DESTRESS

Demonstration of soft stimulation treatments of geothermal reservoirs

Is Reservoir Monitoring by Pressure Pulsing Possible?

Is Reservoir Monitoring By Pressure Pulsing Possible?

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WHY?

Is Reservoir Monitoring By Pressure Pulsing Possible?

HOW?

WHAT?

SO?

WHY??

Coupled Processes in EGS

- **Flow** in porous medium
  - Darcy's law
  - Continuum equation
  - Fracture Permeability according to the cubic law (Poisseuille flow)
  - Porosity change due to volumetric strain

- **Mechanics**
  - Rock matrix: Linear Elastic
  - Fracture zone: Mohr-Coulomb Model
  - Poro-elastic stresses
  - Thermo-elastic stresses

- **Heat Transfer**
  - Conduction & Diffusion: Heat equation
  - Convection: Darcy velocity field
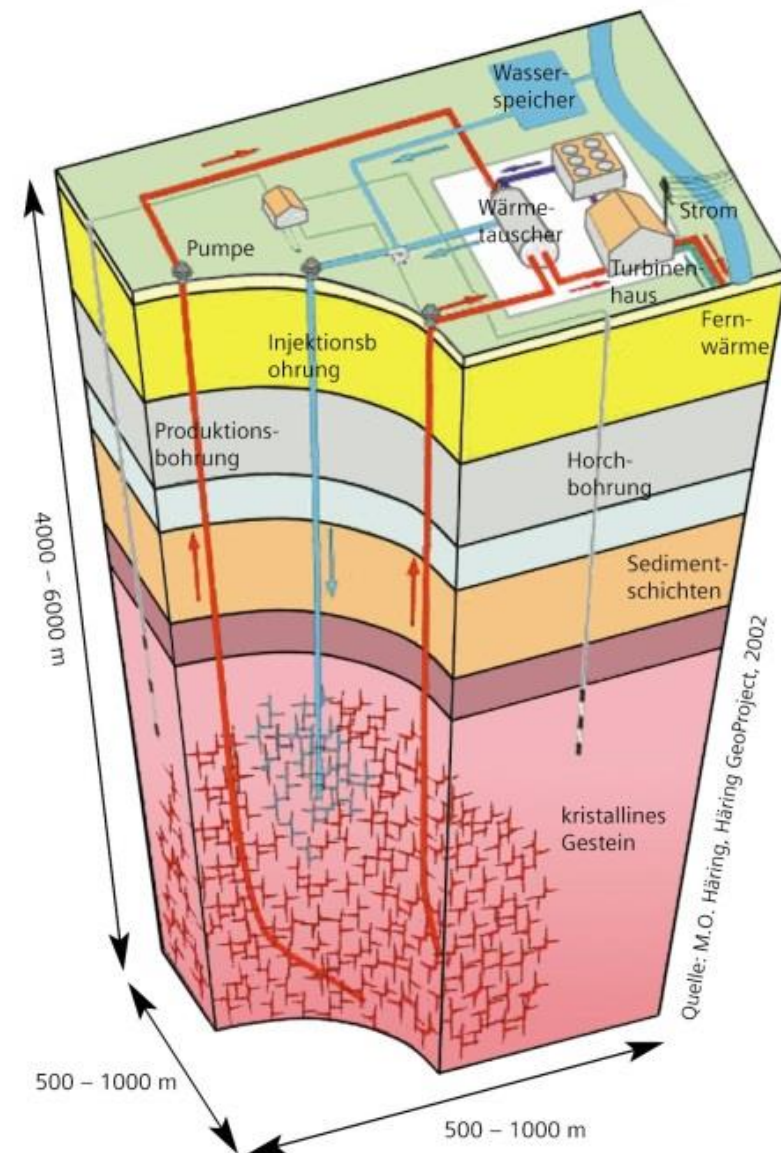
Optimization – Monitoring

BUT – What is helping optimization?

Productivity / Injectivity

PERMEABILITY

SKIN

- Passive monitoring:
  - Pressures
  - Rates
  - Temperatures
  - Microseismicity
  - Surface movement

- Active monitoring
  - Well testing
  - Seismics

Conventional Well Testing
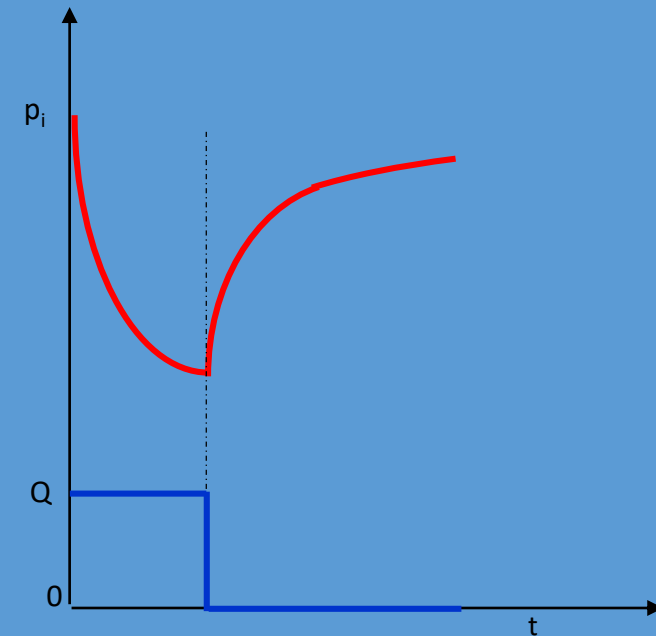
Inject / Produce for limited time

Shut in

Monitor pressure

Interpretation with pressure derivative vs time

Well closure required
- Losing time
- No interpretation during productions

Nearby well closure required
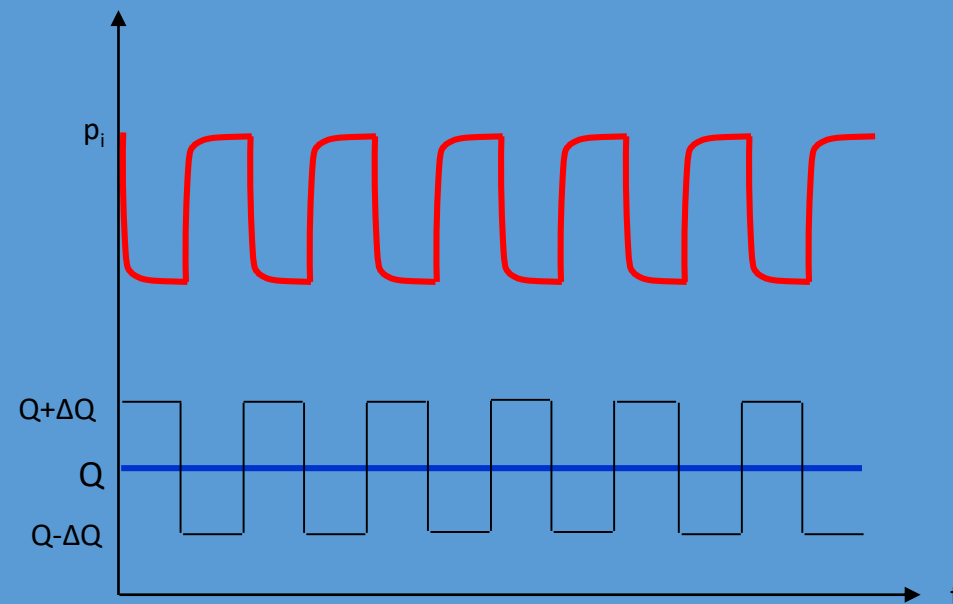
Harmonic Pulse Testing

Apply a train of pulses

Monitor the pressure
- In the "active well"
- In an "observer well"

Do the interpretation in the
FREQUENCY DOMAIN

Possibility of testing
WHILE PRODUCING

HOW??

What do we need?

Theoretical framework
- How to work in Frequency domain?
- Solving the equations?
- Role of reservoir storativity?
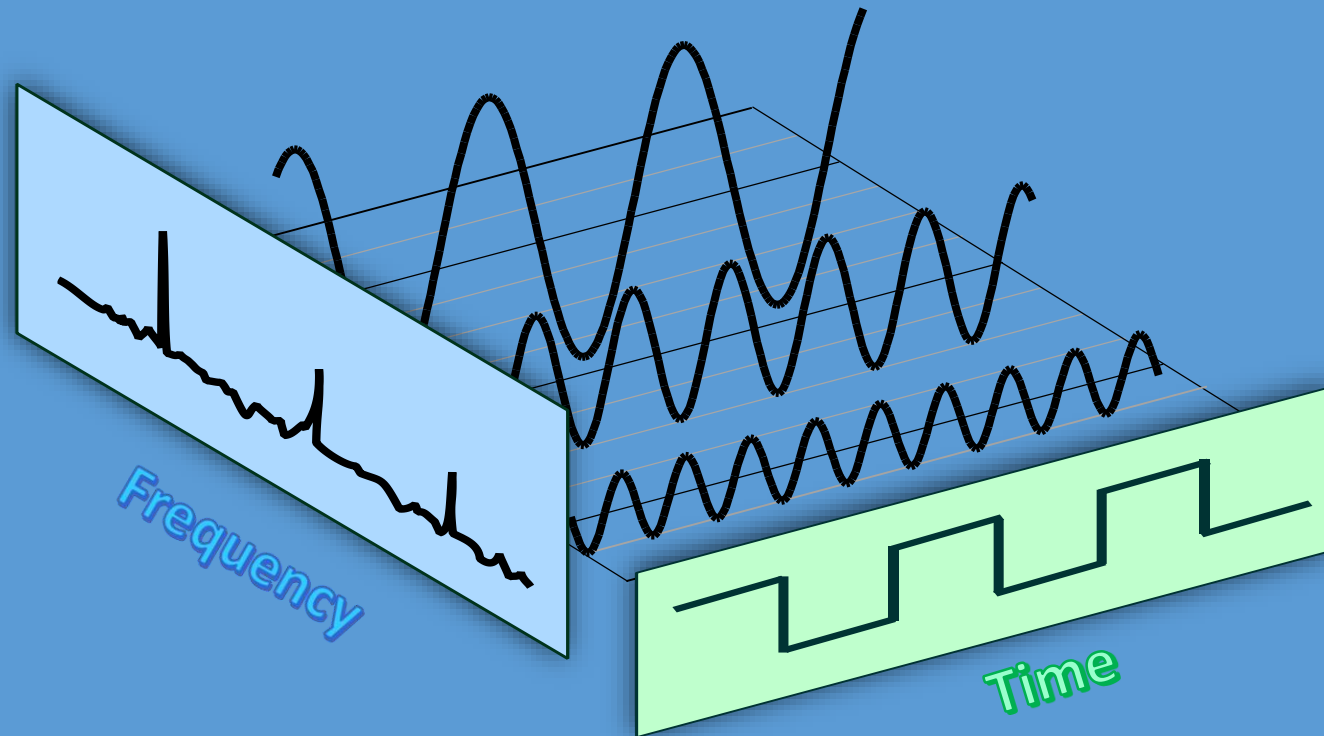- Role of wellbore storage?

Do we have a model?

Would data contain information?

Field test
- Can we obtain a signal?
- Can we derive critical paramaters?
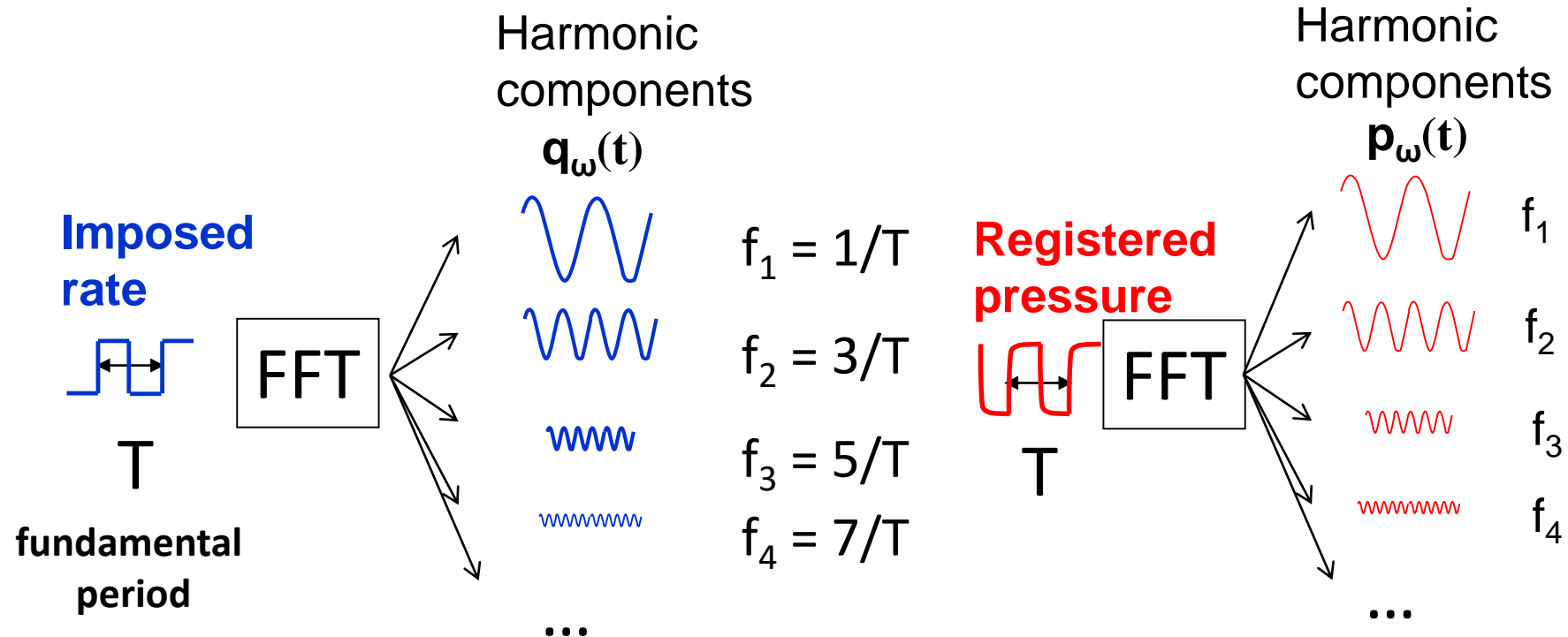- What are the sensitivities?
- What are the pitfalls?

Does it work in practice?
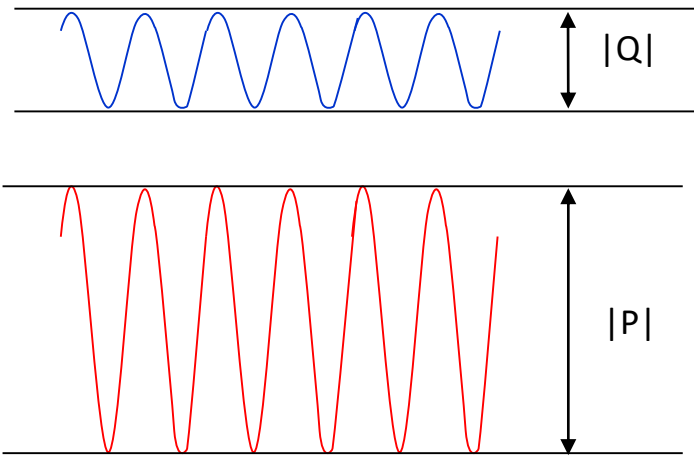
Signal Decomposition

Signal Decomposition

Fourier Analysis
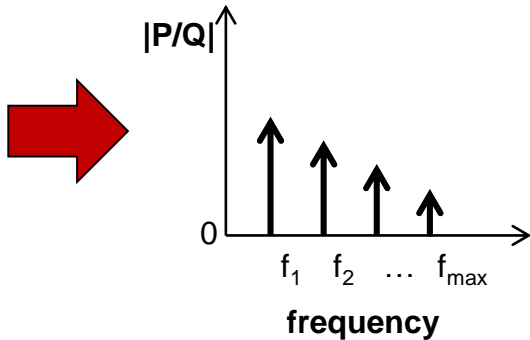

Harmonic components $q_\omega(t)$

Imposed rate

FFT

T

fundamental period

$f_1 = 1/T$

$f_2 = 3/T$

$f_3 = 5/T$

$f_4 = 7/T$

$\ldots$

Registered pressure

FFT

T

Harmonic components $p_\omega(t)$

f_1

f_2

f_3

f_4

$\ldots$

Component Information

Amplitude Ratio

$|P/Q|$

Phase shift

$\angle (P/Q)$

$|Q|$

$|P|$

Spectrum of **Amplitude ratio**

$|P/Q|$

0

f_1 f_2 … f_{max}

frequency

Spectrum of **Phase shift**

$\angle (P/Q)$

2π
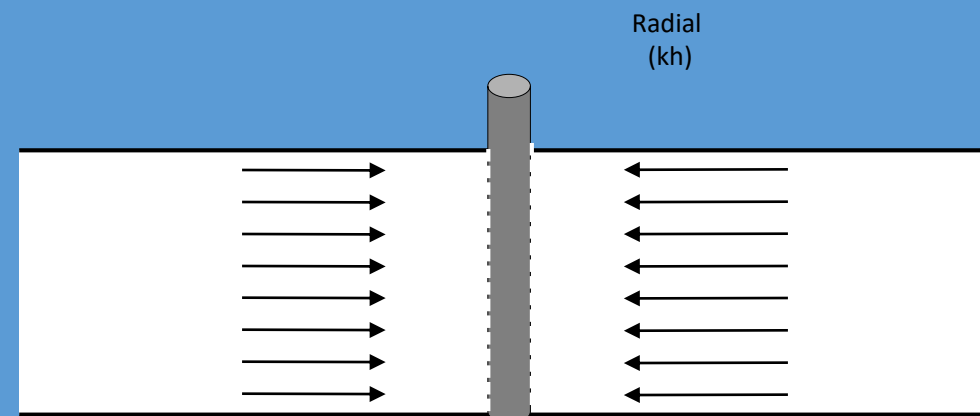
0

f_1 f_2 **…** f_{max}

frequency
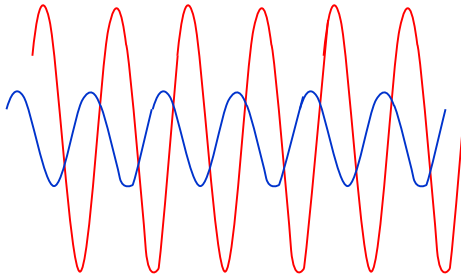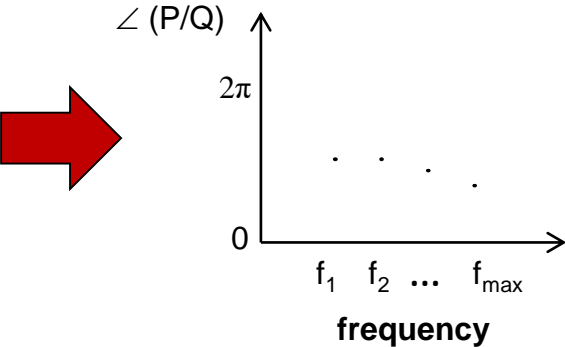
Infinite Acting Radial Flow

❑ Response function in Fourier space: combination of Bessel functions with complex argument

$$R = \frac{p_{well}(t)}{\tilde{q}} = \frac{K_0[\xi] + S}{k + i\omega W_S \cdot (K_0[\xi] + S)}$$

$$W_S = \frac{\mu C}{2\pi h}; \xi = r_w \sqrt{\frac{i\omega}{\kappa}}$$

❑ Similarity to solution in Laplace space for conventional well test

❑ Containing amplitude and phase information

Radial (kh)

WHAT??

Does Harmonic Pulse Testing work in practice??
Pohang! (South Korea)

Granitic rock ~4 km depth

Stimulation treatments for demonstration

First stimulations showing seismicity

Newest stimulation to assess onset and location of seismicity

Possibility to perform Harmonic Pulse Testing

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Stimulation record

Soft Stimulation (07-14 August 2017)
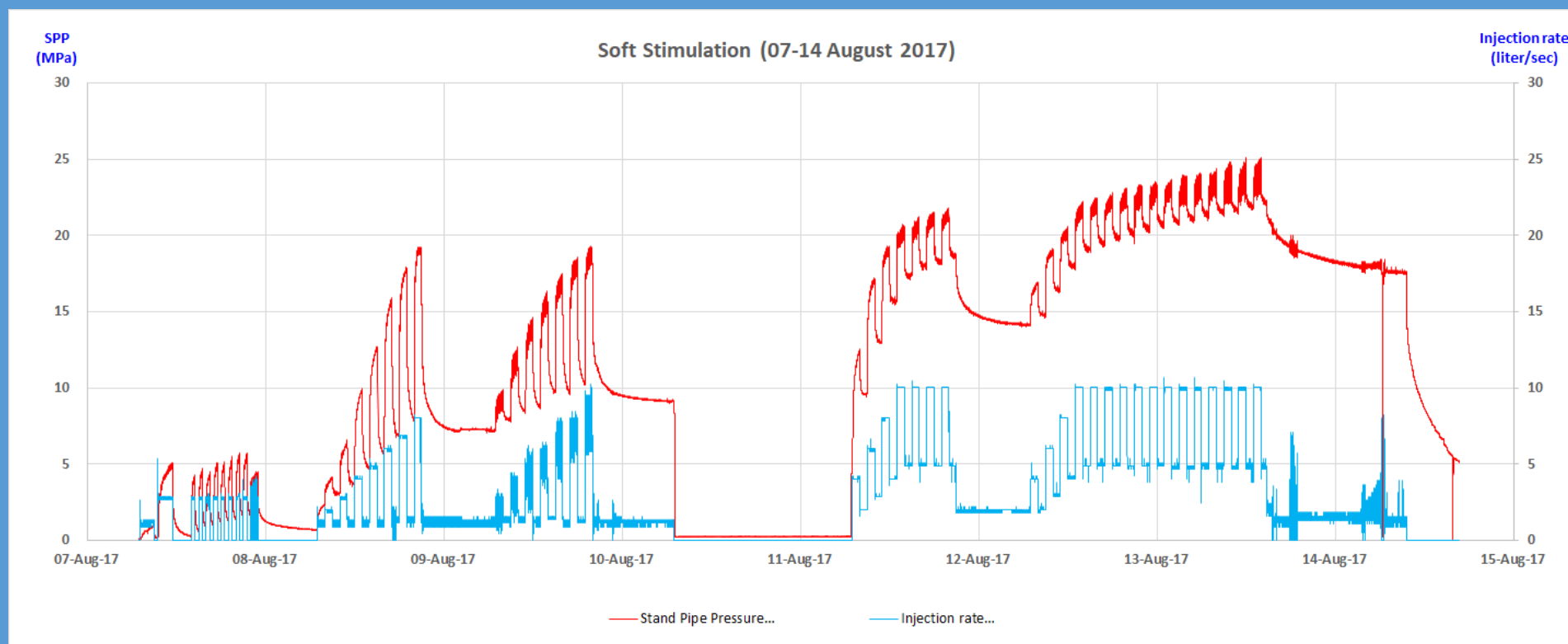
Interpretation

Baseline:
1-h period Harmonic Pulse Test (30 minutes on – 30 minutes off)
6-min period Harmonic Pulse Test (3 minutes on – 3 minutes off)

Monitoring during injection:
Injection cycles at increasing background rate: 6-min Harmonic Pulse Tests for monitoring

Monitoring during Soft Stimulation: 2-h period Harmonic Pulse Test on top of injection rate
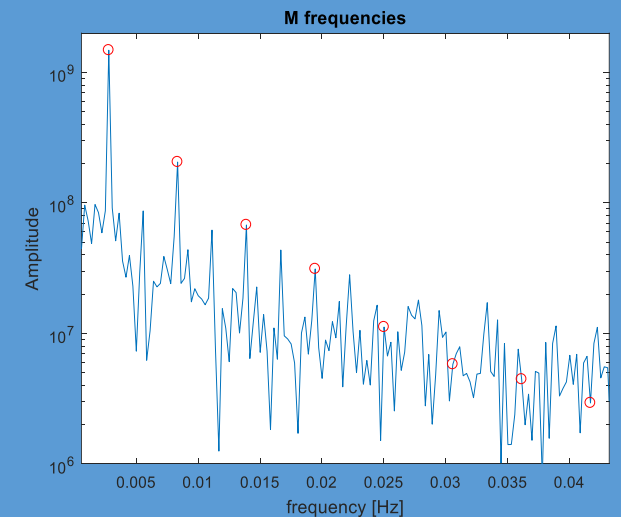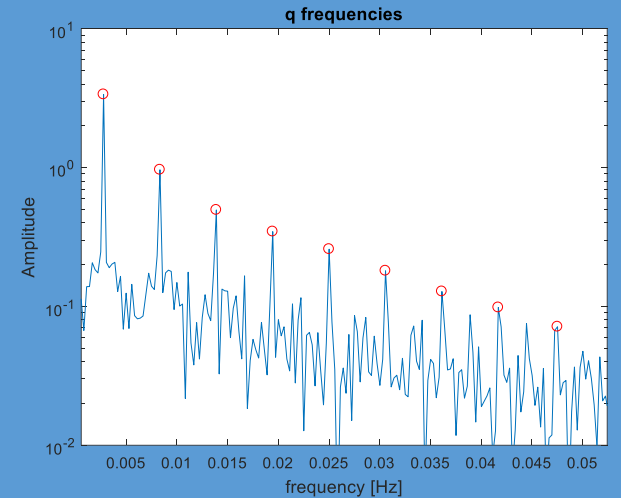
Baseline test

Series1   Series2
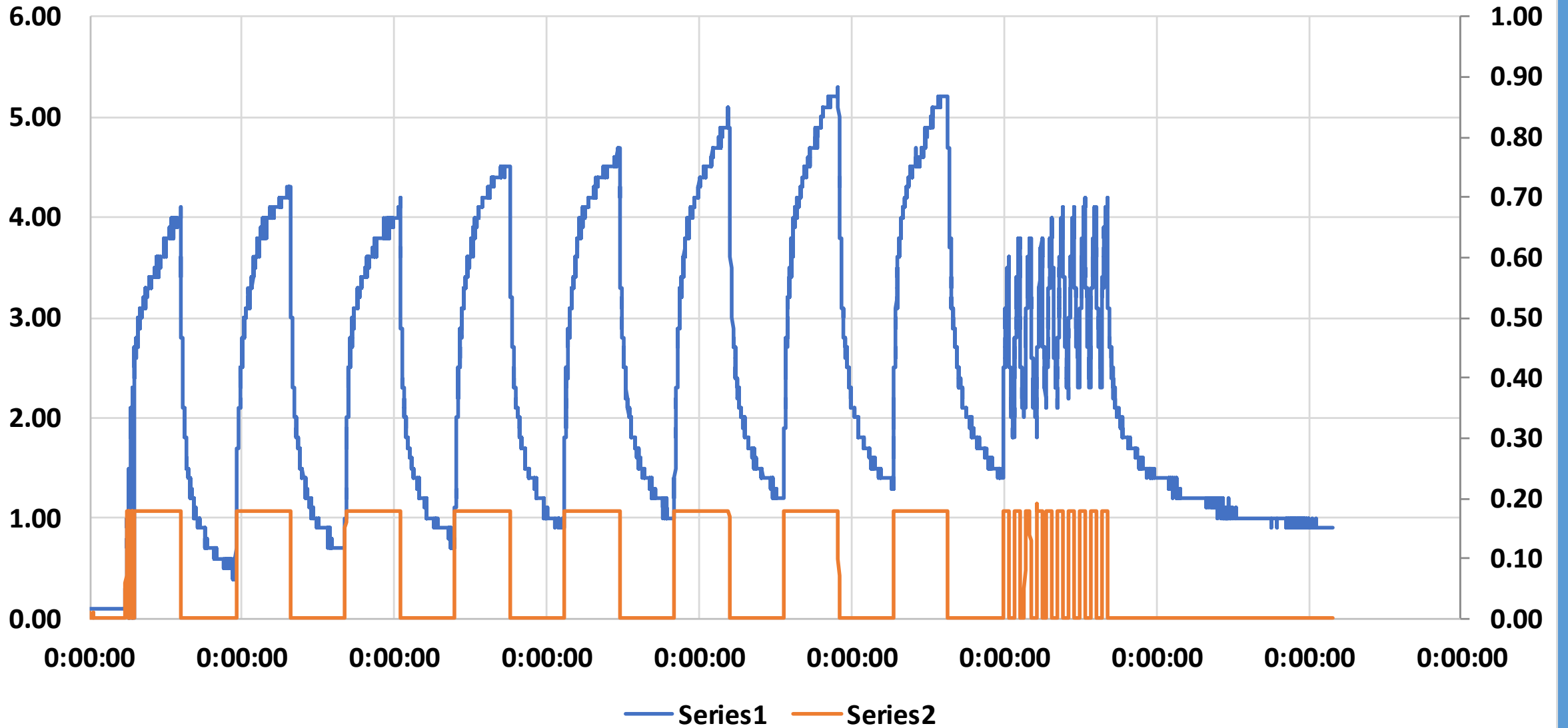
Fourier Transform of 6-minute pulses

Reasonable number of peaks in
Rate spectrum

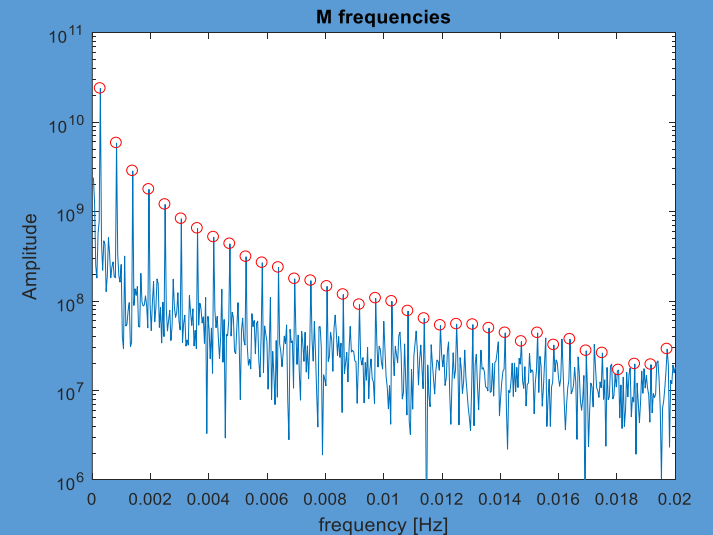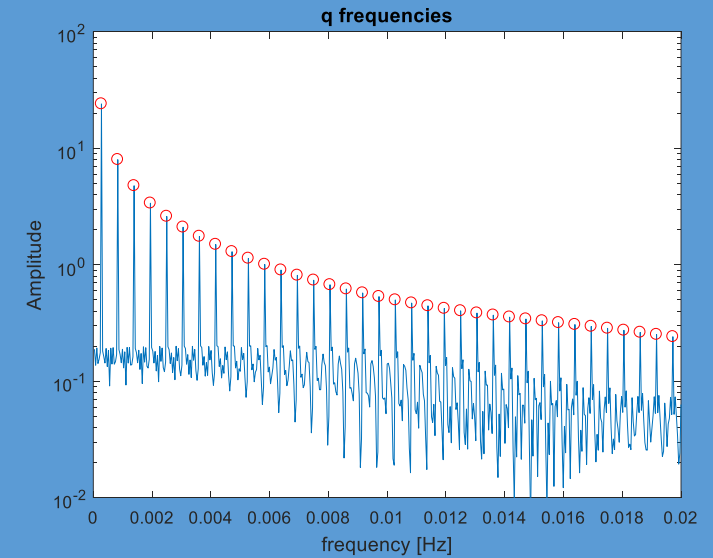Limited number of peaks in
Pressure spectrum

High frequencies disappear in the noise –
damping by wellbore storage /
reservoir compressibility

Fourier Transform of 60-minute pulses

Many frequencies in the Rate Spectrum and in the Pressure Spectrum

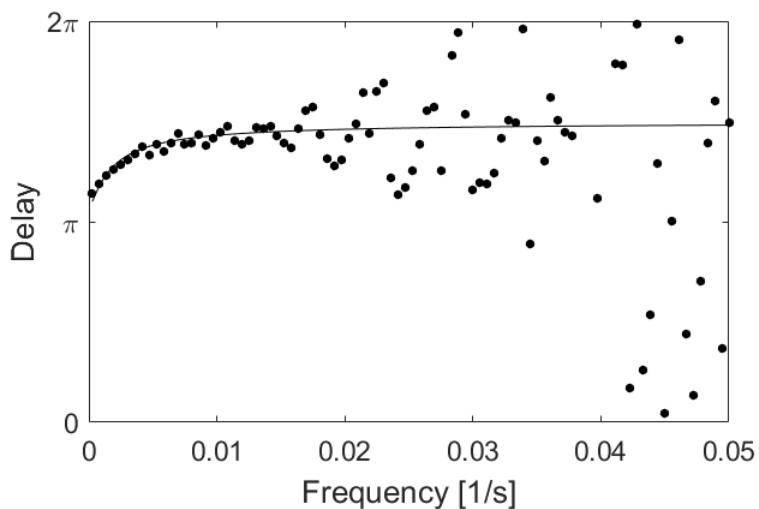# Highest observable frequencies similar to 6-minute test
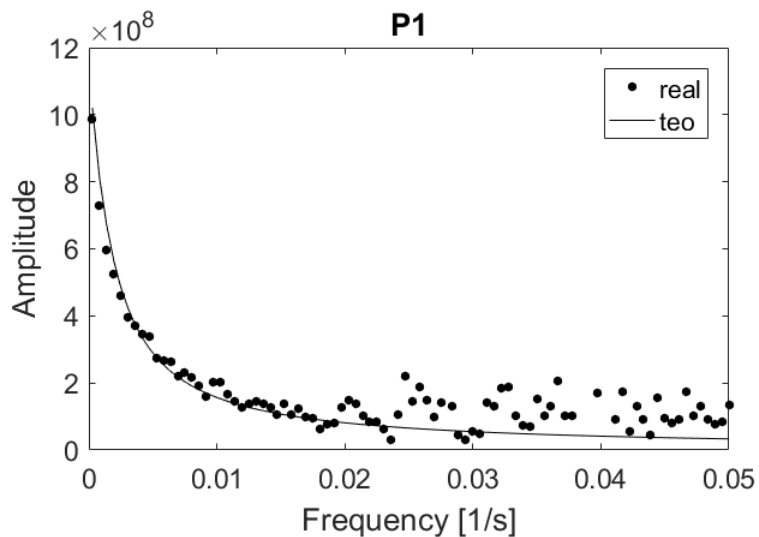

q frequencies

M frequencies

Interpretation

Evaluate response:
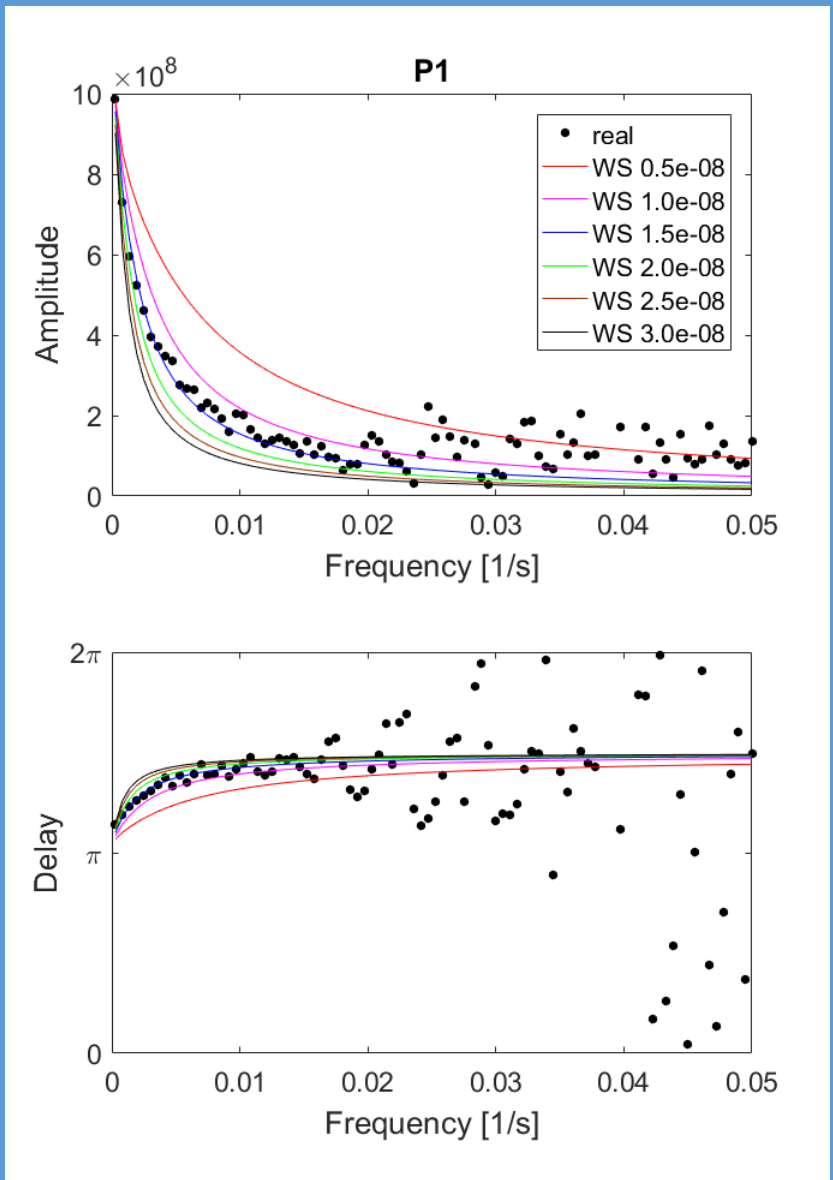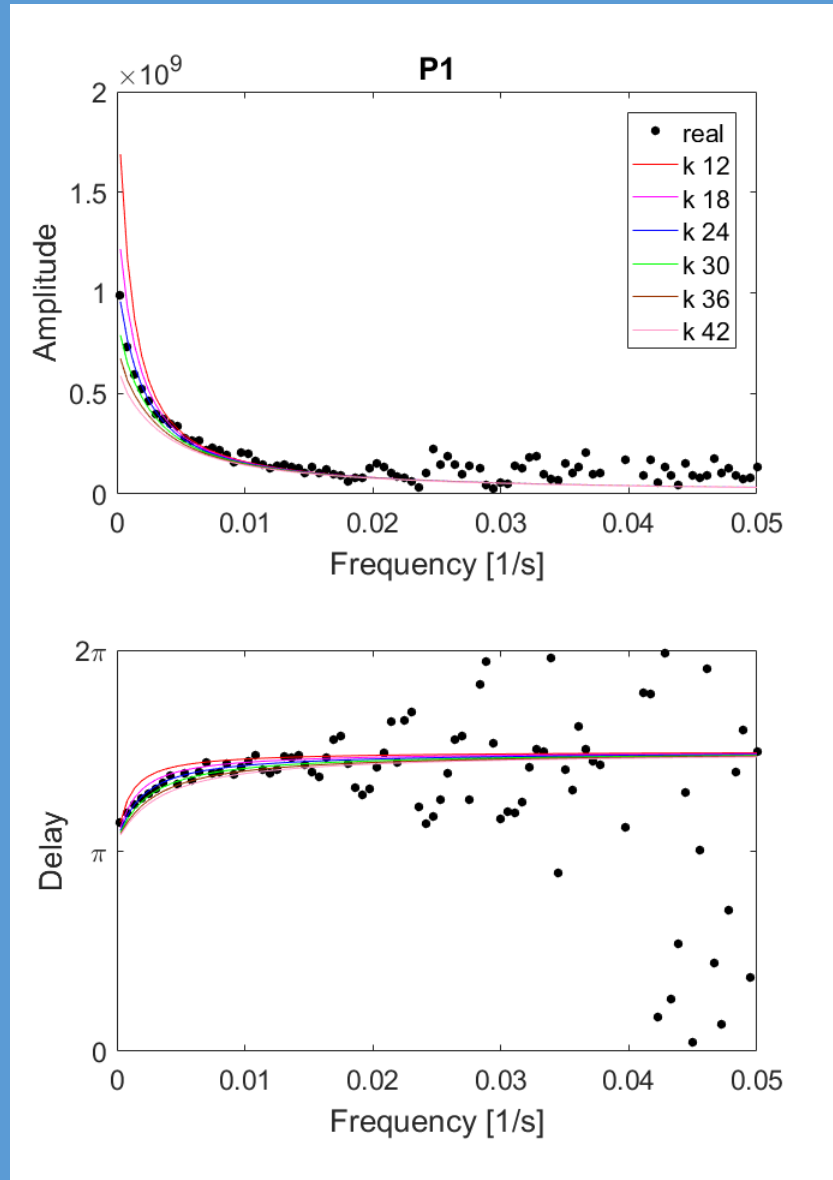- Amplitude of pressure / rate
- Delay of pressure wrt rate

Sensible numbers up to ~0.02 Hz

Fit with adjusting parameters
- Permeability: k.h = 240 md.m
- Skin: S = 0
- Wellbore storage: 0.0015 bar/m^3
- Compressibility: ~10^{-4} bar^{-1}
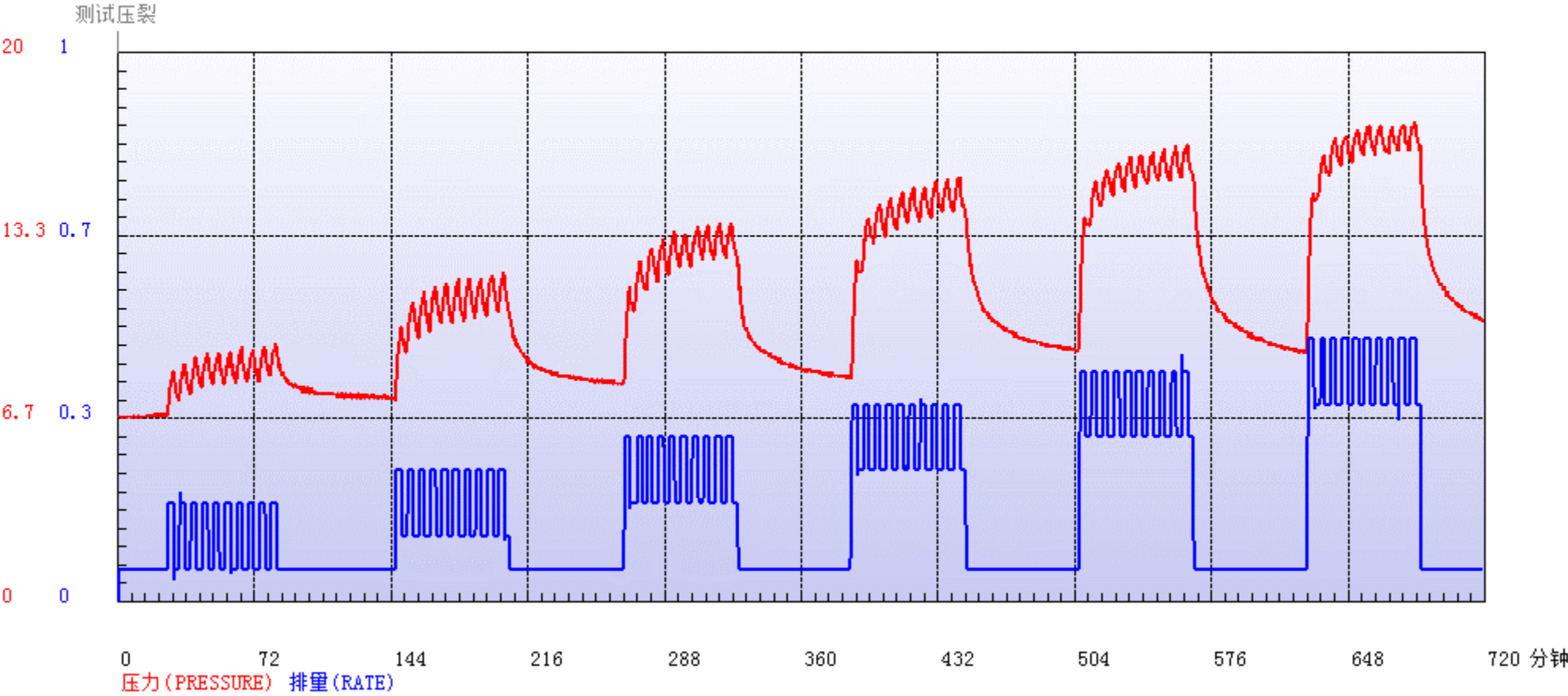
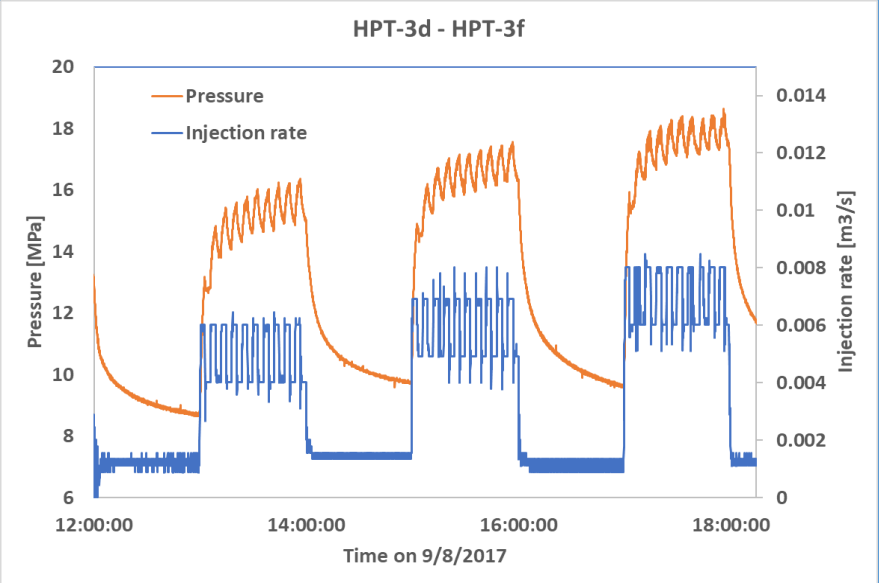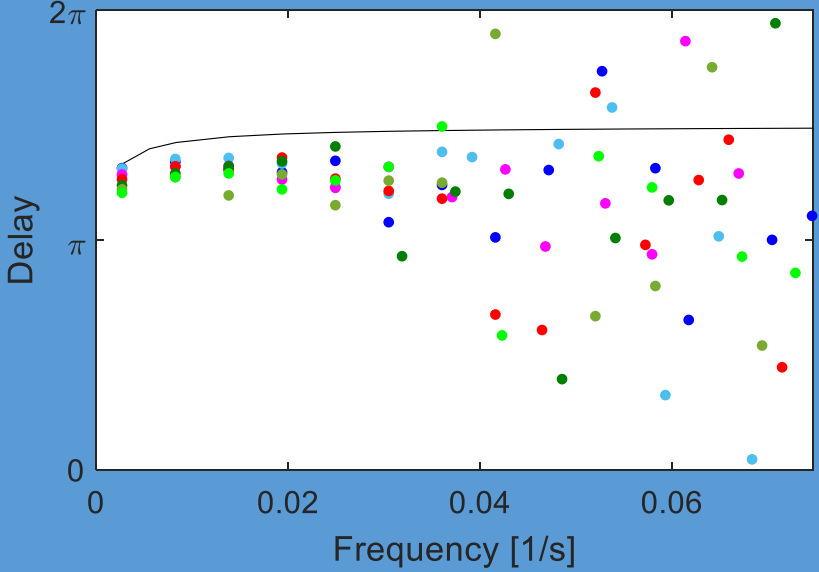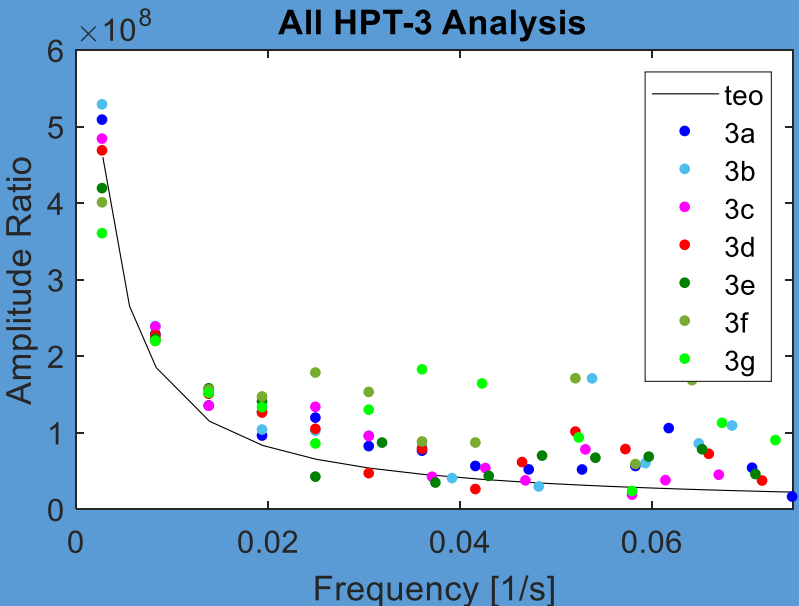# Sensitivities: Permeability and Wellbore Storage

Monitoring Phase

Monitoring with 6-minute pulses

Few frequencies give signal

Small differences

Large contribution of wellbore storage

Stimulation phases

Comparison and analysis HPT-1, 4, 5
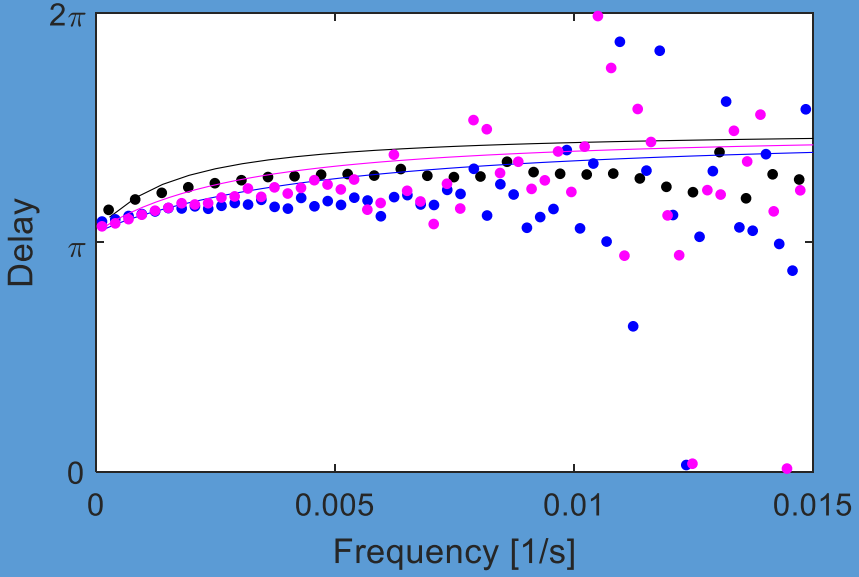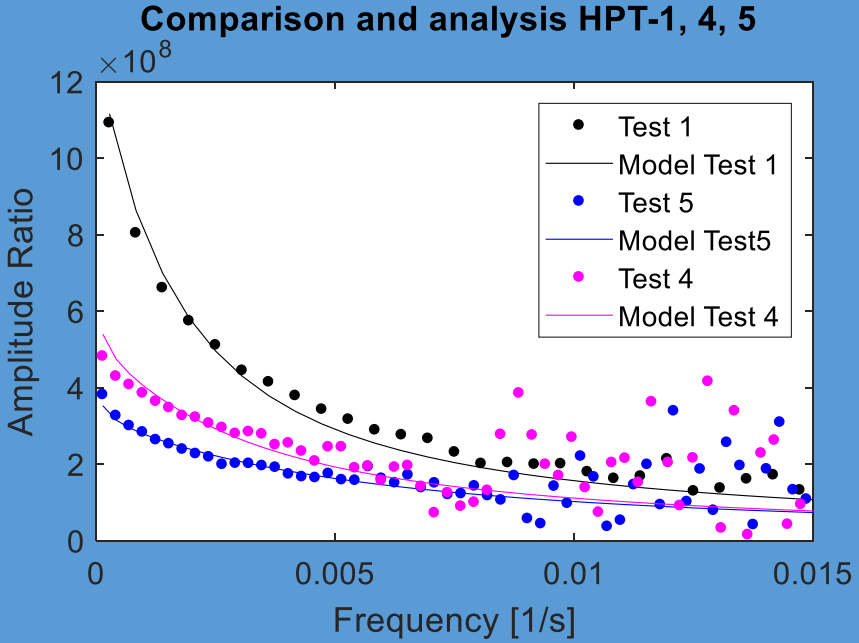

Later tests show smaller amplitudes:
Increase in effective permeability
- HPT-1 – HPT-3: 10 md
- HPT-4: 30 md
- HPT-5: 40 md

Opening fractures during background injection rate?

No permanent stimulation effect found?

Some seismicity during & after last test

SO??

Conclusions, Learnings, Way Forward

Harmonic pulse testing works well
- Simple deployment
- Application on top of ongoing operations
- Monitoring in active well / observer

But:
- Pulse durations
- Timing of rate switching
- Sampling rate, Number of pulses
- Synchronization
- Importance of wellbore storage

- What's Next?
  - Comprehensive analysis of this test
  - Skin
  - What is the role of storativity / compressibility?
  - Sensitivity?
  - Application to really changing reservoir
  - Extension to include mechanics & coupled models

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