Advancing Reservoir Performance

New Insights On How Vibration Modeling Improves Reach



Silviu Livescu, Coiled Tubing Research and Engineering (CTRE)

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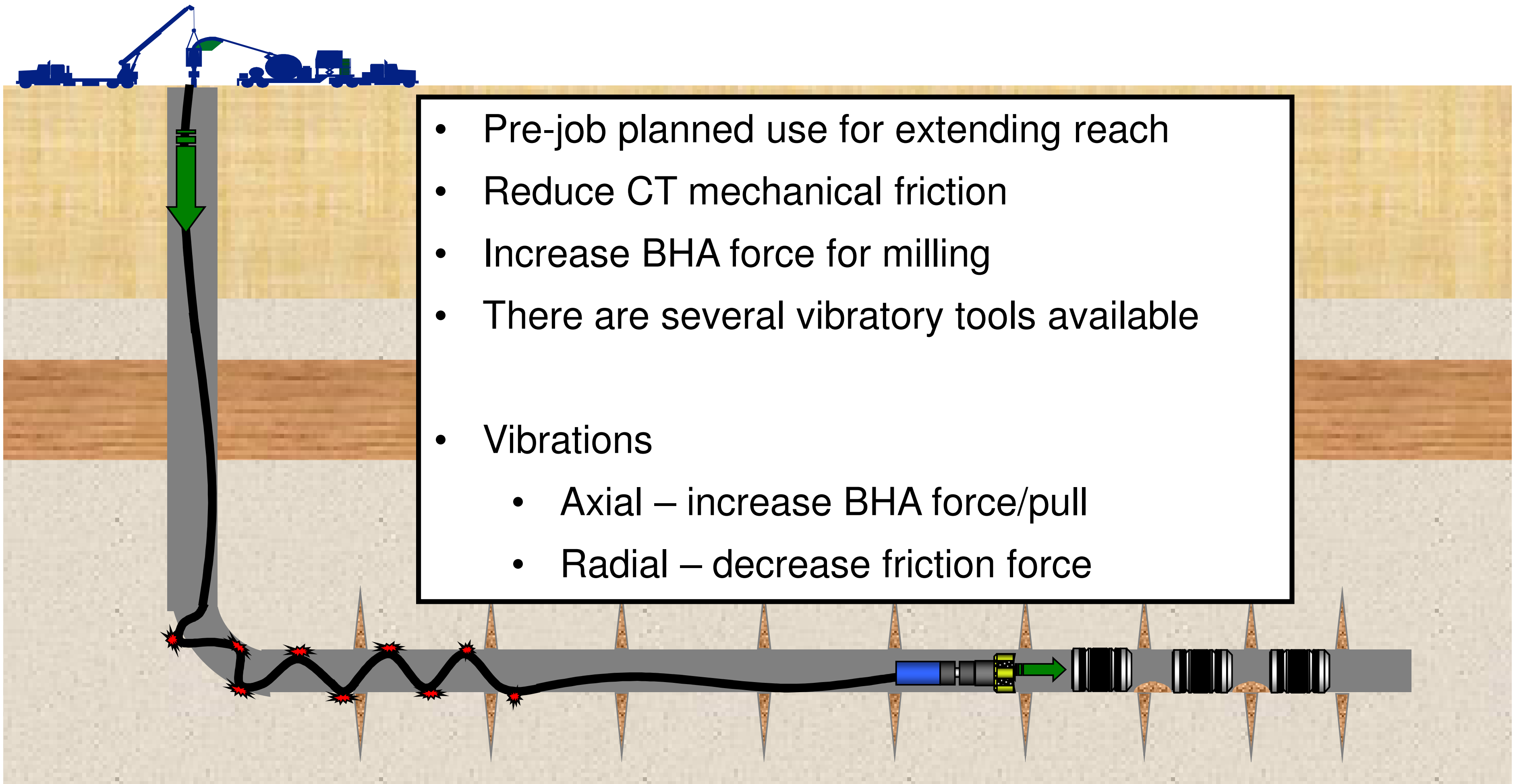
BAKER HUGHES

Why Are Vibrations Used in Extended-Reach Wells?



- Pre-job planned use for extending reach
- Reduce CT mechanical friction
- Increase BHA force for milling
- There are several vibratory tools available

- Vibrations
  - Axial – increase BHA force/pull
  - Radial – decrease friction force

SPE Papers on CT Vibrations

- OnePetro papers
  - 2299 papers found with “water hammer”
  - 298 papers found with “coiled tubing vibrations”
  - Fewer than 10 papers on modeling CT vibrations
- Outside of oil and gas industry
  - Significant interest in modeling pipe flow vibrations
  - A.S. Tijsseling, Eindhoven University of Technology, The Netherlands, 1993 – present
    - Fluid-structure interactions, water hammer effects
  - Several papers in Journal of Fluid Mechanics between 1980 – 2000
    - Helical pipe flow

CT Water Hammer Modeling

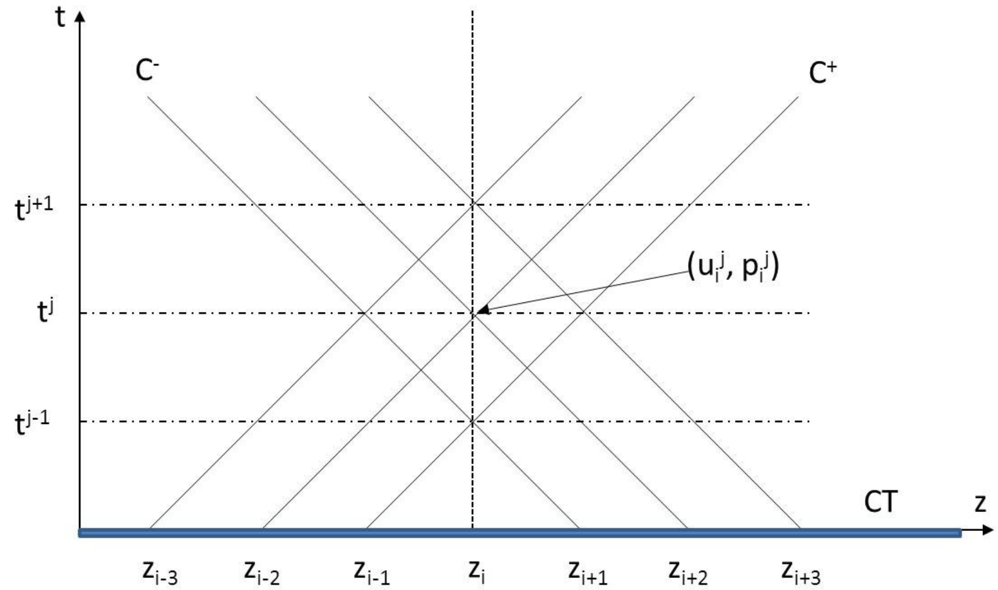
- SPE-168297: first published CT water hammer mathematical and numerical study
- Fluidic switch based on Coandă effect (1936)
    - Tendency of a fluid jet to adhere to a curved surface
- Main assumptions for “classic” water hammer theory
    - CT fluid flow is one-dimensional
    - No cavitation (local pressure greater than liquid vapor pressure)
    - Wave speed is constant
    - CT wall and fluid have similar elastic behavior
    - CT-induced pressure transients are small compared to the fluid pressure wave
    - CT is a straight pipe

CT Water Hammer Modeling for Straight Pipes

- Solve continuity equation and the equation of motion
- Method of Characteristics

$$\rho c^2 \frac{\partial u}{\partial z} + \frac{\partial p}{\partial t} = 0$$

$$\frac{\partial u}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{f}{2d_{in}} u|u| = 0$$



u = axial fluid velocity, m/s^2
p = fluid pressure, psi
t = time, s
z = axial coordinate along CT length, m
ρ = fluid density, kg/m^3
c = acoustic wave speed through fluid, m/s
f = frictional pressure drop factor, -
d_{in} = CT internal diameter, in

Weak Helical Pipe Flow Modeling

- Analytical solutions for helical pipe flow using the Perturbation Method

$$\kappa d_{CT} = \frac{(D/2)d_{CT}}{b^2 + (D/2)^2} = \varepsilon \ll 1$$

$$\tau d_{CT} = \frac{b d_{CT}}{b^2 + (D/2)^2} = \varepsilon\lambda \ll 1$$

$\Rightarrow$

$$u(t,z) = u_0(t,z) + \varepsilon u_1(t,z) + \mathcal{O}(\varepsilon^2)$$

$$p(t,z) = p_0(t,z) + \varepsilon p_1(t,z) + \mathcal{O}(\varepsilon^2)$$

κ = pipe curvature, -

τ = pipe torsion, -

D = wellbore/casing internal diameter, in

b = CT pitch, ft

d_{CT} = CT diameter, in

d_{CT} = 2-in.

D = 5.5-in.

b = 60 ft

$\Rightarrow$

$$\varepsilon = 8 \cdot 10^{-6} \ll 1$$

$$\varepsilon\lambda = 2 \cdot 10^{-3} \ll 1$$

- The Perturbation Method can be used for CT pitches as small as 20-in.!

$$max(\varepsilon, \varepsilon\lambda) \cong 0.1 \ll 1 \Rightarrow b \cong 20\text{-in.}$$

- Helical pipe flow is **weak** if $d_{CT} \ll b$

CT Water Hammer and Radial Vibrations Modeling

Leading order, ε^0 (straight pipe)

$$\rho c^2 \frac{\partial u_0}{\partial z} + \frac{\partial p_0}{\partial t} = 0$$

$$\frac{\partial u_0}{\partial t} + \frac{1}{\rho}\frac{\partial p_0}{\partial z} + \frac{f}{2d_{in}} u_0 |u_0| = 0$$

First order, ε^1 (weak helical pipe)

$$\rho c^2 \frac{\partial u_1}{\partial z} + \frac{\partial p_1}{\partial t} = 0$$

$$\frac{\partial u_1}{\partial t} + \frac{1}{\rho}\frac{\partial p_1}{\partial z} + \frac{f}{2d_{in}} (u_0|u_1| + u_1|u_0|) = 0$$

Radial displacement and acceleration and normal force per unit mass

$$u_r = \frac{{d_{in}}^2}{4wE} p$$

$$a_r = \frac{{d_{in}}^2}{4wE} \frac{\partial^2 p}{\partial t^2}$$

$$n = g - a_r$$

w = CT wall thickness, in.

E = CT Young modulus, Pa

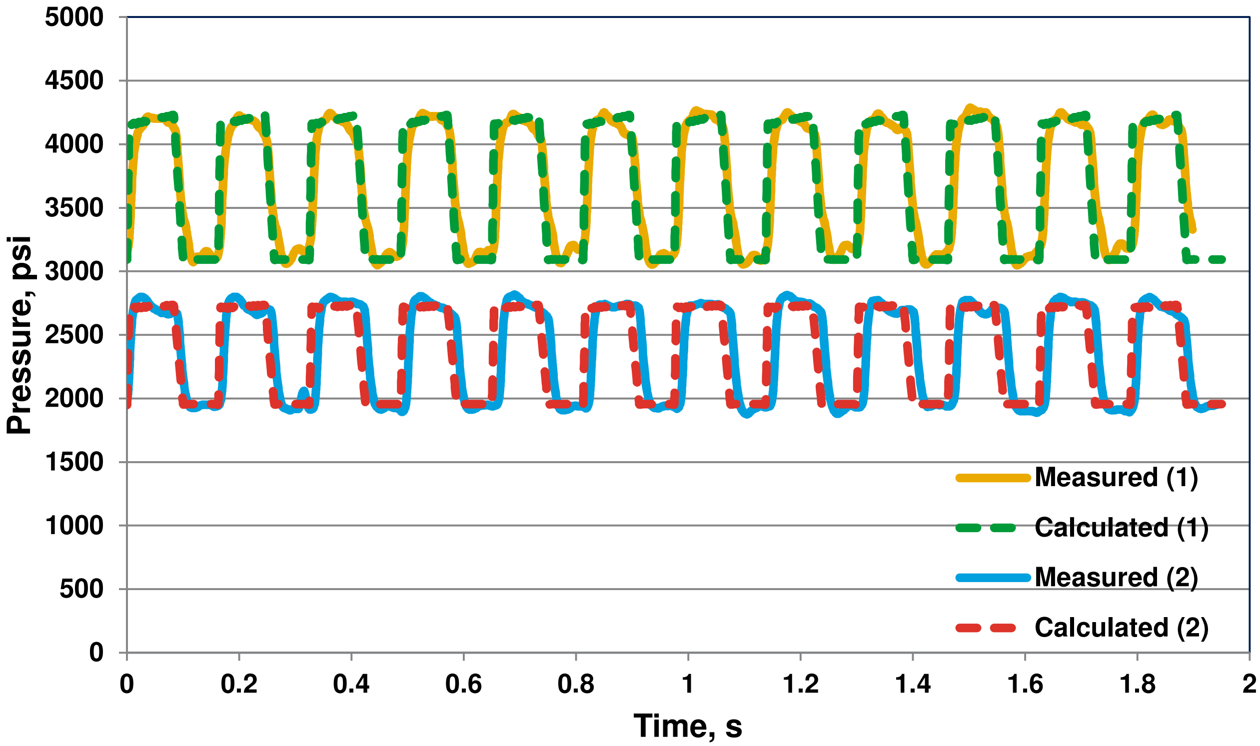
u_r = radial displacement, m

a_r = radial acceleration, m/s^2

n = CT normal force per unit mass, m/s^2

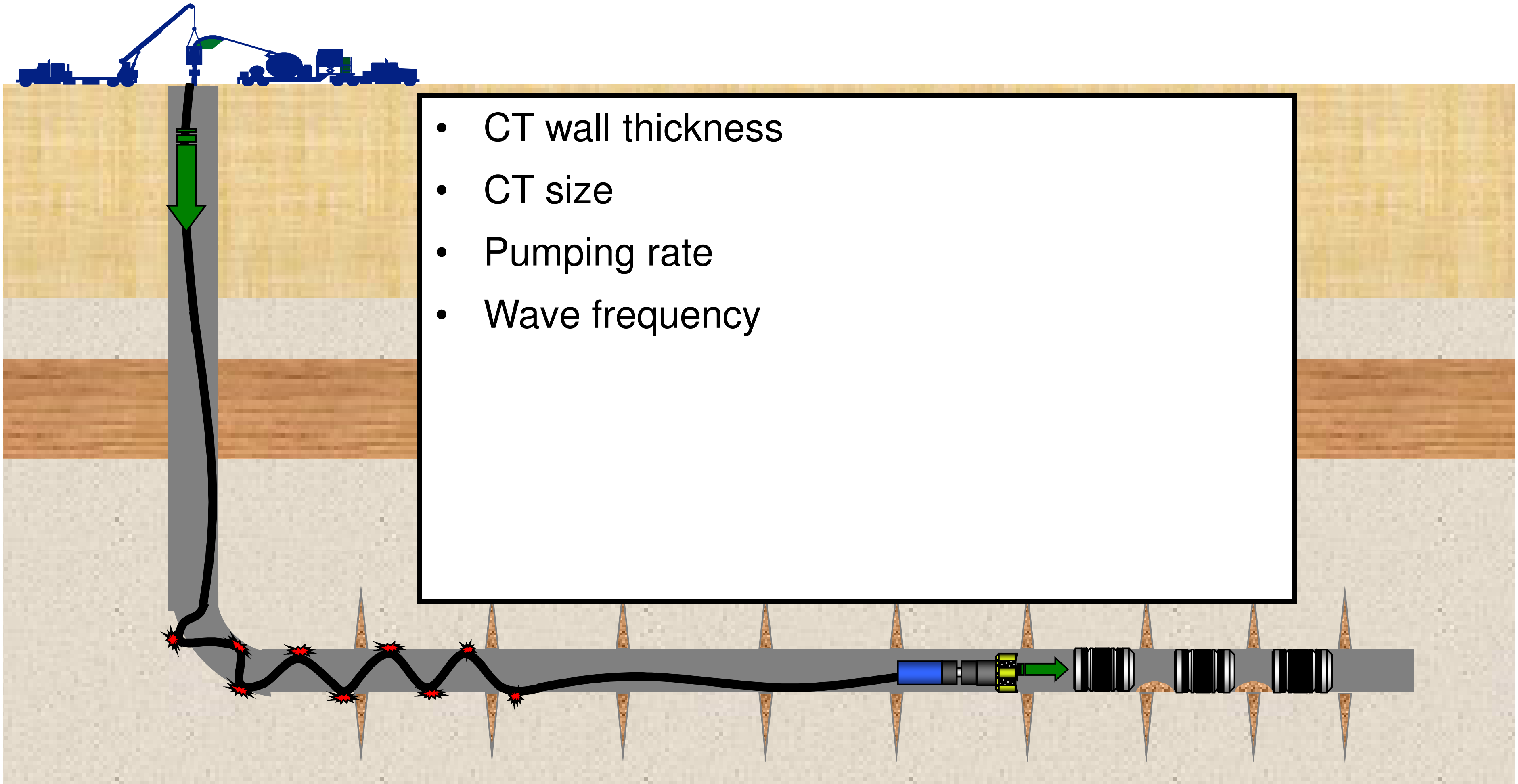
g = gravitational acceleration, m/s^2

Water Hammer Model Validation Against Lab Data



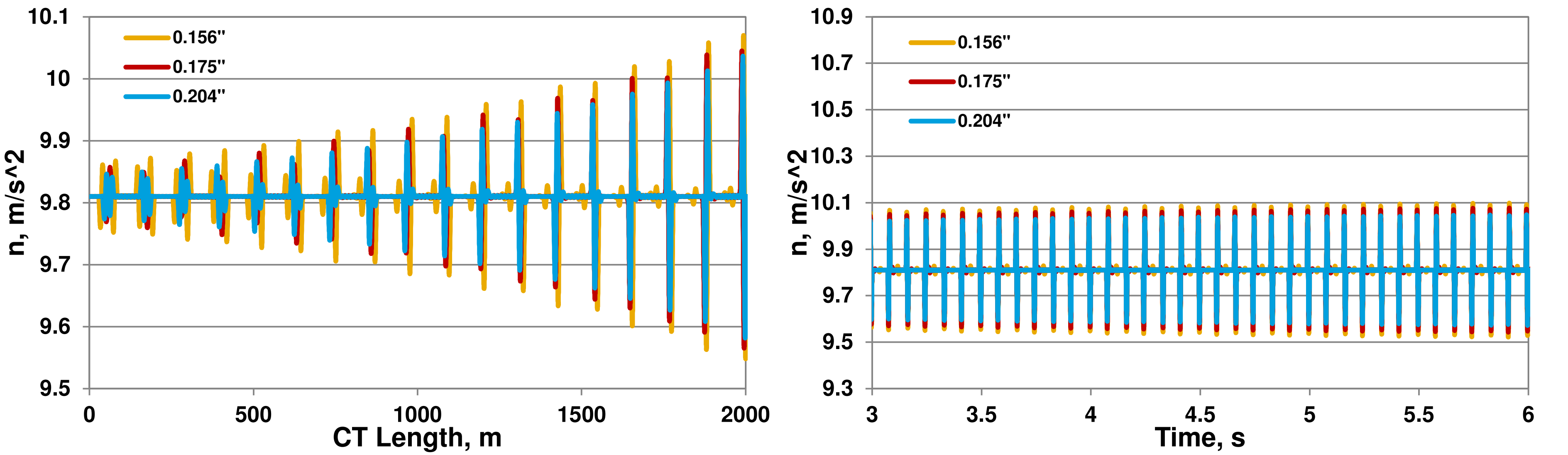
Case 1: Pumping Rate = 3 bpm, Back Pressure = 2,100 psi
Case 2: Pumping Rate = 1.5 bpm, Back Pressure = 1,720 psi

Four Parameter Effects on Radial Vibrations



- CT wall thickness
- CT size
- Pumping rate
- Wave frequency

CT Wall Thickness Effect on Radial Acceleration

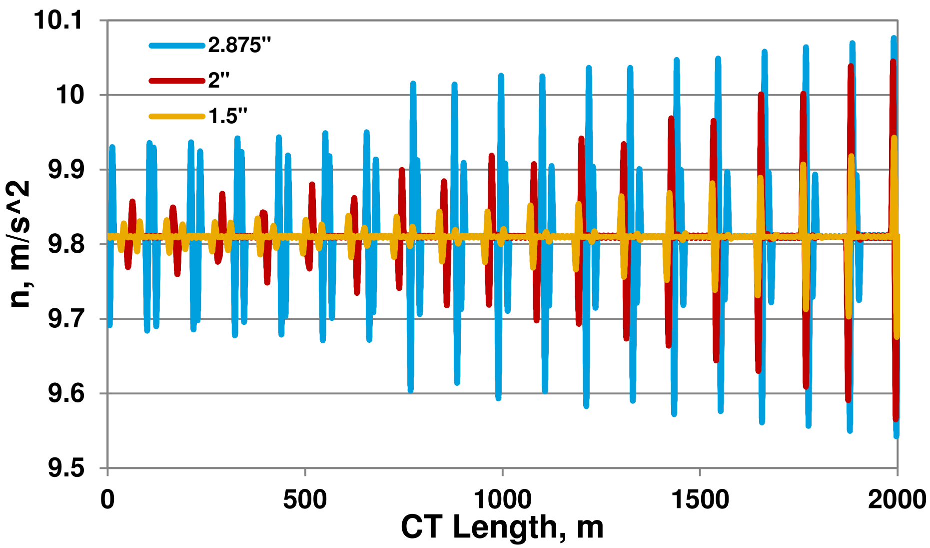


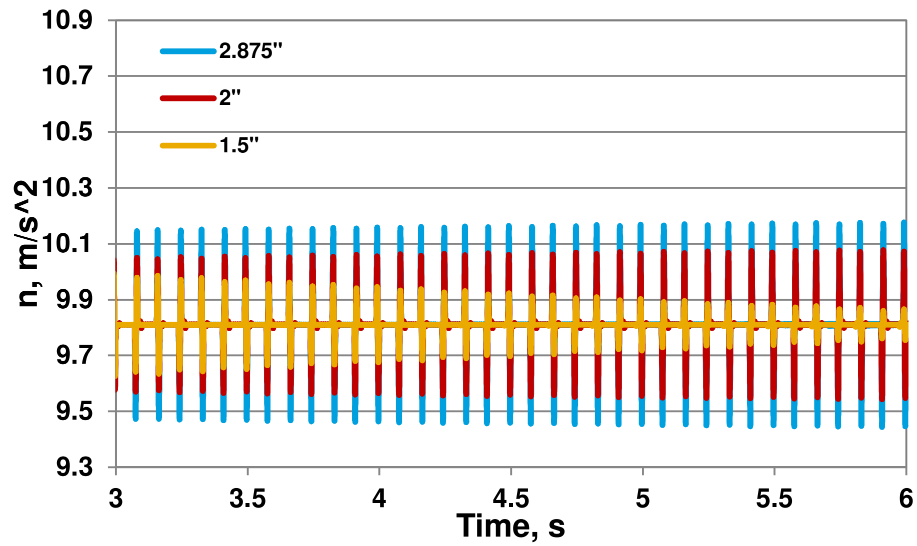
Main parameters

d_{CT} = 2-in.
Q_{inj} = 2.5 bpm
D = 5.5-in.
ϑ = 6 Hz
P_{BH} = 3630 psi

CT wall thickness, in.	Total normal force per unit mass, m/s^2	Change, %
0.156	10.094	0.5
0.175	10.073	0.3
0.204	10.044	-

CT Size Effect on Radial Acceleration



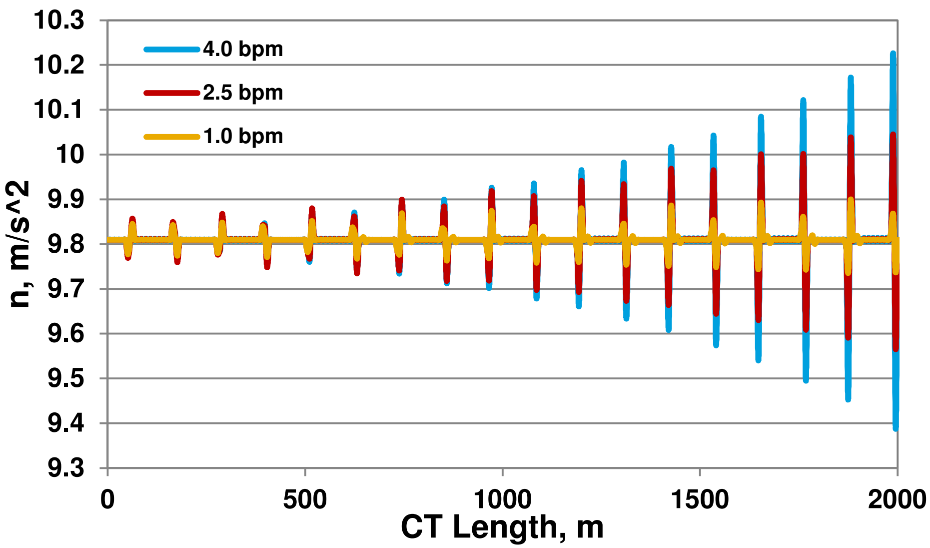


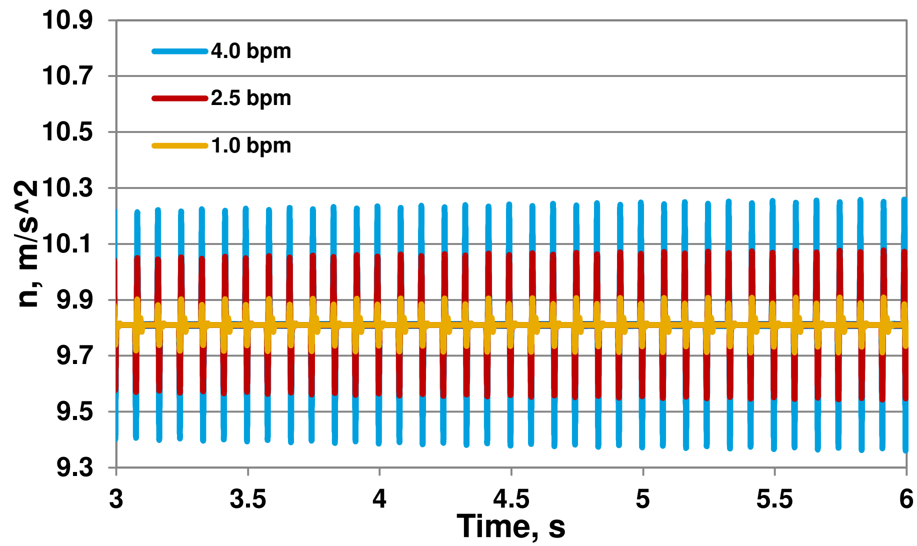
<u>Main parameters</u>

Q_{inj} = 2.5 bpm
w = 0.175-in.
D = 5.5-in.
ϑ = 6 Hz
P_{BH} = 3630 psi

CT size, in.	Total normal force per unit mass, m/s²	Change, %
1.5	10.058	-
2	10.074	0.2
2.875	10.228	1.7

Pumping Rate Effect on Radial Acceleration



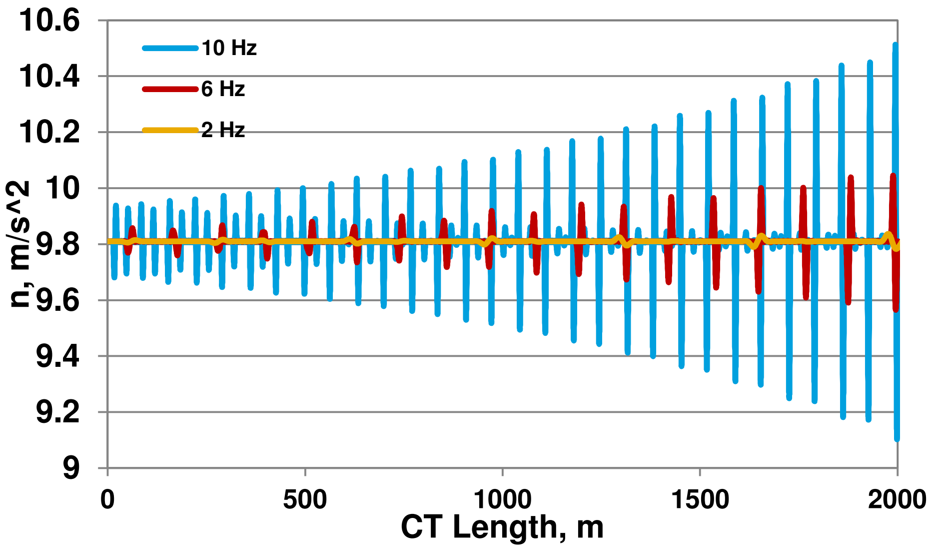


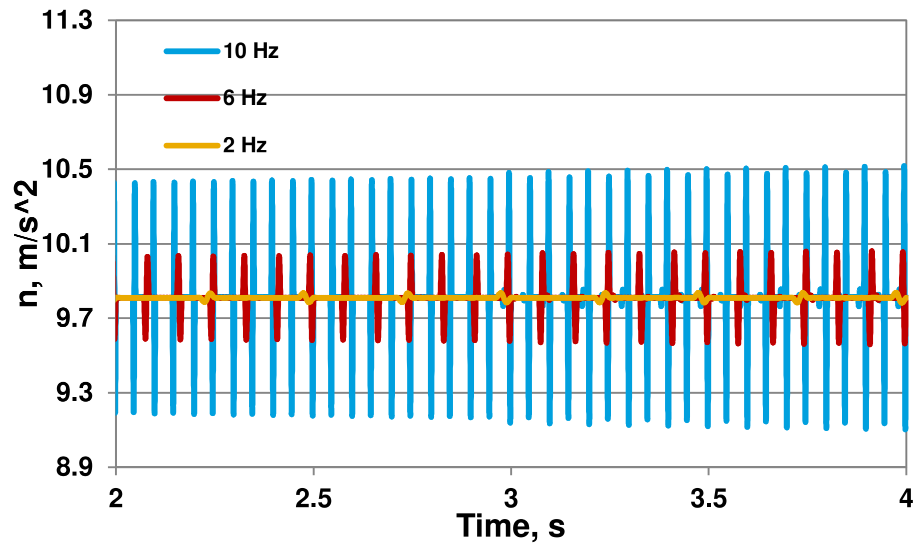
Main parameters

d_{CT} = 2-in.
w = 0.175-in.
D = 5.5-in.
ϑ = 6 Hz
P_{BH} = 3630 psi

Pumping rate, bpm	Total normal force per unit mass, m/s^2	Change, %
1.0	9.907	-
2.5	10.073	1.7
4.0	10.252	3.5

Wave Frequency Effect on Radial Acceleration



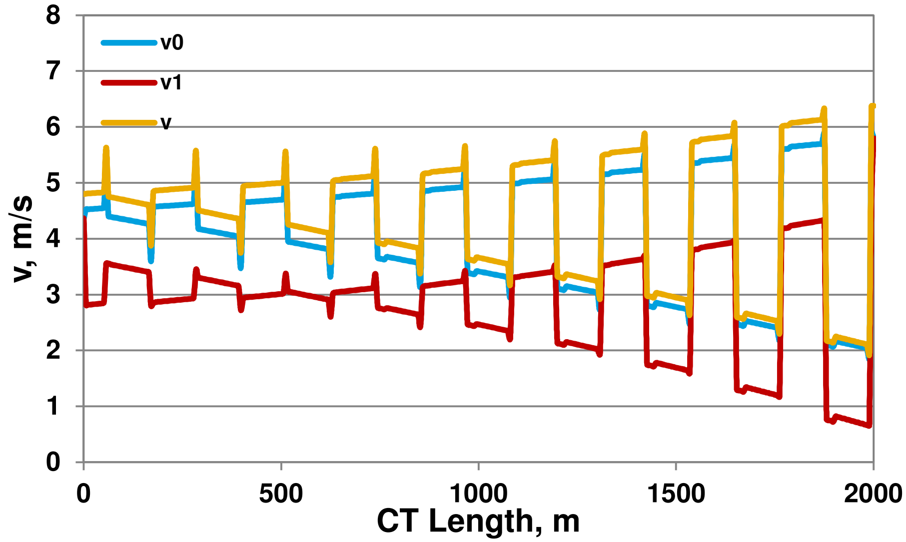


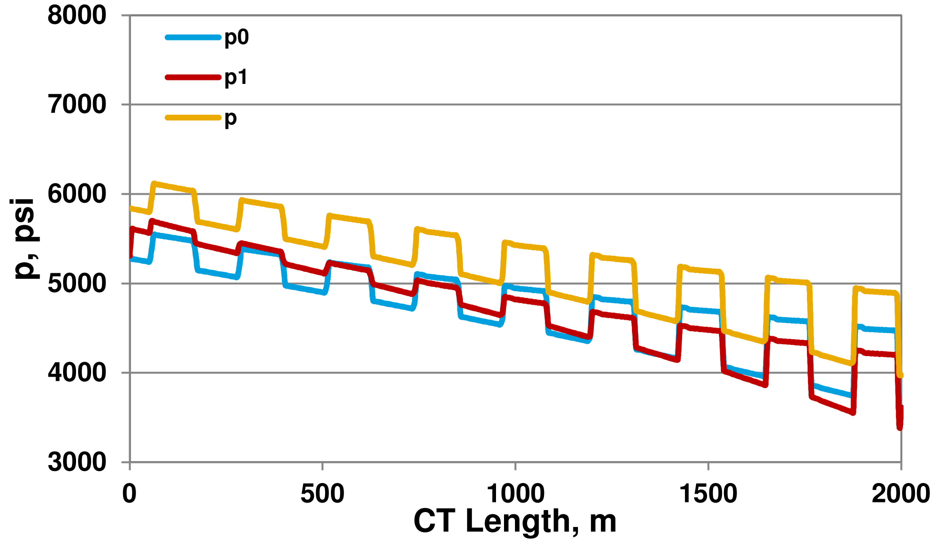
Main parameters

d_{CT} = 2-in.
Q_{inj} = 2.5 bpm
D = 5.5-in.
w = 0.175–in.
P_{BH} = 3630 psi

Wave frequency, Hz	Total normal force per unit mass, m/s^2	Change, %
2	9.843	-
6	10.073	2.3
10	10.529	7.0

Weak Helical Pipe Flow Effect on Water Hammer





<u>Main parameters</u>

d_{CT} = 2-in.
w = 0.175-in.
D = 5.5-in.
ϑ = 6 Hz
P_{BH} = 3630 psi
Q_{inj} = 2.5 bpm

<u>Take-away</u>

- $v(t,z) \cong v_0(t,z) + \mathcal{O}(\varepsilon)$
- $p(t,z) \cong p_0(t,z) + \mathcal{O}(\varepsilon)$
- Weak helical pipe flow effect is small and can be ignored (i.e., CT can be considered as a straight pipe)

Conclusions

- Developed first CT water hammer model for straight and weak helical pipes
  - Method of Characteristics
  - Perturbation Method
- Validated model against lab data
- Studied the effects of four parameters on radial acceleration in horizontal wells
  - CT wall thickness (smallest)
  - CT size (small)
  - Pumping rate (large)
  - Wave frequency (largest)
- For CT operations, weak helical CT vibrations can be modeled as for straight pipes

Acknowledgements

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Thank You / Questions