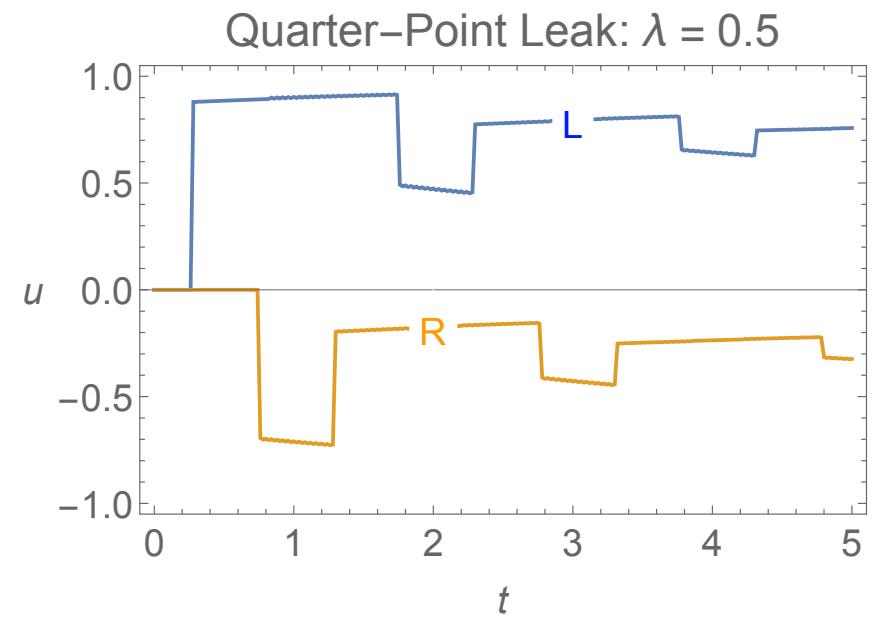
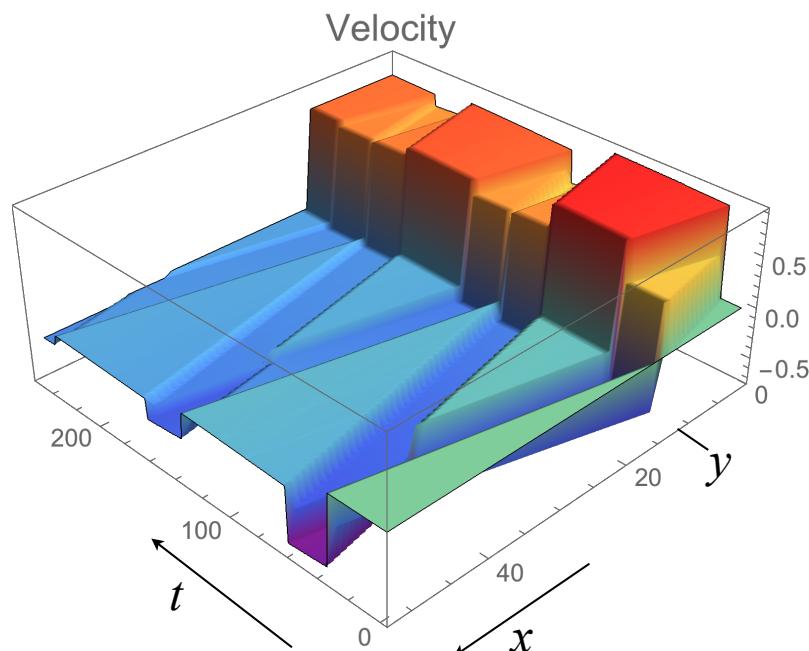


Computational Algorithm

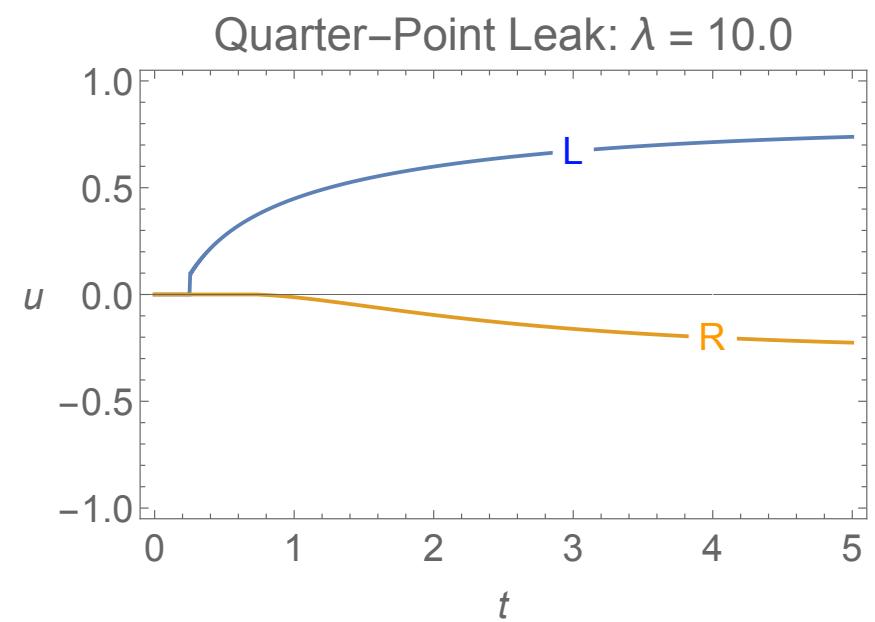
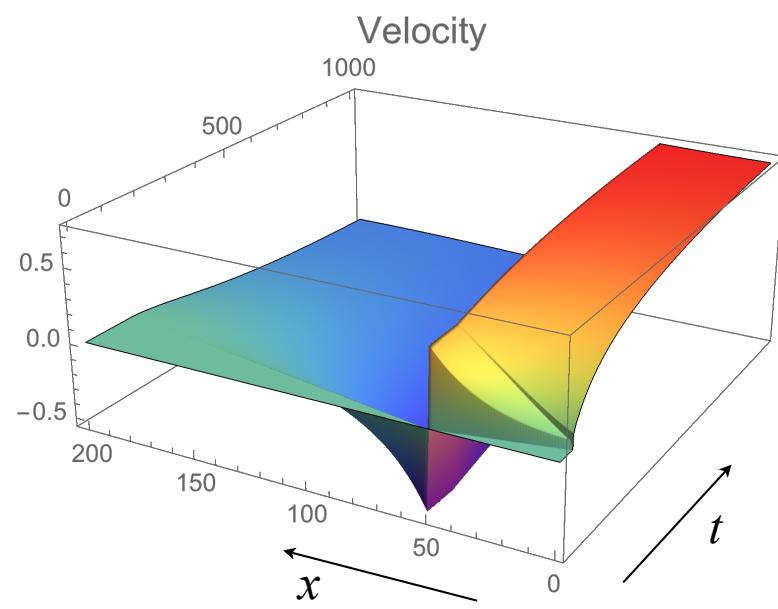


- Implicit Euler integration
- Exact solution of 2×2 linear equations
- Specified pressure or velocity at boundaries
- Pressure continuity and velocity jump at leak
- 2 ms per timestep (51 spatial nodes)

Inertial Leak Dynamics

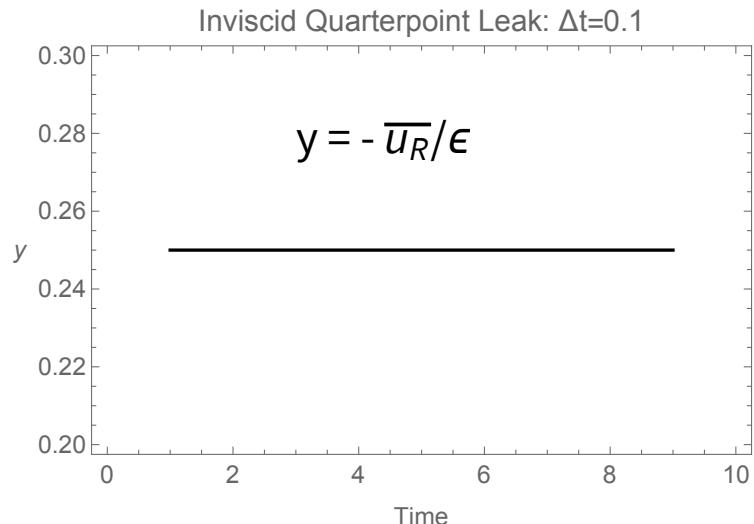
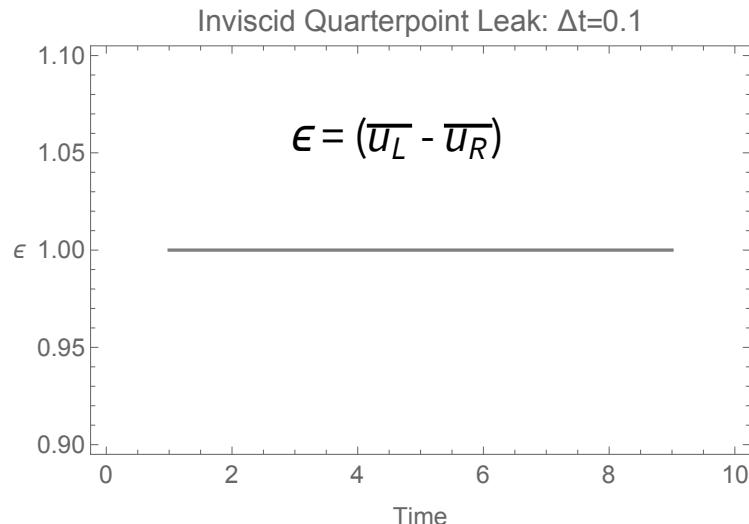
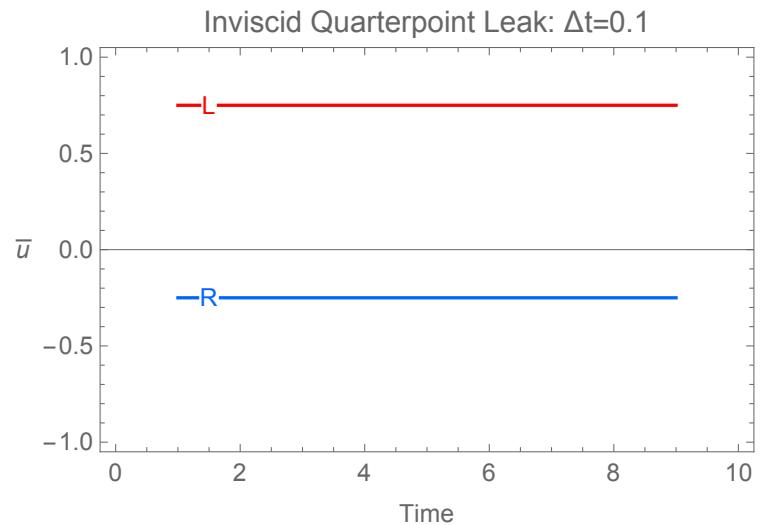
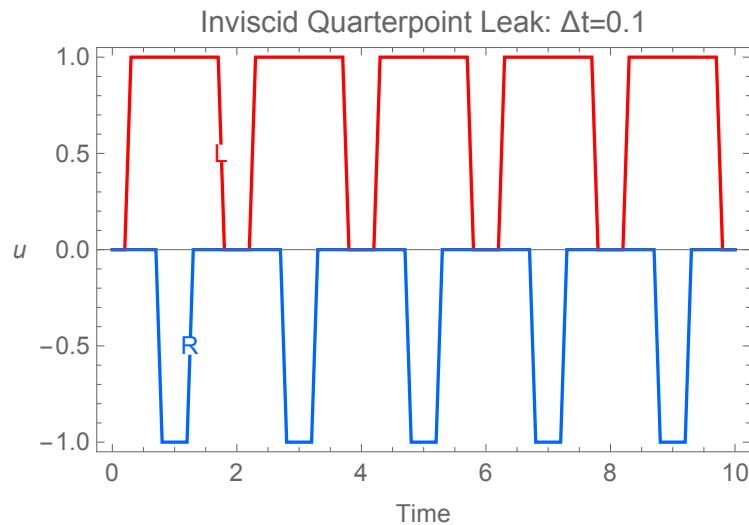


Frictional Leak Dynamics



Detection Algorithm

- Compute moving averages over the echo period -



Data Acquisition

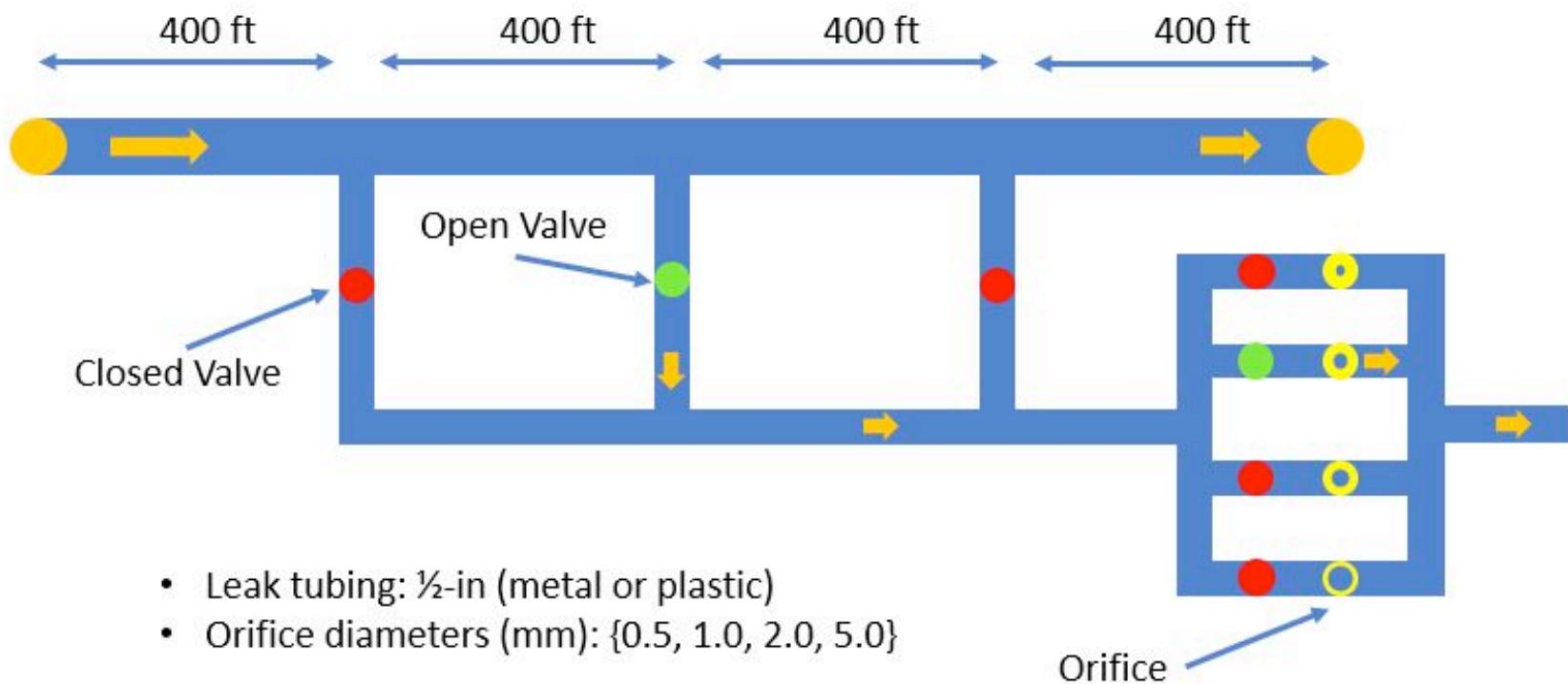
- Triple-redundant sensors (P, F, T)
- Modified Welch test for statistical consistency
- Sensor sample times < 100 ms
- Optical fiber data transfer to LDS PC

Challenges

- Temperature variation: will temperature changes along the pipeline alter the echo time?
- Transient turbulence: will rapid distortion of mean flow significantly increase friction?
- Data quality: will rapid response sensors generate large fluctuating errors?

Pipeline Laboratory I

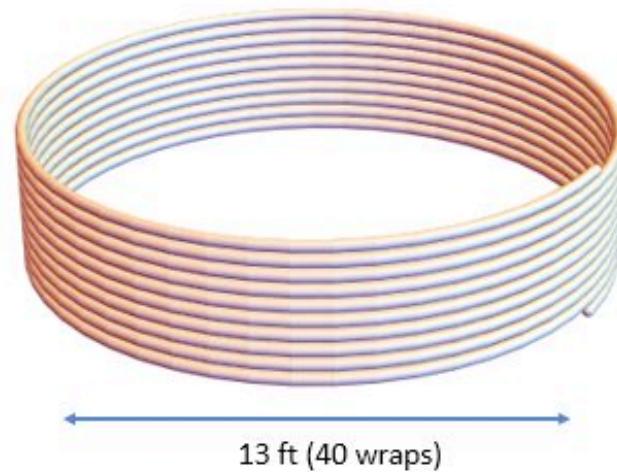
Piping Schematic



Pipeline Laboratory II

Dimensions & Parameters: 1 Inch Tubing

- $R = 0.5245 \text{ in}$ (1 in diameter aluminum tubing)
- $L = 1600 \text{ ft}$ ($c = 4066 \text{ ft/s} \rightarrow \tau_c = 0.39 \text{ s}$)
- $10^4 \leq R_e \leq 3 \times 10^4$
- $0.081 \leq \lambda \leq 0.207$
- $6 \leq \Delta P(\text{psi}) \leq 40$
- $2.5 \leq Q(\text{gpm}) \leq 7.5$



Summary

Rapid (seconds) leak detection is possible on short liquid pipelines provided that possible complications of...

- variable sonic velocity
- transient friction
- rapid response sensors

... can be resolved. Tests will show!