Kick Signatures through Advanced Multi-Phase Data

Project Number: FWP 1022409

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NATIONAL ENERGY TECHNOLOGY LABORATORY

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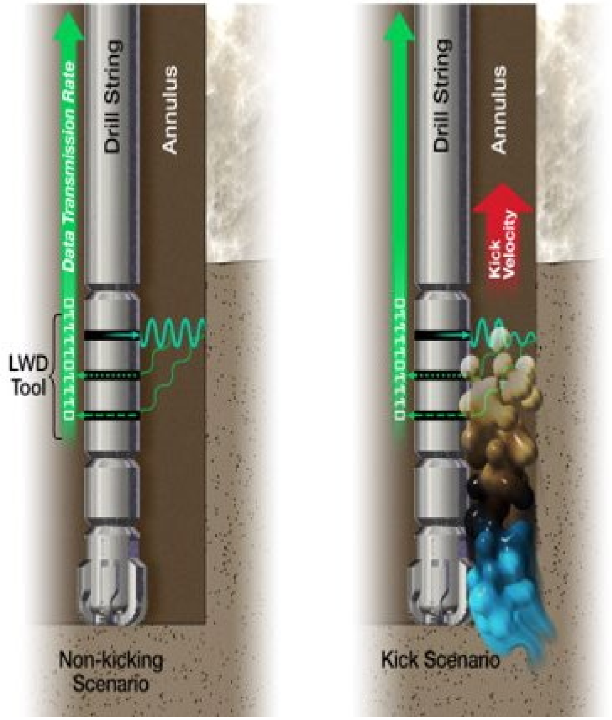
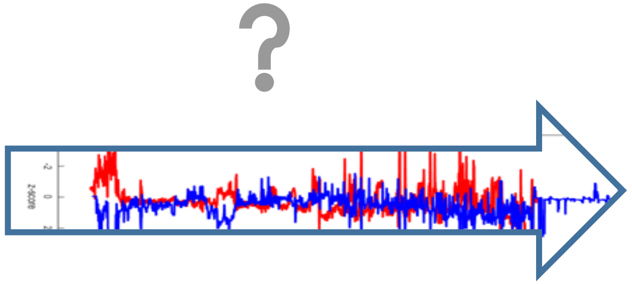
Motivation

Gas kicks represent a persistent threat during the drilling process. Traditional kick detection has significant time lag (hours) and is affected by missed and false detection.

Proposed Early Kick Detection (EKD) using geophysical signals from Logging-While-Drilling (LWD) sensors[2,3] : real-time (minutes)





a comprehensive multiphase flow dataset to support advanced EKD

- field/lab data is limited and not readily available
- synthetic data via experiments & advanced modeling offer a low-cost controlled opportunity.
  - https://edx.netl.doe.gov/offshore/portfolio-items/advanced-low-cost-downhole-kick-detection/
  - https://edx.netl.doe.gov/offshore/portfolio-items/signatures-of-kicks-to-inform-drilling-operations-and-safety/

2) Rose, K., et. al., 2019, USPO #10253620;
3) Adapted from Tost, B., et. al., 2016, ttps://doi.org/10.2172/1327810

Objective/Approach

Produce synthetic data to help fill the knowledge gap and to aid in Early Kick Detection (EKD) algorithm development

Create *Digital* Logging-While-Drilling (LWD) Tool

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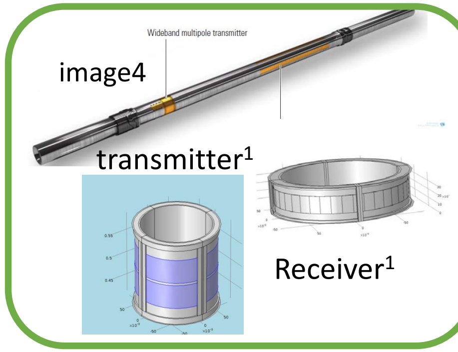
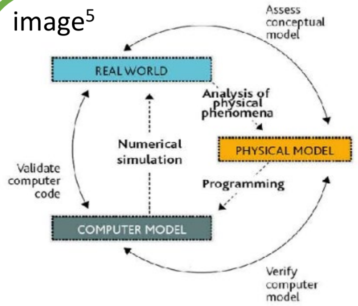


transmitter[1]

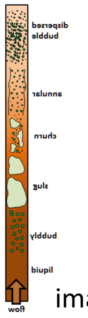
Receiver[1]

Validate Digital Tool

image[5]



Evaluate tool tolerance(s)



Assess instrument accuracy as f(conditions) modify geometry as needed

image[6]

Early Kick Detection

Develop experiments with analogous LWD tool

Create Database

Test/Modify/Optimize EKD algorithm

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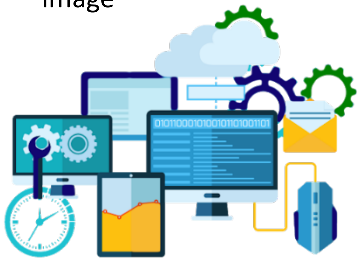


1) Jiang, et al., Proceedings of the 2014 COMSOL Conference in Boston, Understanding Logging-While-Drilling Transducers with COMSOL Multiphysics® Software; 4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.; 5) Lapuerta, C., et al., Nuclear Eng. And Design, 2012, 253, https://doi.org/10.1016/j.nucengdes.2011.09.068; 6) **Unalmis, O. H., 2015,** doi: 10.1121/2.0000069 7) web: Custom Advisory Group http://www.customeradvisorygroup.com/grc---process-control-implementations.html

Background: Acoustic Velocity

✓ **Literature review and numerical analysis show promising results for early kick detection via LWD and acoustic methods**

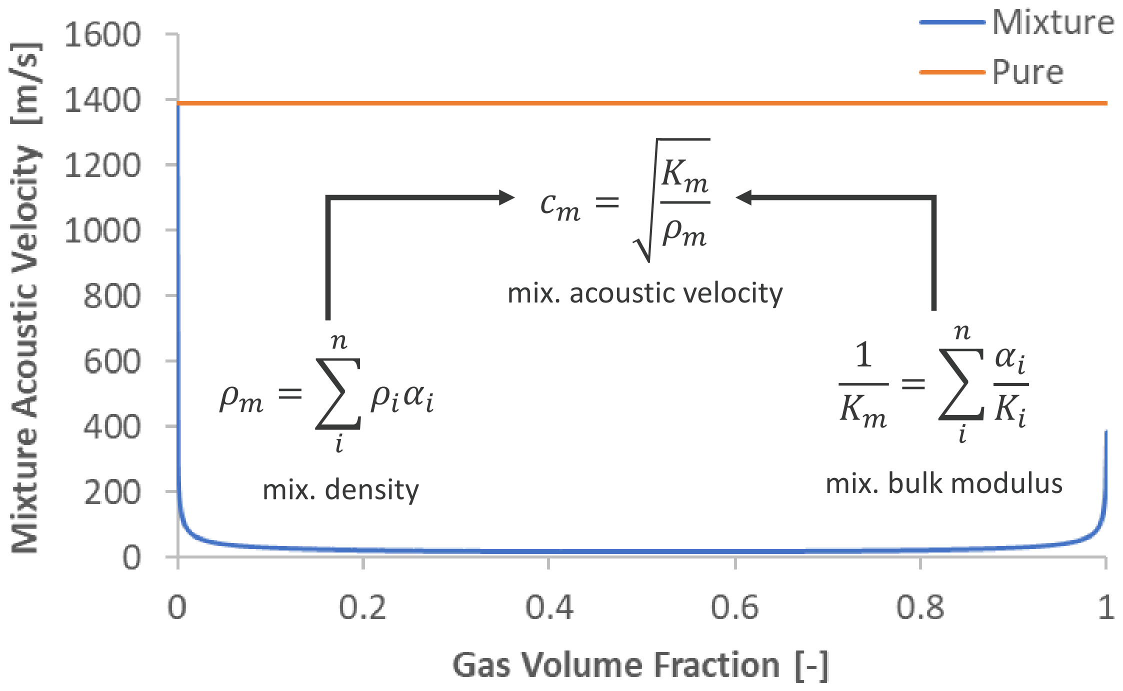


Fig. Estimated change in drilling-fluid (WBM) acoustic velocity as a function of the natural gas volume fraction at 27°C (80°F) and 0.1 MPa (14.5 psi)

✓ **Viable method for free and dissolved gas during kick events**

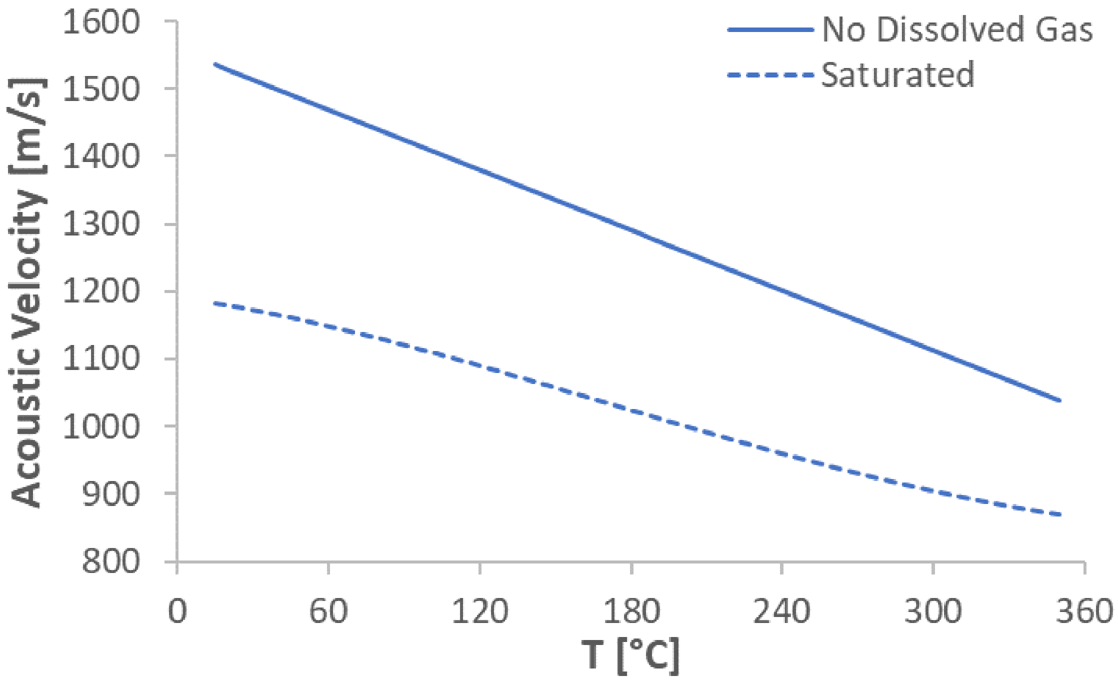


Fig. Estimated change in oil-based drilling fluid (OBM) acoustic velocity as a function of dissolved methane at 40 MPa (5800 psi)

Background: Acoustic Velocity

- ✓ **Numerical results show good sensitivity to gas-volume fraction in needed range**

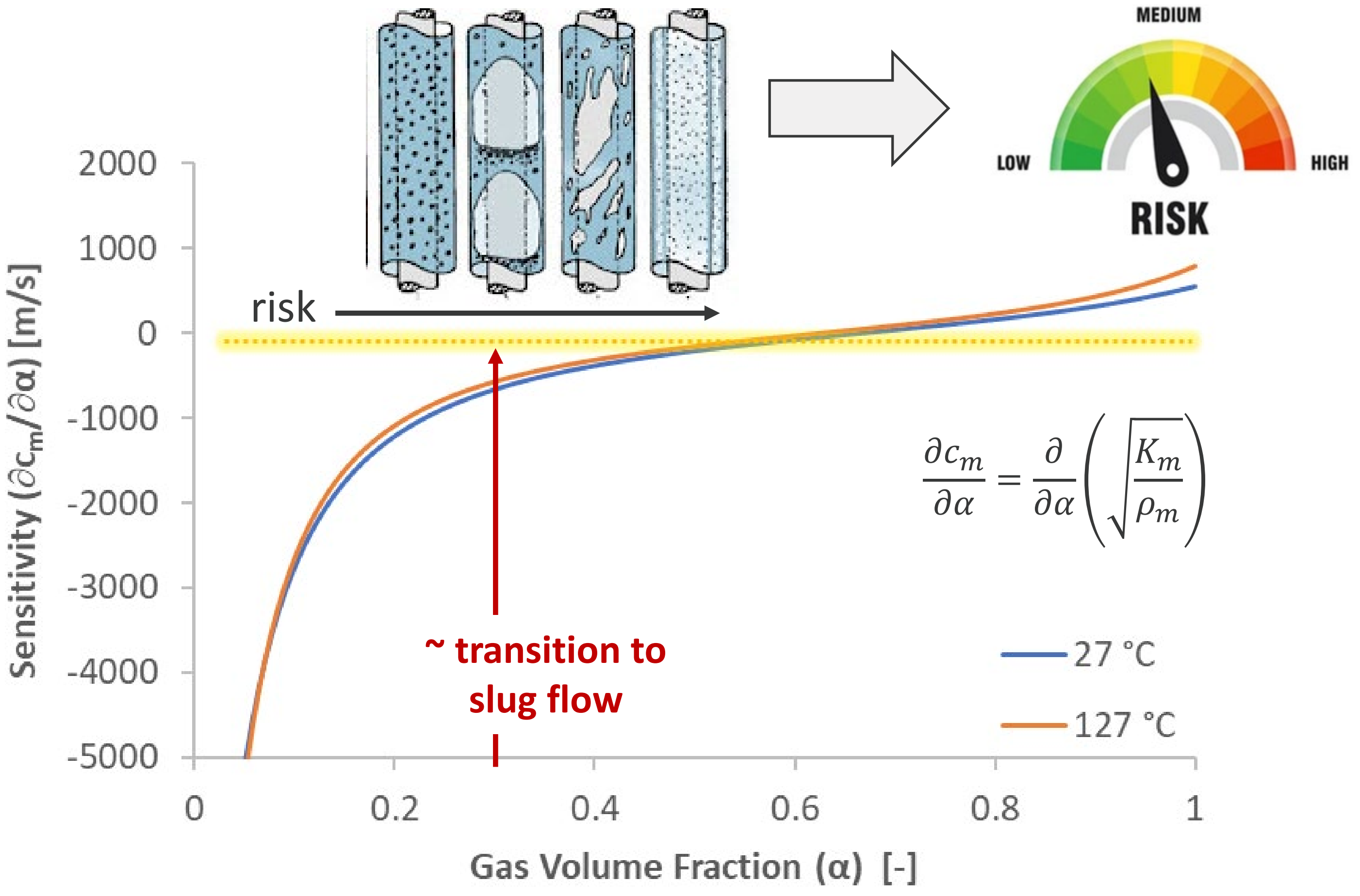
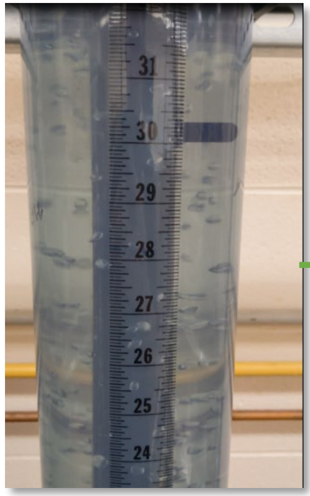


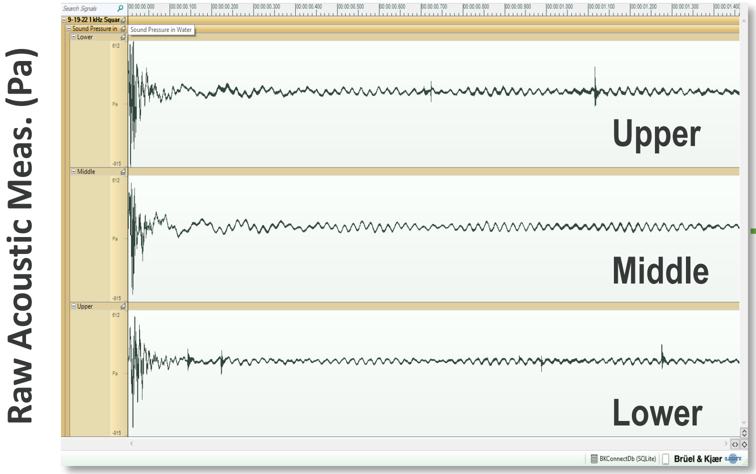
Fig. Sensitivity of drilling-fluid (WBM) acoustic velocity to changes in natural gas volume fraction as a function gas volume at 50. MPa (7250 psi)

Experimental Analysis

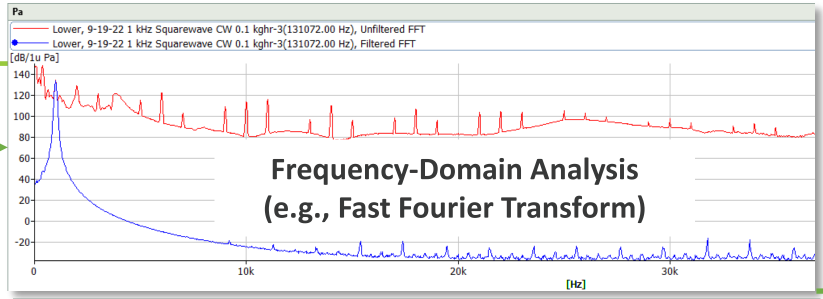
Gas-Liquid Test Conditions

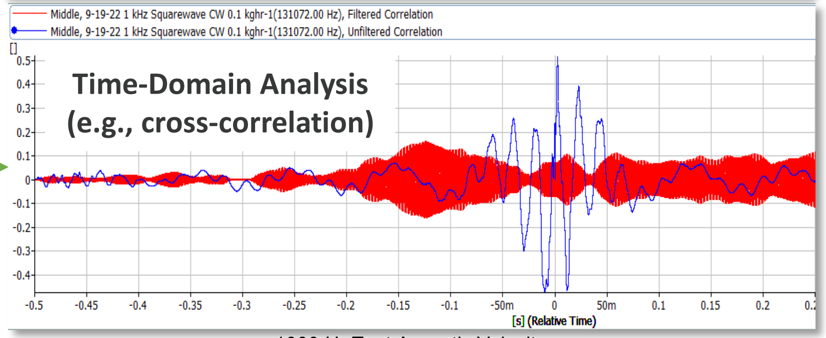


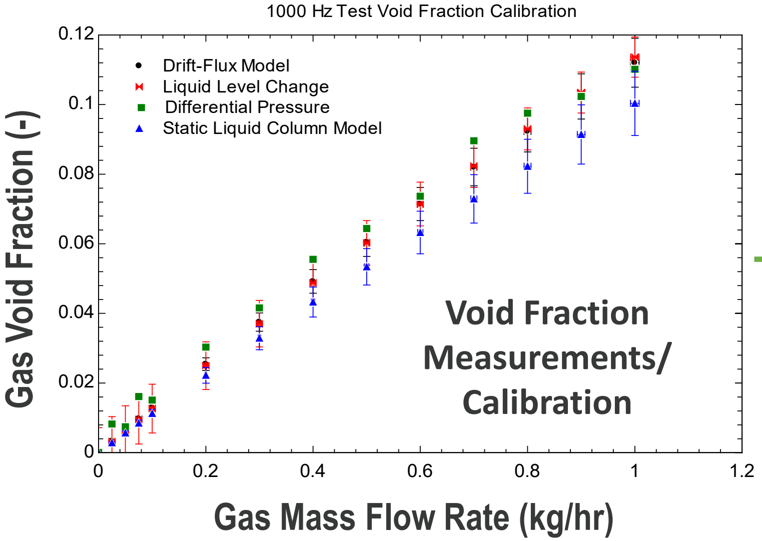
Gas Mass Flowrate = 0.1 kg/hr
(~ 1% Void Fraction)
Bubble Diameter ~ 5 mm
Resonance Frequency ~ 1313 Hz

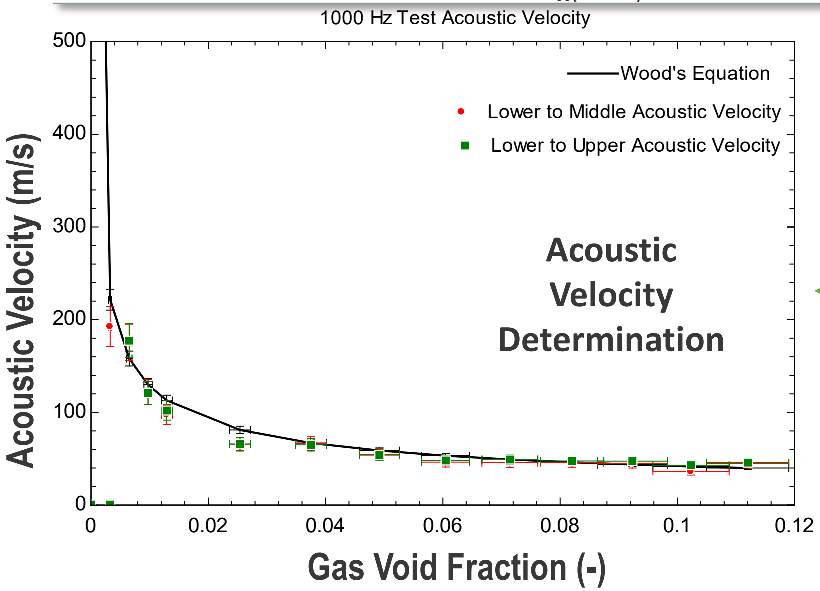


Signal Processing – SOS analysis









9) Tost, B.C. et al., Offshore Technology Conference, May 4-7, 2020, Houston, Texas, USA. https://doi.org/10.4043/30831-MS
10) Carney, J., et al., DOE-NETL'S Integrated Project Review Meeting - Oil & Natural Gas, 2020.

Modeling & Simulation

Goal: develop a digital twin using acoustic-CFD

- **Beyond simplified 1D-type systems acoustic problems quickly become mathematically intractable (require a numerical approach)**
- **Computational fluid dynamics (CFD) offers through ability to simulate wave propagation through a material as it interacts with its environment**
- **Several classic theories for describing acoustic properties are available; based on varying simplifying assumptions**
  - Describe the speed of sound in gas-liquid mixtures
    - e.g., Wood's equation: only considers the two-phase compressibility but neglect losses.
  - Include estimates for attenuation
    - e.g., Commander & Prosperetti (1989): incorporates thermal/viscous/acoustic loss but neglects other interphase transfer behavior.

CFD/Computational Acoustics

CFD is a broad category of numerical simulation

General but not all inclusive map of sound prediction methods

<table>
<tr><td rowspan="5">Computational Acoustics *</td><td colspan="6">CFD: Full Navier Stokes Equations (unsteady, compressible)*</td></tr>
<tr><td colspan="6">Resolved Physics → Modeled Physics → Additional Assumptions (simplifications)</td></tr>
<tr><td rowspan="2">DNS</td><td rowspan="2">LES/DES</td><td rowspan="2">URANs/RANS</td><td colspan="3">Linearized NS and derivatives</td></tr>
<tr><td>Full Linearized Equations</td><td>Linear Thermoviscous Equations</td><td>General Scalar Wave Eqn (linear)</td></tr>
<tr><td>Attractive but infeasible</td><td colspan="2">Discretization schemes designed for CFD not acoustic problems</td><td>Still numerically challenging</td><td>No background flow</td><td>Neglect viscosity & conductivity</td></tr>
</table>

Challenges:

- Traditional **CFD** does not work very well in acoustic applications due to relatively large diffusion errors compared to acoustic perturbation
- Existing acoustic modeling tools tend to be application orientated

Computational Pressure Acoustics

Basis for the computational work to examine 3D acoustic wave propagation

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General Scalar Wave Equation

$$\frac{1}{\rho c^2}\frac{\partial^2 p_t}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho}(\nabla p_t - \mathbf{q}_d)\right) = Q_m$$

- ✓ Describes small acoustic pressure variations (p_t)
- ✓ Accommodates monopole (Q_m) and dipole sources ($\mathbf{q}_d$)
- ✓ Damping/losses can be included:
  - details/limitations vary depending on form (frequency or time)
- ✓ Flexibility to incorporate fluid-solid interactions -> different modes of propagation

Challenges:

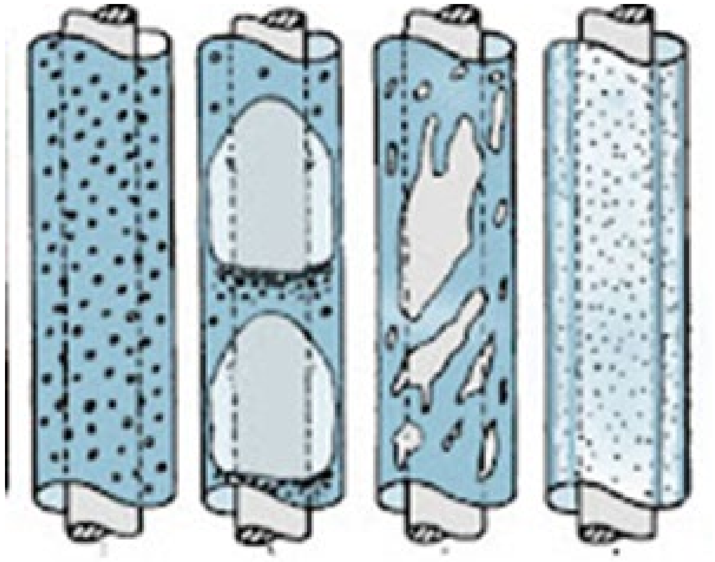
- Spatial-temporal discretization constraints

$$\Delta x = \frac{\lambda_{min}}{N} = \frac{c_{min}}{N \cdot f_{max}} \qquad \Delta t = \frac{CFL{\cdot}\Delta x}{c} \approx \frac{1}{60 f_{max}} \cdot \frac{c_{min}}{c_{max}}$$

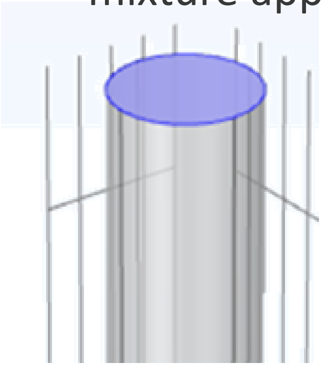
- Existing computational acoustics software are based on a single phase – effects of a secondary phase must be approximated

Modeling Two-Phase Medium

Two-phase gas-liquid mixtures may be expected in the event of a gas kick



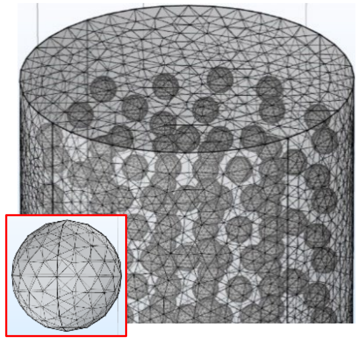
- Homogenized model using a mixture approximation:



$$\frac{1}{c_{mix}^2} = \rho_{mix}\left(\frac{\varepsilon_l}{\rho_l c_l^2} + \frac{\varepsilon_g}{\rho_g c_g^2}\right)$$

$$\rho_{mix} = (\varepsilon_g \rho_g + \varepsilon_l \rho_l)$$

- Discrete bubble approach



\+ Does not require a mixture model
\+ Allows for scattering
– Computationally expensive

Current simplifications/challenges:

- Resonance effects are neglected
- Interphase (mass/momentum) transfer is neglected

Modeling Progress

- ✓ Developed simulation study to explore and evaluate two methods of incorporating the effects of a secondary phase into the simulation model.
- ✓ Comparison of simulation results to analytical models and experimental data
- ✓ Developed an early-stage model to simulate acoustic waves in stagnant two-phase flow in vertical wellbores.

Speed-of-Sound Post-Processing (1)

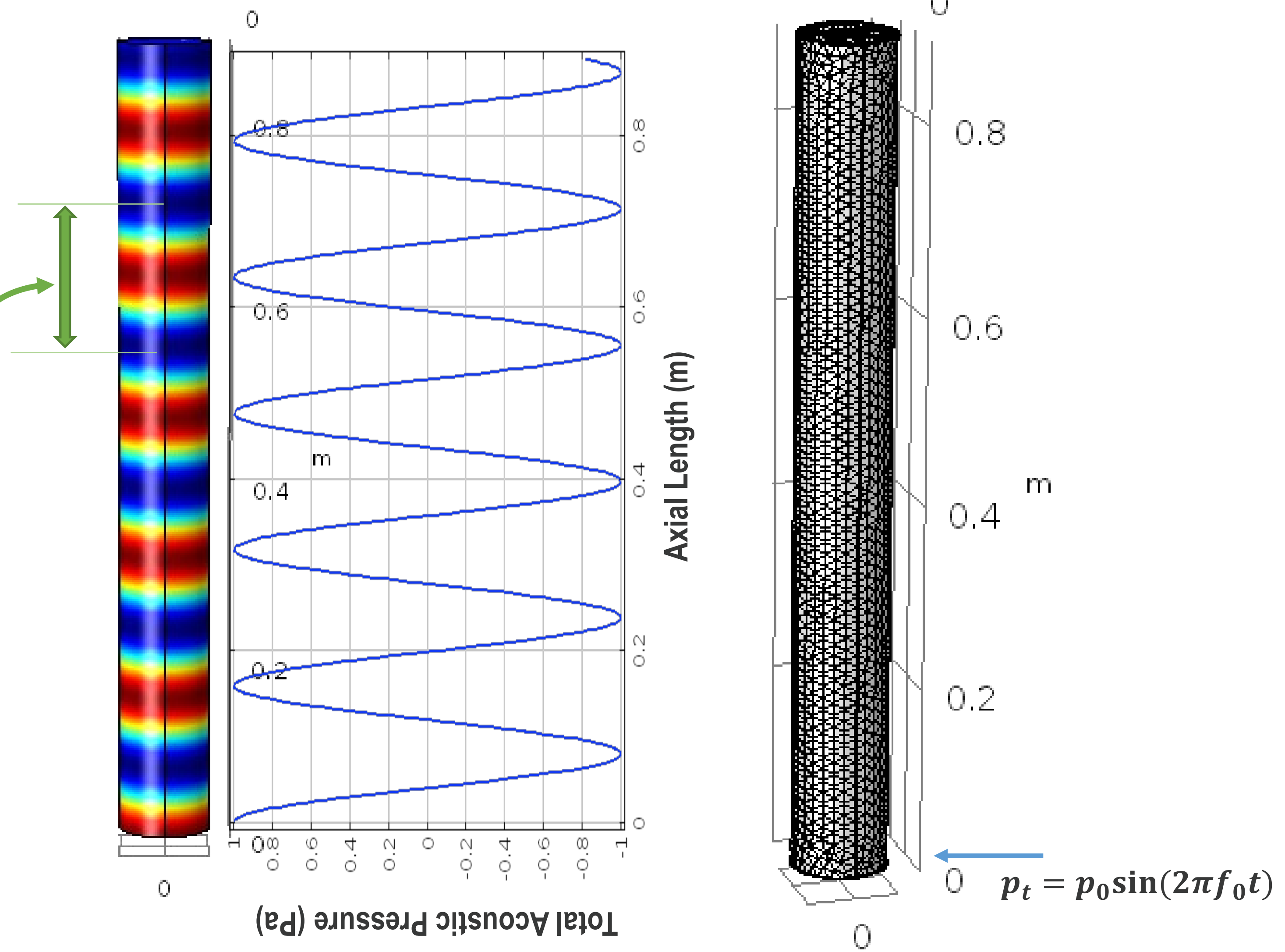
Measuring Speed-of-Sound from Acoustic Pressure Field: Method 1

Wave Speed

$$v = \frac{\lambda}{T} = \lambda \cdot f$$

- Measure distance between corresponding points on the wave (λ) = 0.157m
- Known source frequency (f) = 250Hz
- $c = 0.157 \cdot 250 = 39.3\ m/s$
  (corresponds to air-water at $\varepsilon_g = 0.1$)

Technique is like those used in previous experimental investigations



Speed-of-Sound Post Processing (2)

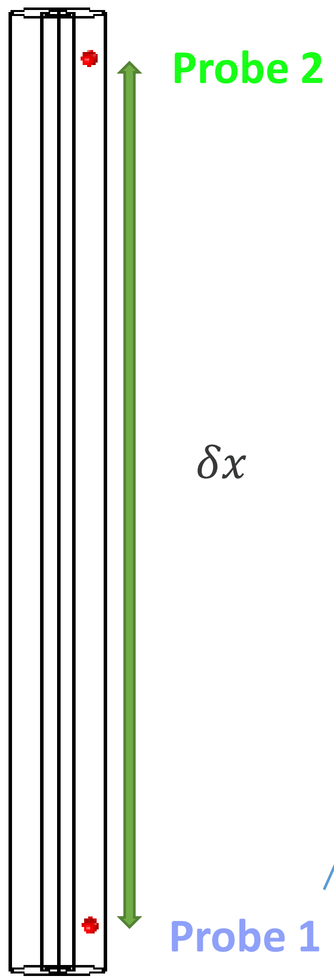
Measuring Speed-of-Sound from Acoustic Pressure Field: Method 2 (in annulus)

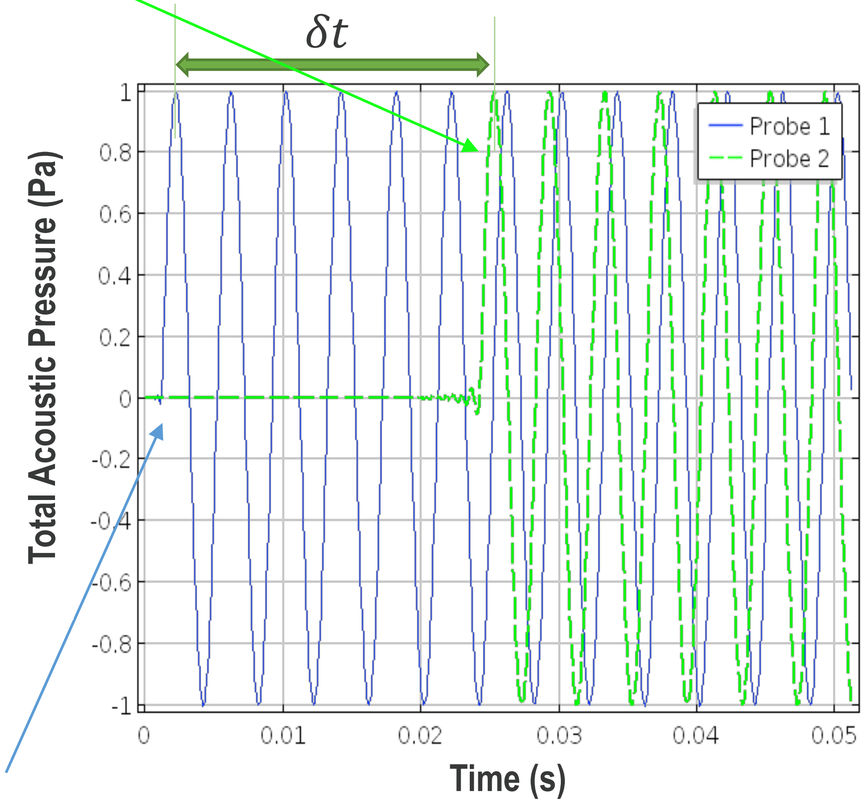
Wave Speed

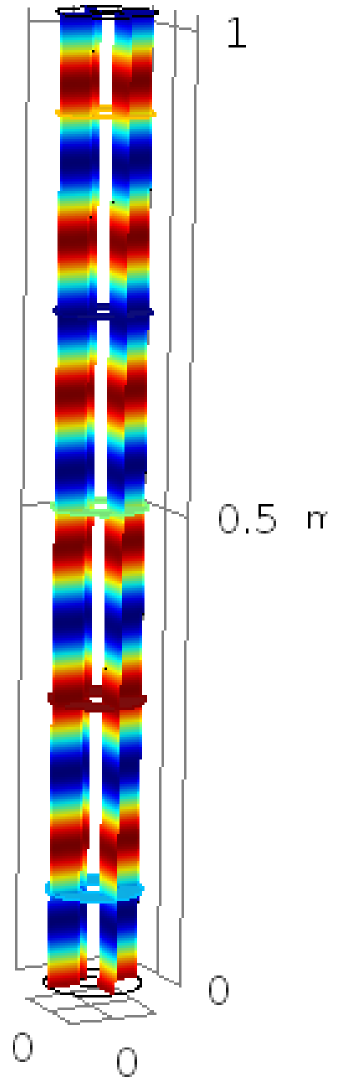
$$v = \frac{\lambda}{T} = \lambda \cdot f$$

- Known distance between probes (δx) = 0.9144m
- Time elapsed between (first arrival) same point on wave (δt) = 0.023
- $c = \frac{0.9144}{0.023} = 39.8\, m/s$
  (corresponds to air-water at $\varepsilon_g = 0.1$)

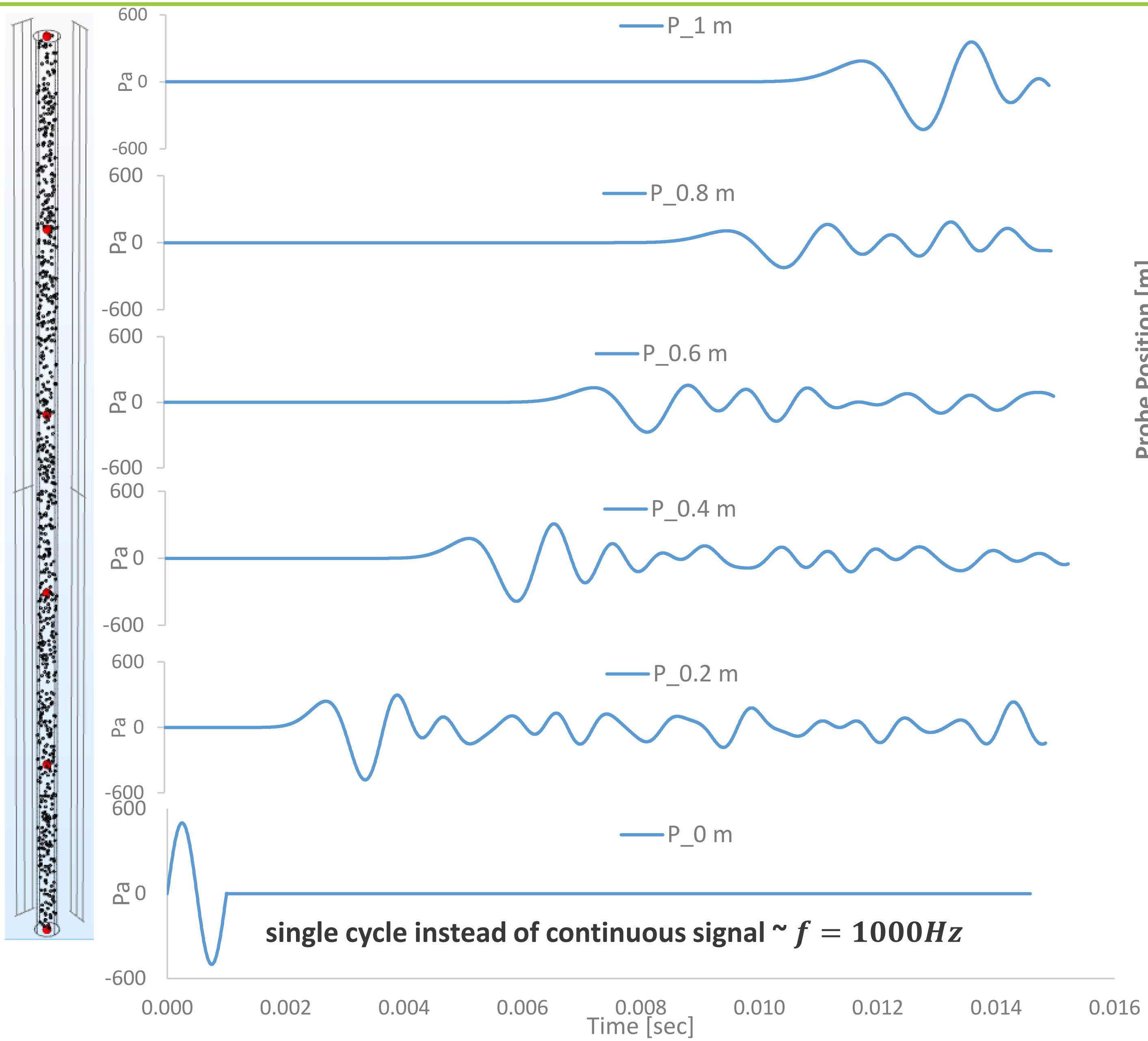
Technique is the basis for corresponding field measurements

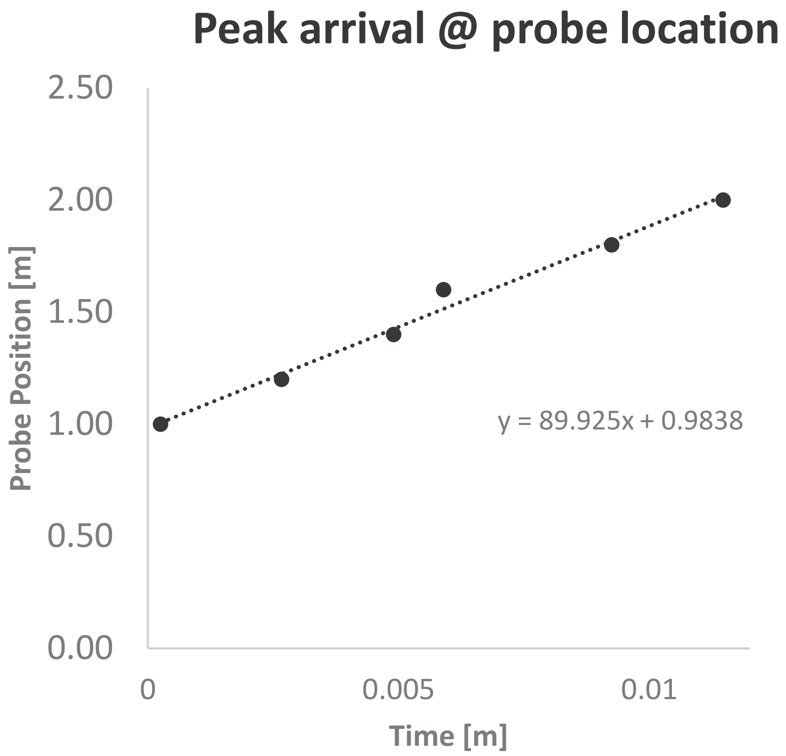






Speed-of-Sound Validation: Discrete Bubble Approach





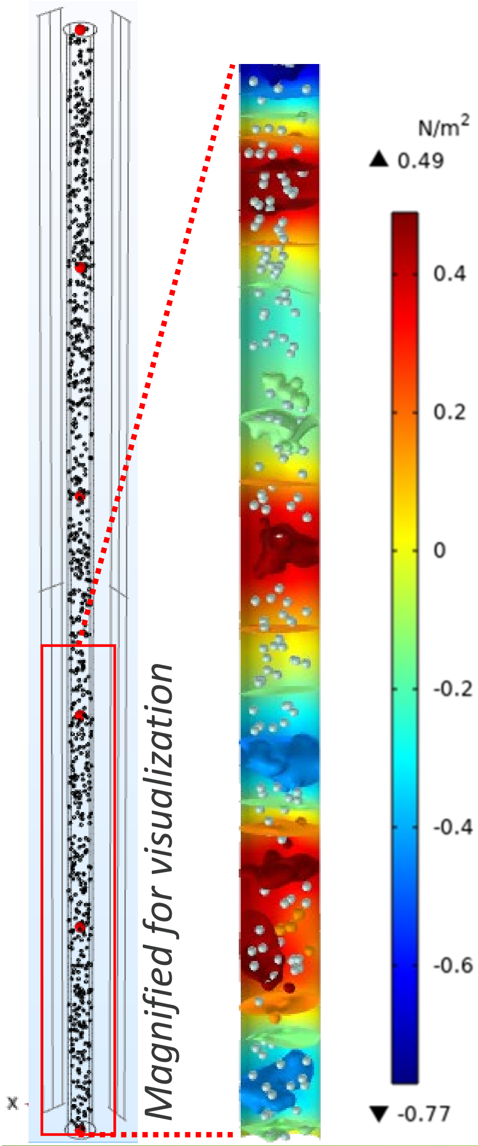
$c_{mix} = 85.6m/s$ (for air-water at $\varepsilon_g = 0.02$)

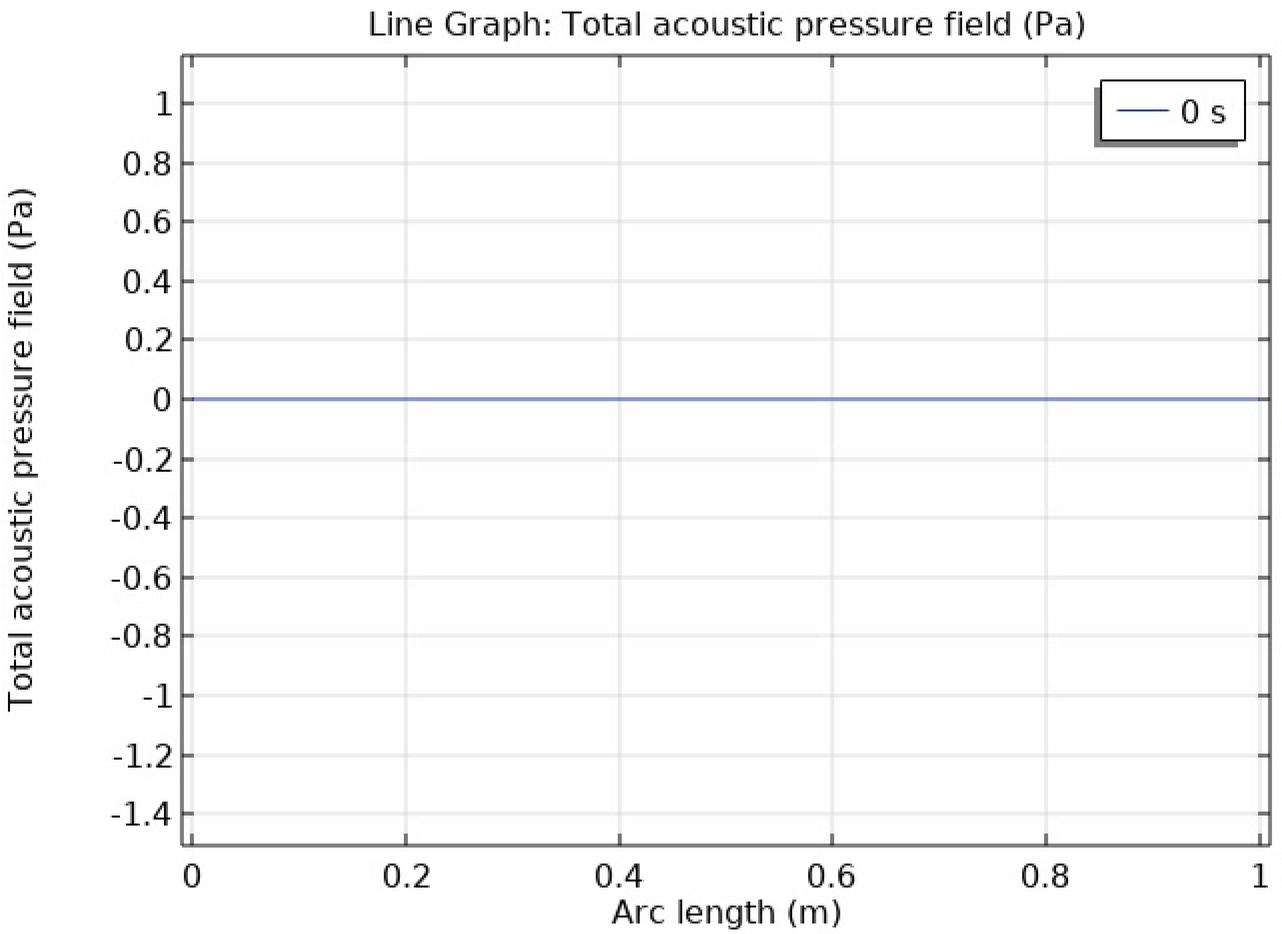
$c_{sim} = 89.6m/s\ (d_{bub} = 3mm)$

Difference: 4.7%

Discrete approach yields a similar speed of sound to the effective mixture model

Propagation Behavior

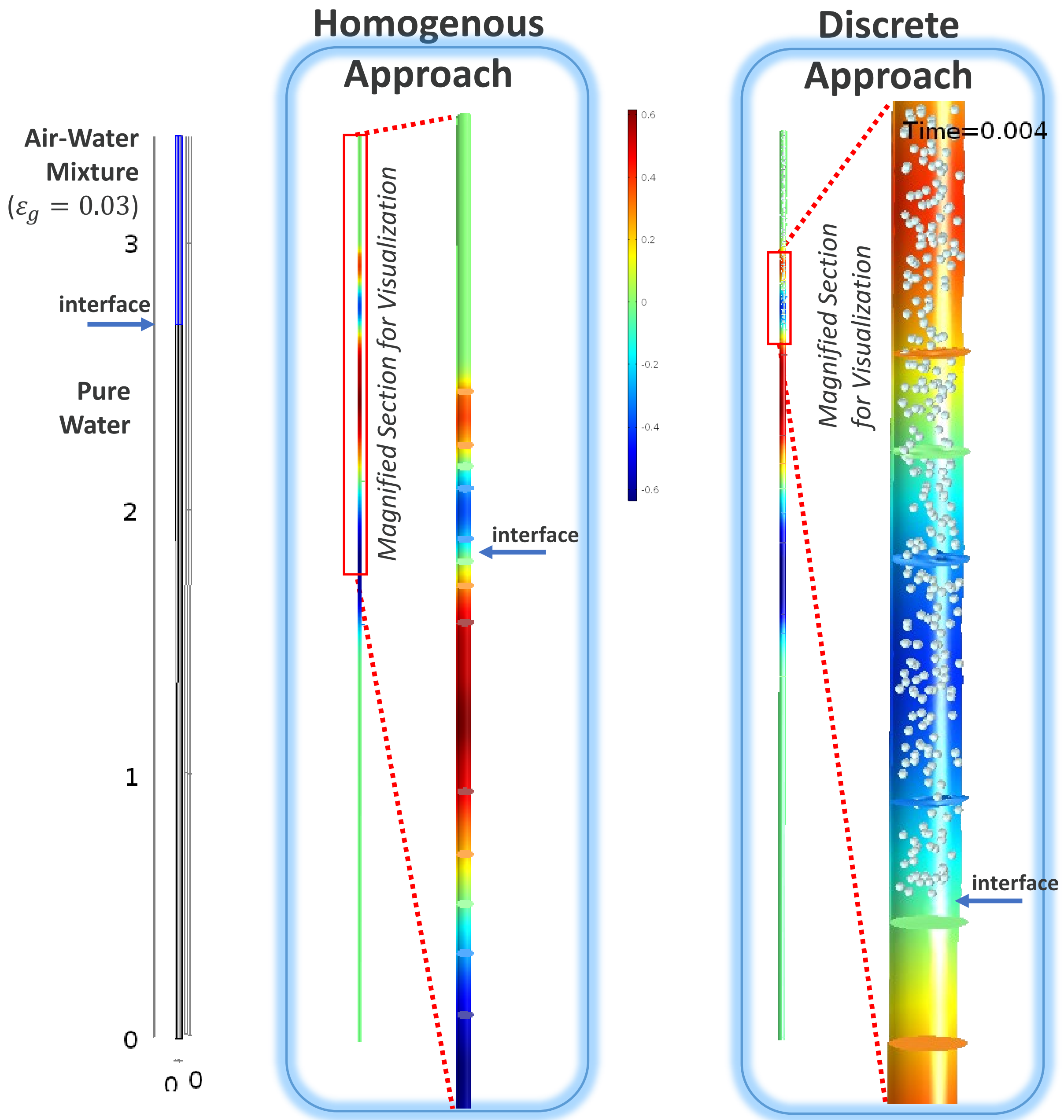


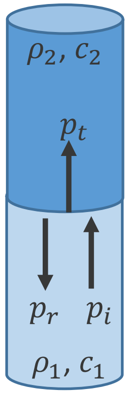


Discrete Bubble Approach

- Noise in signal (successive reflections)
- Considerably more expensive

Reflection & Transmission Validation





Analytic Model

$Z_i = \rho_i c_i$

$R_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$

$T_{12} = \frac{2Z_2}{Z_2 + Z_1}$

$(T_{12} = 1 + R_{12})$

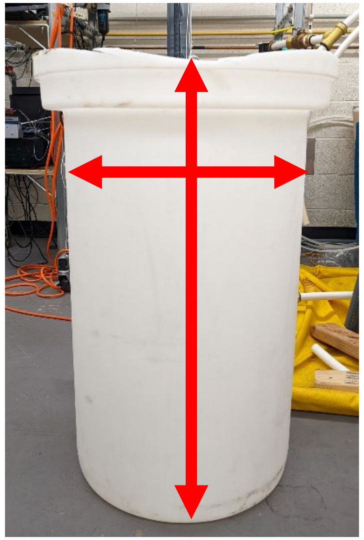
Liquid into Mixture (bubbles)

Impedance Ratio (Z_2/Z_1) 0.2369

Approach	Incident P_i (Pa)	Reflected P_r (Pa)	Transmitted P_t (Pa)	$(P_t-P_r)/P_i$
Analytic Model	1	-0.6169	0.3831	1
Sim. Homogeneous	1	-0.628	0.38	1.008
Sim. Discrete Bubble	1	-0.605	0.375	0.98

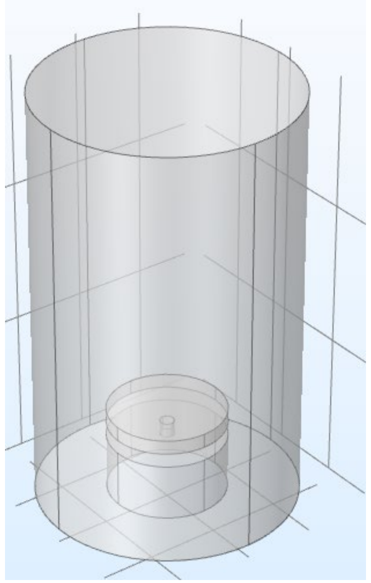
- **Similar *initial* incident reflected & transmitted pressure amplitudes are predicted for both approaches**
- **Agree well with analytic theory**

Preliminary Validation

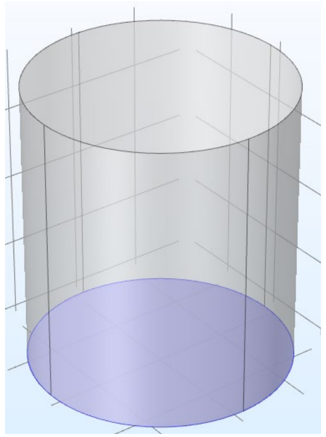


$D = 17.5''$
$H = 29.25''$

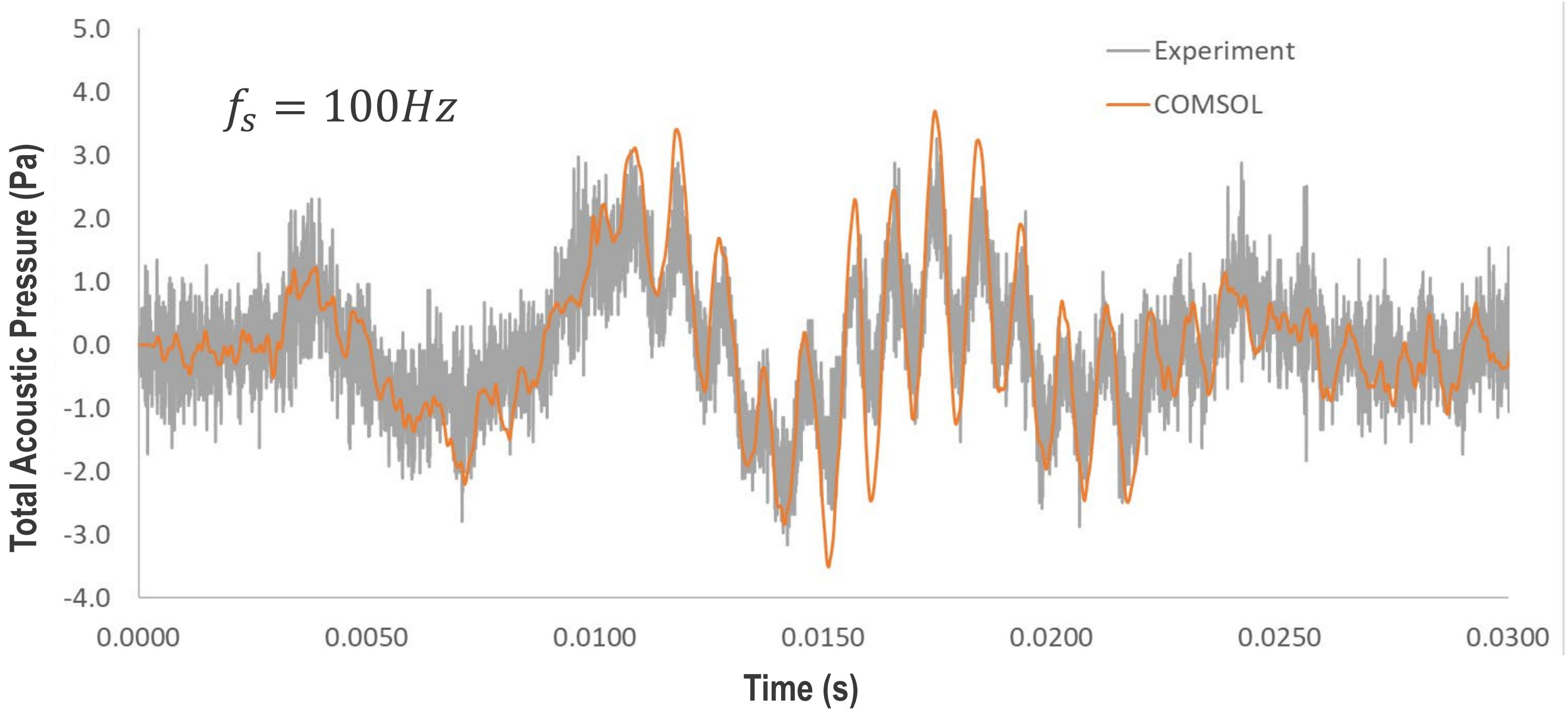
$D_s = 8''$



Tank with speaker



Trimmed Tank at 9.5 in from the bottom



✓ **Good match between experiment and simulation**

Borehole Simulation: Propagation Features

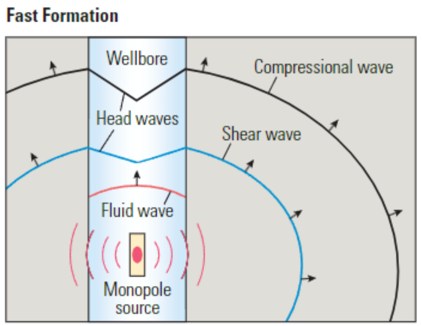


Image from[4]

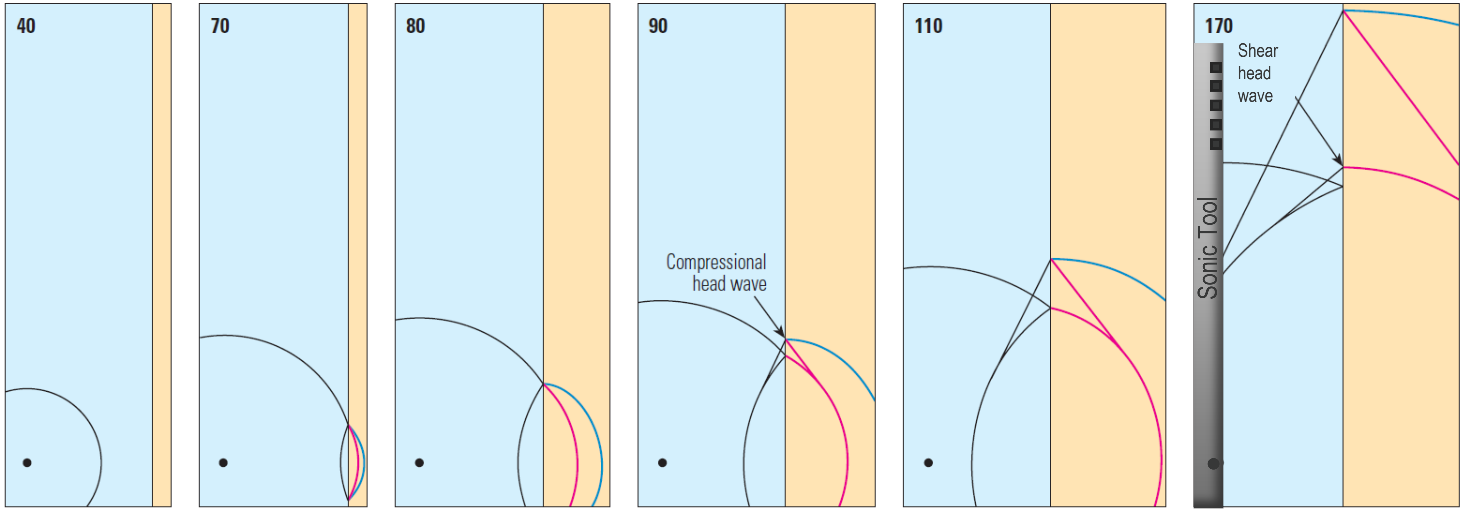


Image adapted from[11]

Wellbore: Fluid Domain

$\rho = 1000\frac{kg}{m^3}$; $c = 300\frac{m}{s}$

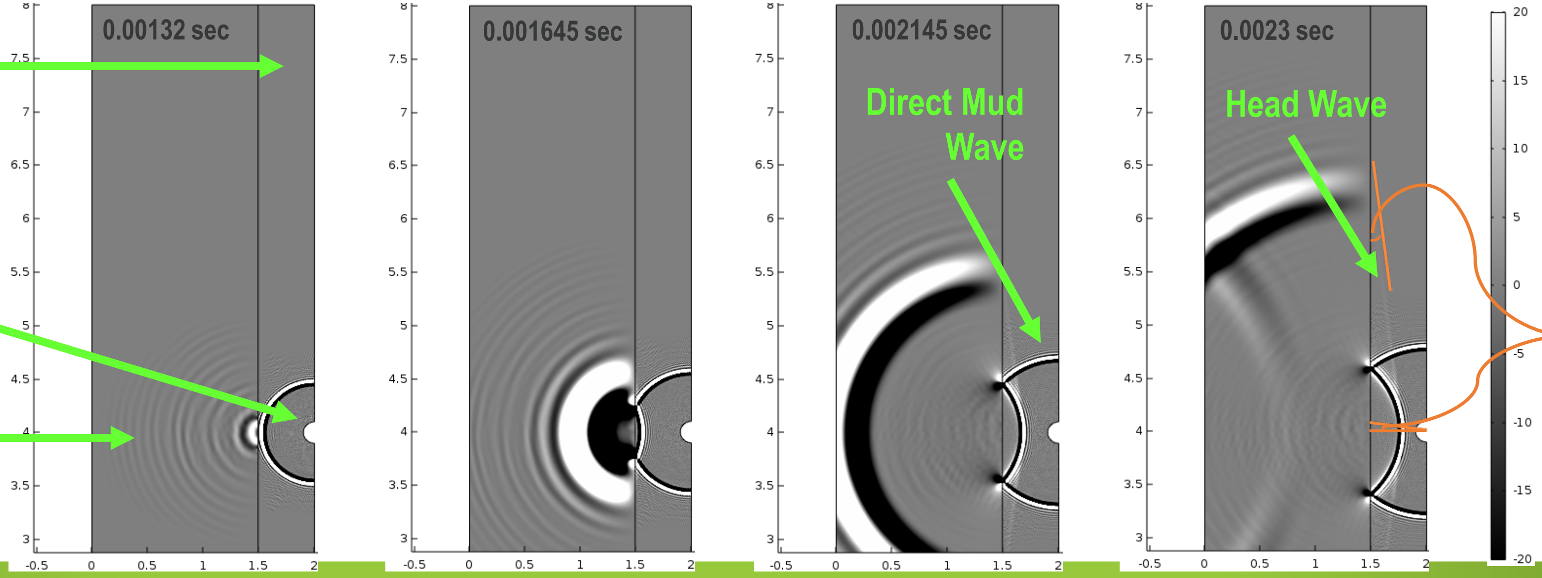
$(\varepsilon_g \sim 0.0015)$

Pressure Pulse:

$f = 5kHz$

Formation: Rock Domain

$\rho = 1760\frac{kg}{m^3}$; $c = 2400\frac{m}{s}$



✓ **Capture critical angle**

$$\theta_c = \arcsin\left(\frac{300}{2400}\right) = 7.2°$$

4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1;
11) Haldorsen, et al., Oilfield Review, Borehole Acoustic Waves, Spring 2006.

Borehole Simulation: Wavetrain

Field signal

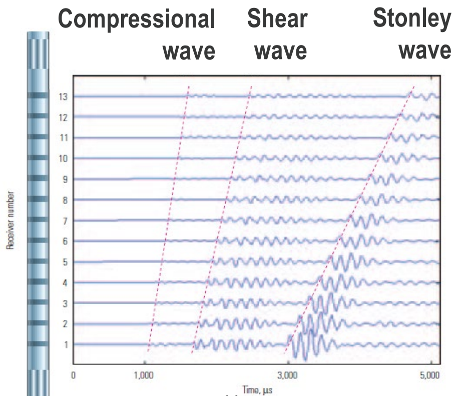


Image from[11]

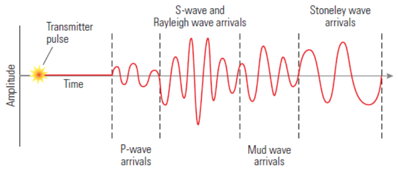
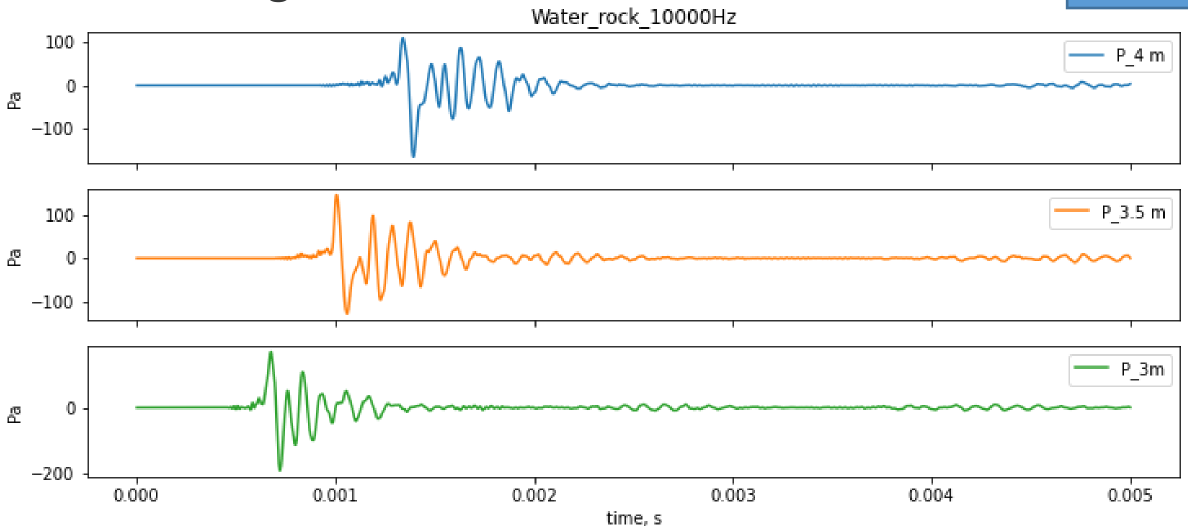
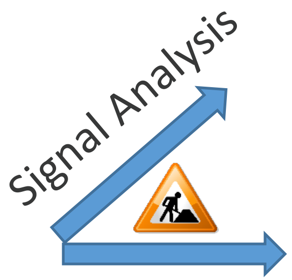


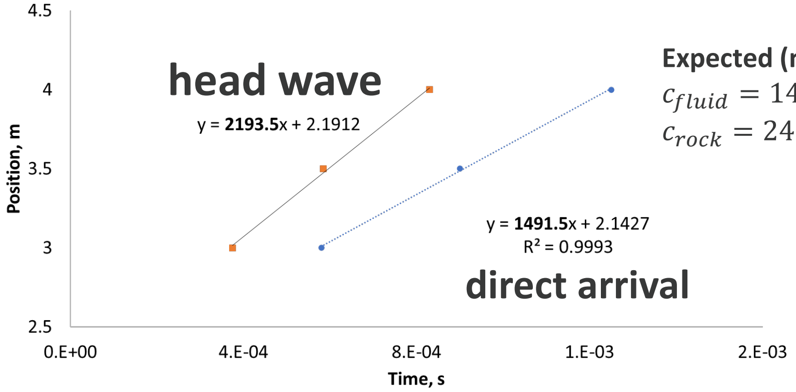
Image from[4]

Simulated signal



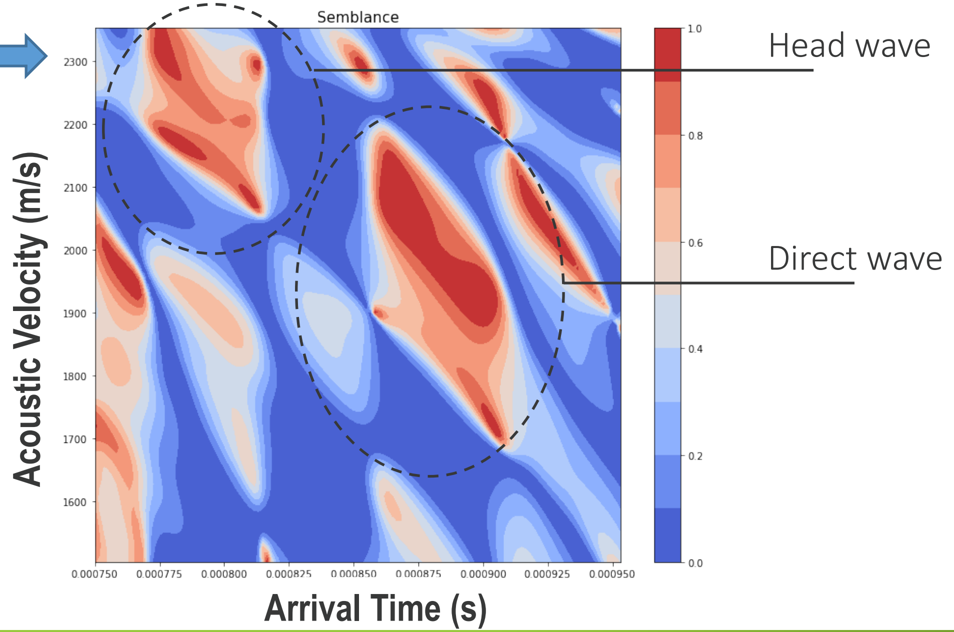


First arrivals identified manually



	Expected (m/s)	Predicted (m/s)
c_{fluid}	$= 1480$	1492
c_{rock}	$= 2400$	2194

Semblance Plot



4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1;
11) Haldorsen, et al., Oilfield Review, Borehole Acoustic Waves, Spring 2006.

Signal Analysis/Algorithm Development

- ✓ Developed python-based algorithm to automatically identify the wave arrival time and velocity and visualize a semblance contour (tested on simulation data)
- ✓ Developed a python-based cross-correlation algorithm to estimate time delay and therefore velocity (tested on passive experimental data; not shown)
- ✓ Developed preliminary supervised machine learning algorithms using early static acoustic pressure measurements at varying void fractions: K-Nearest-Neighbors (KNN), Multi-Layer Perceptron (MLP), and Decision Tree Regression (DTR)

Project Summary & Next Steps

- Continue to develop a numerical model representing acoustic sensor to predict acoustic response in basic environment(s)
  - Investigate limitations of modeling approach (e.g., secondary phase approximations)
  - Incorporate fluid-solid interaction component
- Continue validation with available experimental data
  - Finish experimental campaign and data analysis
- Continue to develop a training set of synthetic data for early kick detection algorithm development.
- Test constraints/limitations of algorithm on test set of synthetic data
  - Utilizing more advanced methods, such as wavelet transformation, dynamic time warping, etc.

Year 2: Continue to develop numerical surrogate of acoustic tool

Does it predict acoustic signal(s) & show potential for incorporating complexities of the system?

assess & refine

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References

1) Jiang, et al., 2014, Excerpt from the Proceedings of the 2014 COMSOL Conference in Boston
2) **Rose, K., et. al., 2019, USPO #10253620**
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4) Alford, et al., Oilfield Review Spring 2012: 24, no. 1.
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Back-up Slides

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Project Overview

- NETL's Offshore research is focused on innovating solutions to challenges associated with geohazard prediction, subsurface uncertainty reduction, and addressing oil and gas infrastructure integrity and optimization for new and existing infrastructure systems

- This project aims to reduce risks to the environment by developing data and an understanding of tool–response for use in early-kick detection which can ultimately prevent oil spills

- This effort supports:
  - Department of Energy's (DOE) mission to provide clean & affordable energy security.
  - DOE Fossil Energy & Carbon Management's (FECM) primary mission to ensure the nation can continue to rely on traditional domestic resources of energy while reducing the footprint of and potential deleterious impacts from these efforts.

• Three kicks, complementary outcomes

NATIONAL ENERGY TECHNOLOGY LABORATORY

Complete: Patented EKD Tech. 2014-2016	Active: Lab/Multi-Phase EKD Study 2018-2022	Startup: CFD Modeling EKD Study 2021-2023

• A conceptual and numerical proof to support the use of LWD geophysical data to *detect* a kick: yes or no (not type/flow rate)
 	
• LWD field data exists but..
  • limited availability (e.g., no. partners, no. of wells)
  • limited useability (annular conditions not isolated in reported log)
	• An experimental, surrogate wellbore-LWD setup to obtain LWD data but over limited conditions (e.g., ambient T/P, simple fluids)
	
	• Appropriate LWD-like sensors not readily available..
	  • Custom acoustic tool now in development to emulate LWD tool
		• A digital twin of the LWD acoustic sensor based on fundamental physics
		
		• Create tool and validate with data from lit. or experiment..

Requires broad dataset to develop and verify	Improved understanding of sensor response to annular conditions **Initial database of *measured* signals that serves as *testbed* for EKD algorithm**	Low-cost platform to guide sensor design and optimization **Comprehensive database of *simulated* signals to *calibrate/refine* EKD algorithm (fingerprinting)**