Marshall Space Flight Center

Chug and Buzz ….
The Neglected and Disrespected Combustion Instabilities

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What is Combustion Instability ?

Embed movie

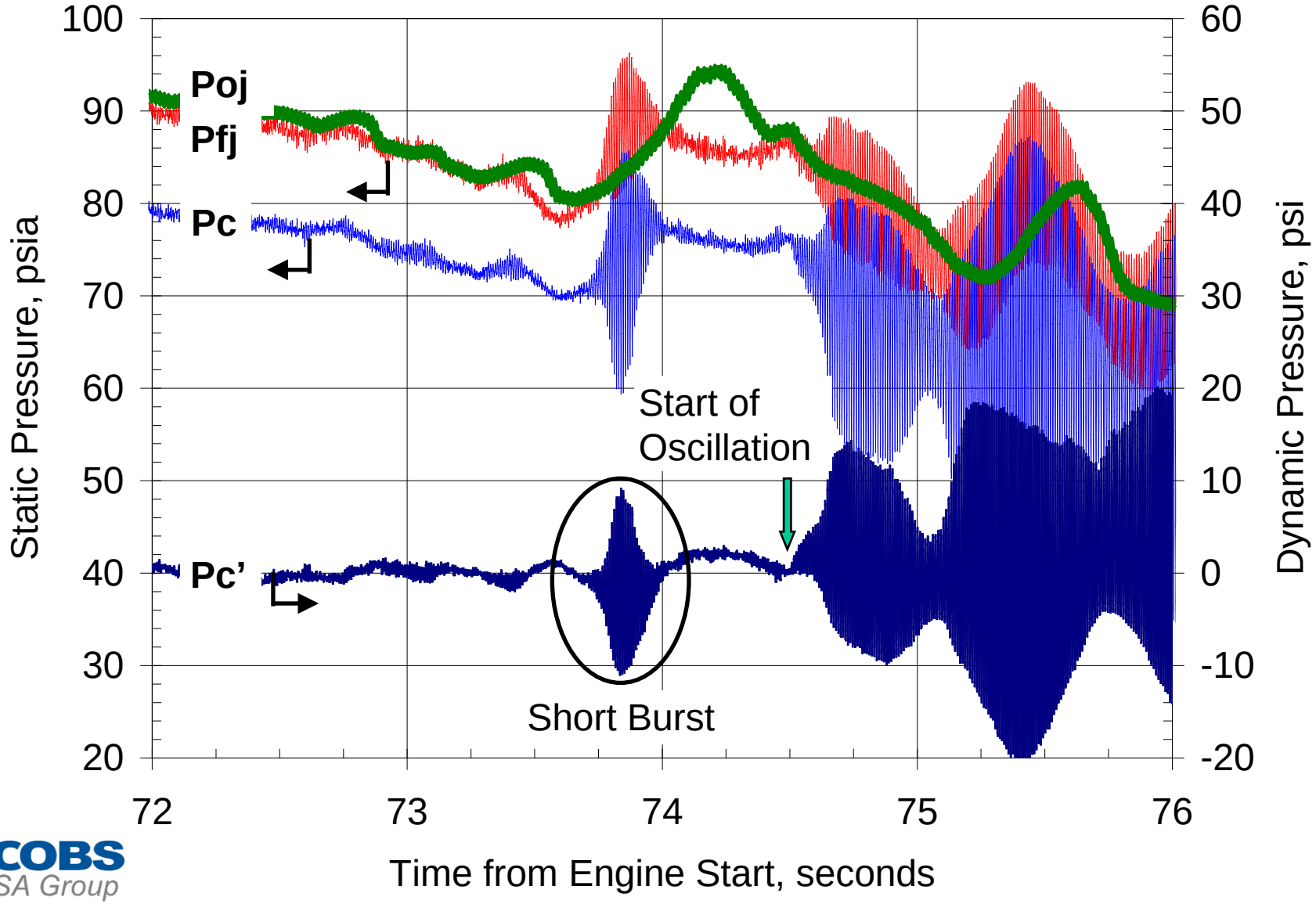
"Low" Frequency versus "High" Frequency

- "High" frequency combustion instability gets all the press
  - "Screech"
  - Can be very harmful when it happens
  - But does not really happen that often any more
  - Associated with the acoustic modes of the combustion chamber
- "Low" frequency combustion instability gets no press
  - "Chug"
  - Yet it happens on almost every program and during almost every start and shutdown transient
  - Can be more harmful than you realize
- Sometimes the two types meet in the middle
  - "Buzz"
    - "intermediate" frequency combustion instability
  - Two types have been observed
    - One combining injector organ pipe modes and chamber transverse modes
    - One combining injector Helmholtz modes and chamber longitudinal modes
  - Has been happening quite often lately

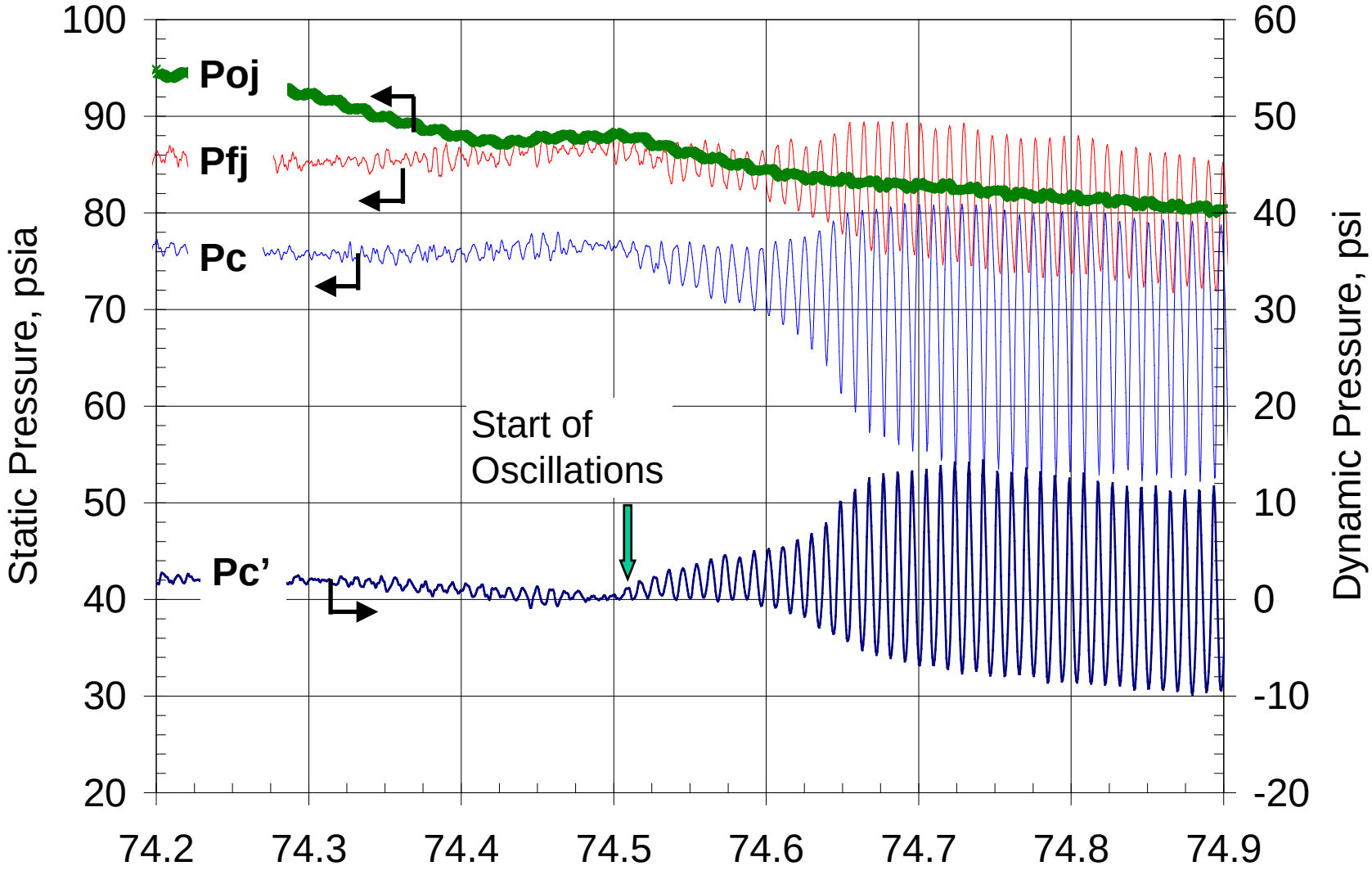
Chug

- Bulk oscillations of the combustion chamber gas
  - No spatial pressure variations in the combustion chamber
  - Pressure wave shapes are *usually* sinusoidal
  - One or both injector manifolds are engaged
- Happens on almost every engine
- You may think there is nothing new here…
  - Predictable, easy to analyze ??
    - Analytical methodology improvements still being made
    - Most methods still rely on calculation of a “timelag”
      - If you estimate incorrectly, chug occurs unexpectedly
  - Happens ? So what ?
    - Things break…
      - Instrumentation, fittings & connections, ceramic parts
    - Performance decreases
      - oscillating mixture ratio and reduced efficiency of injection processes
    - Undesired structural vibrations
    - Trouble with ignition

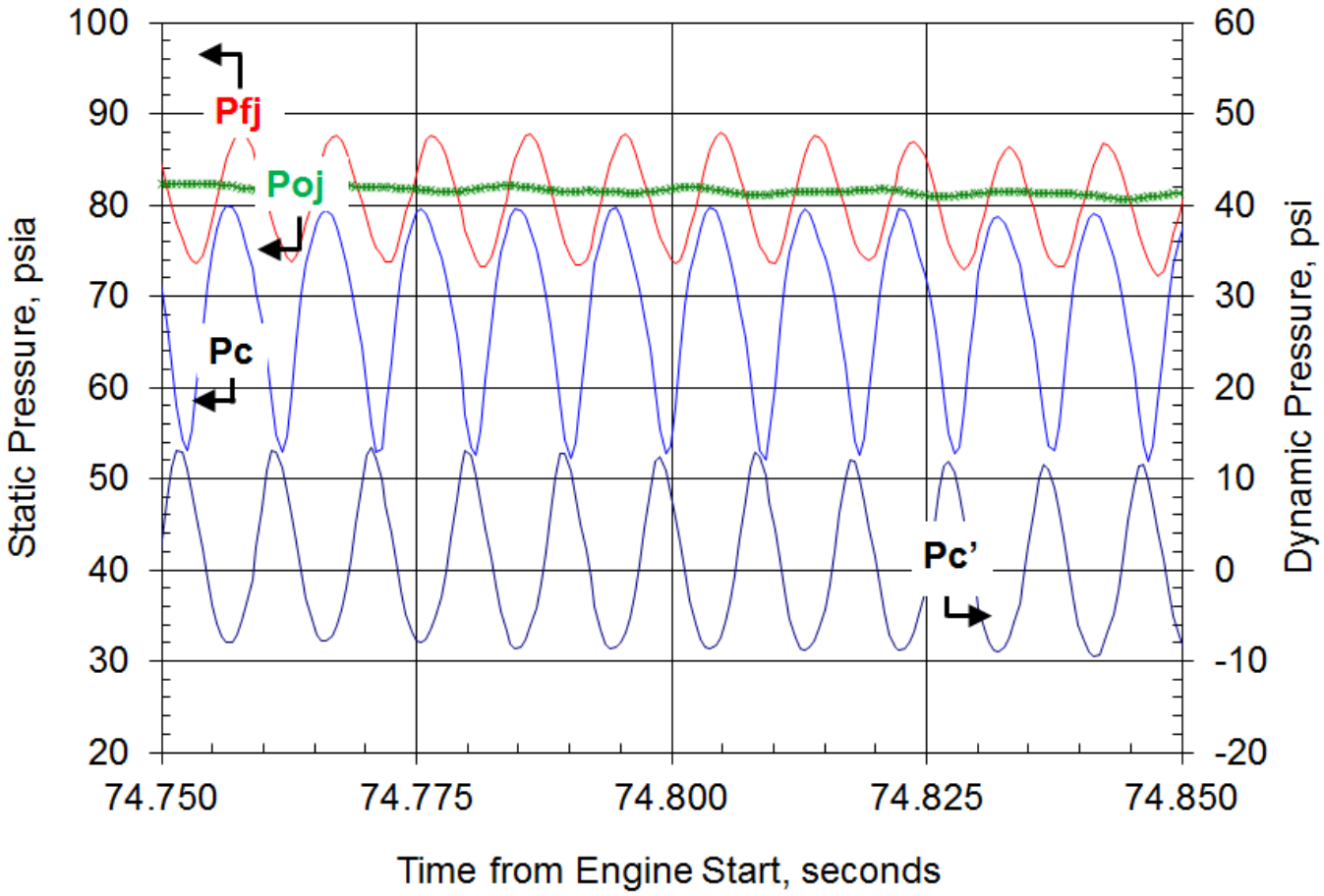
“Nice” Chug


Poj
Pfj
Pc
Pc’
Start of Oscillation
Short Burst
Static Pressure, psia
Dynamic Pressure, psi
Time from Engine Start, seconds
100
90
80
70
60
50
40
30
20
60
50
40
30
20
10
0
-10
-20
72
73
74
75
76

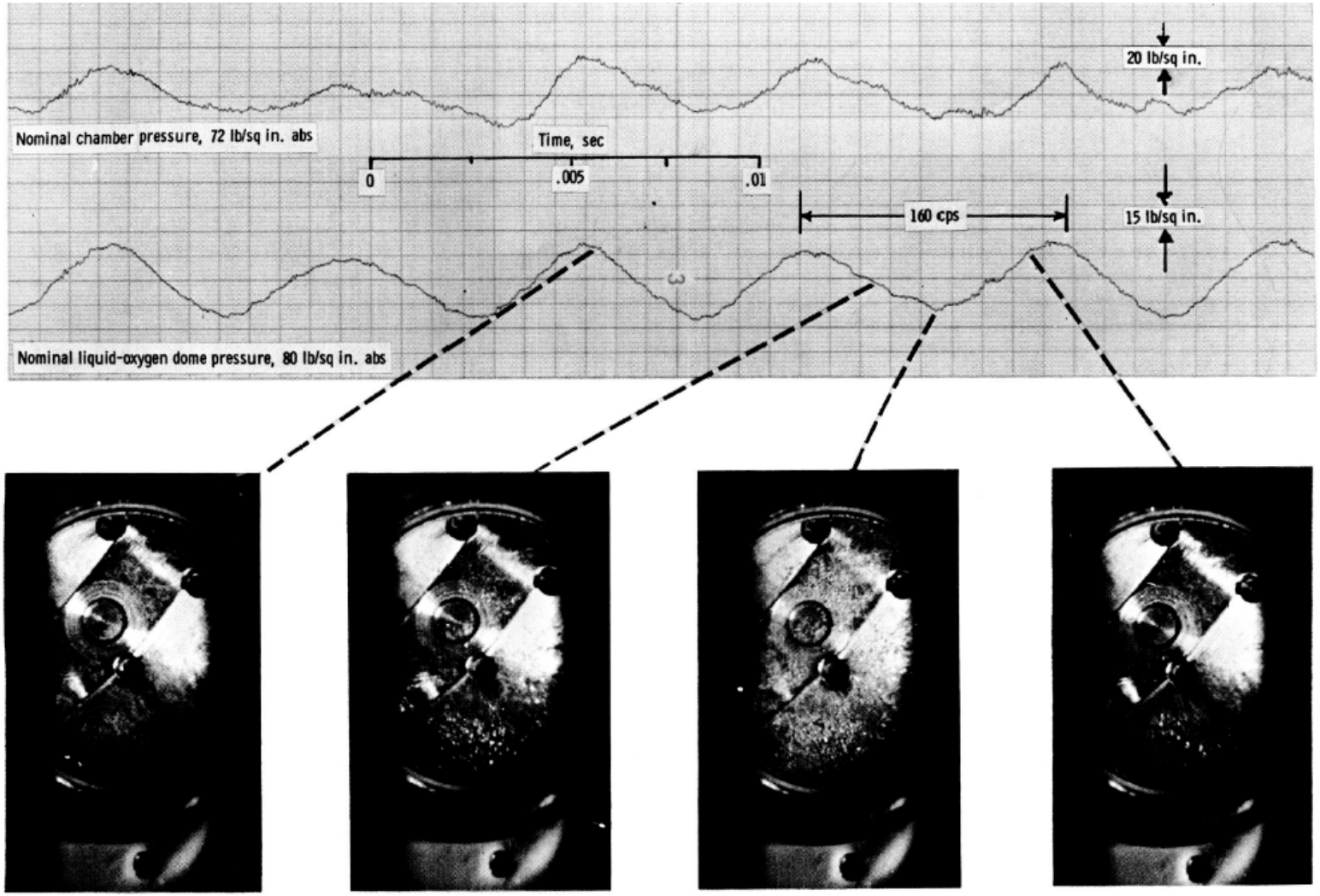
"Nice" Chug (Closeup)



“Nice” Chug (Closeup)

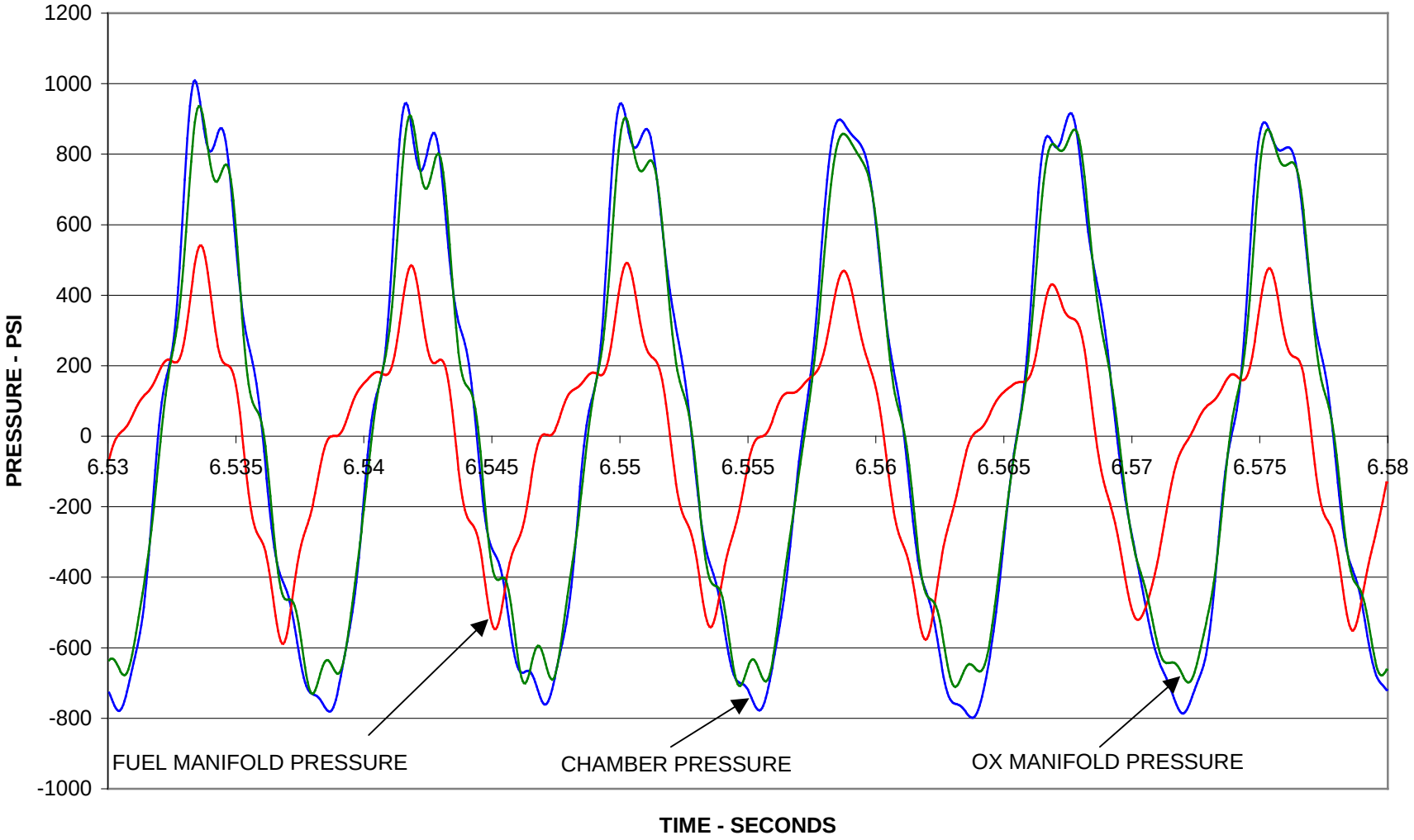


Appearance of Vapor in LOX Manifold During 1964 RL-10 Chugging Tests

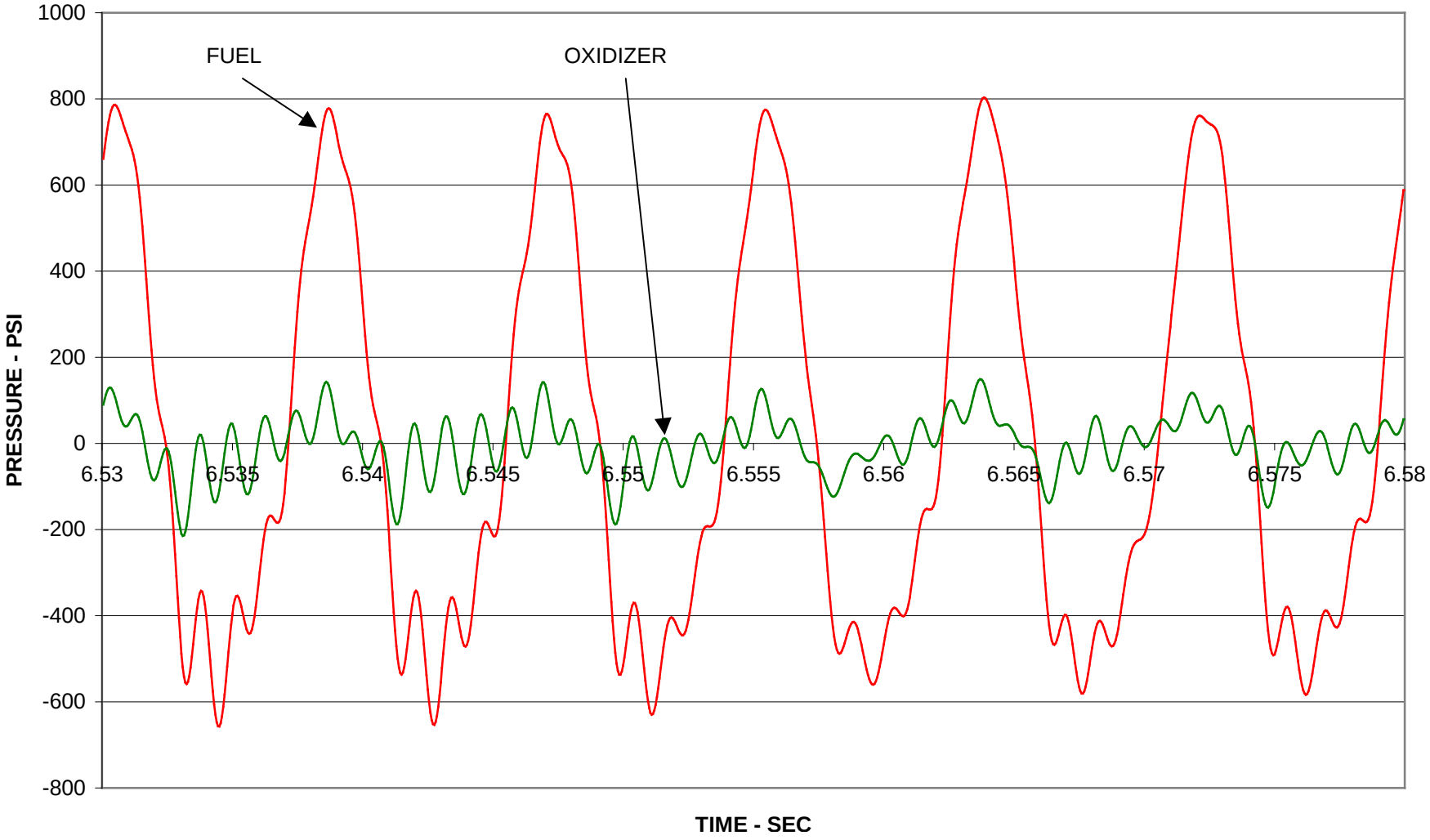


NASA TM X-948, December 1964.

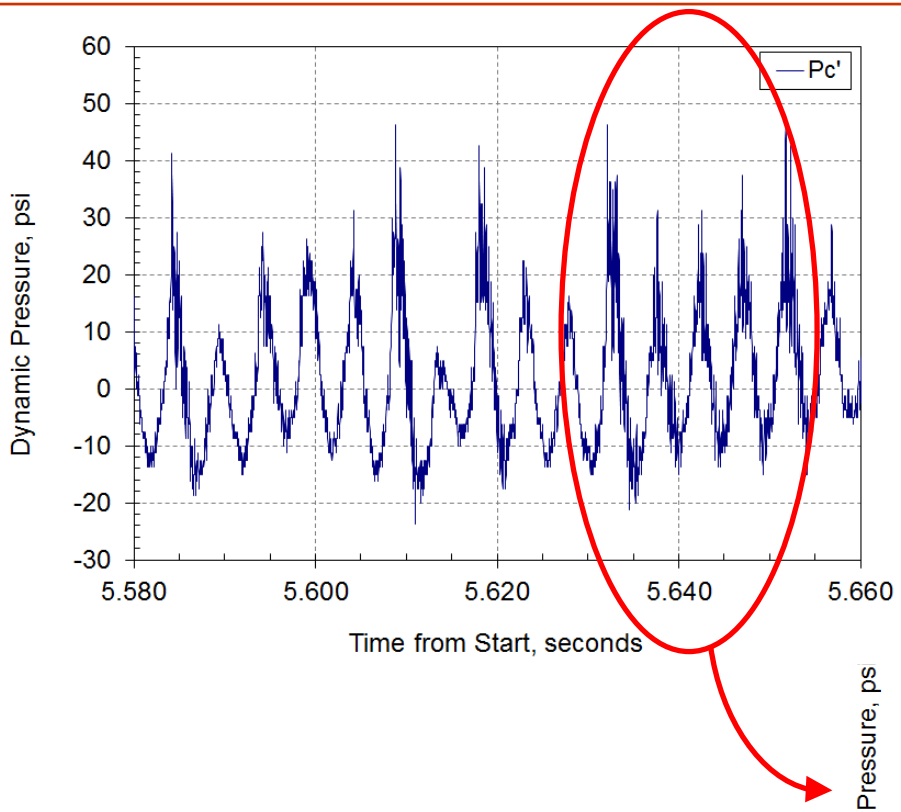
Not So Nice Chug

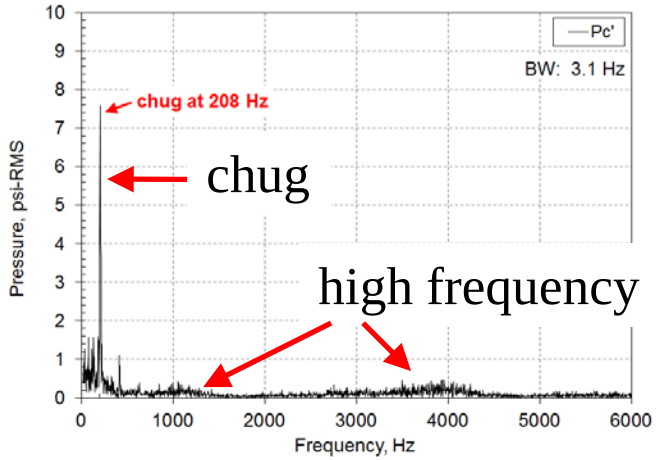


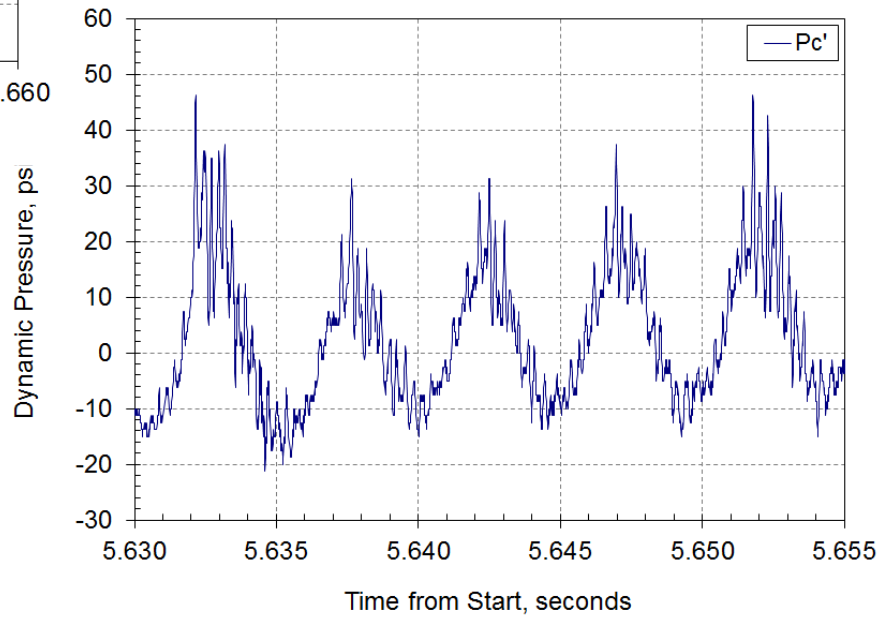
Not So Nice Chug



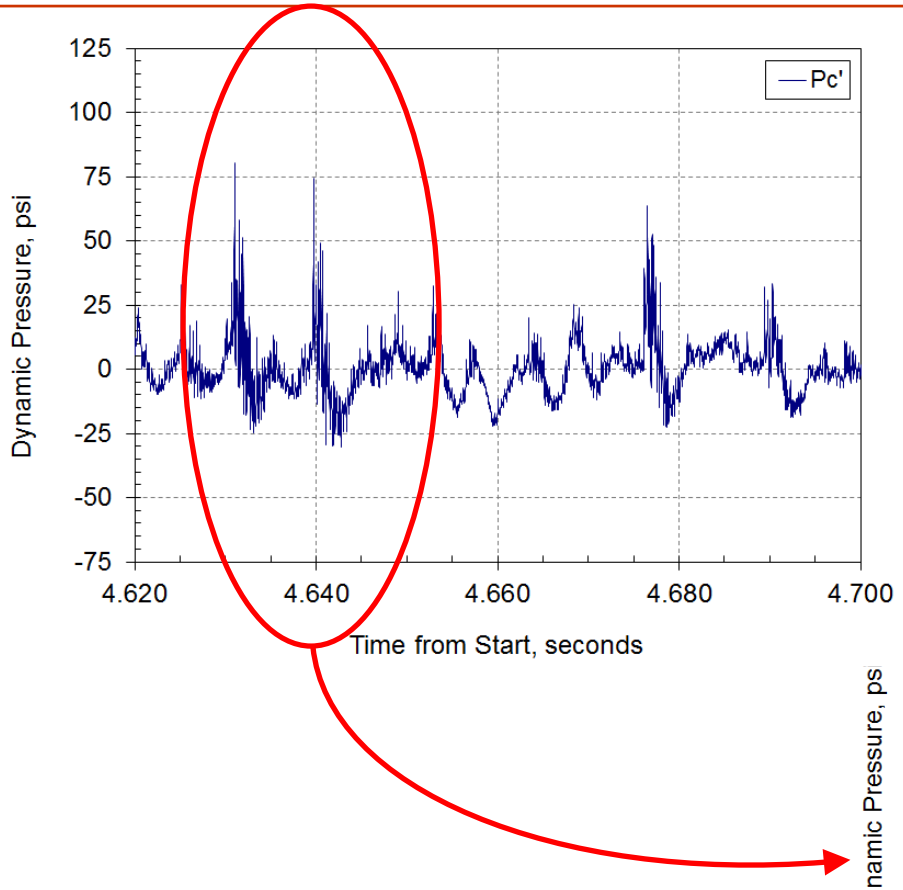
Bad Chug

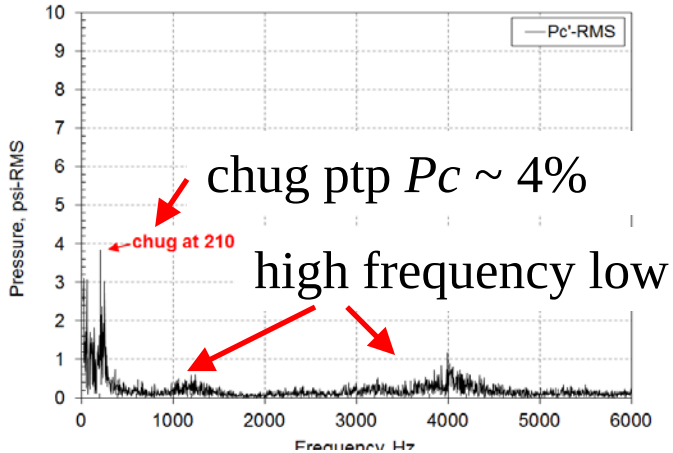

Pc'
Dynamic Pressure, psi
60
50
40
30
20
10
0
-10
-20
-30
5.580
5.600
5.620
5.640
5.660
Time from Start, seconds

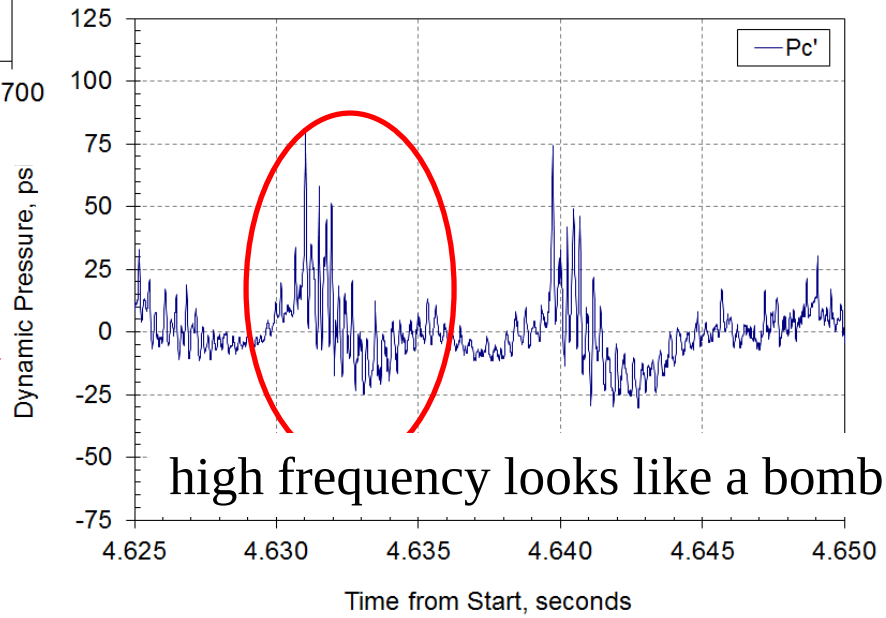

Pc'
BW: 3.1 Hz
chug at 208 Hz
chug
high frequency
Pressure, psi-RMS
10
9
8
7
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000
6000
Frequency, Hz


Pc'
Dynamic Pressure, ps
60
50
40
30
20
10
0
-10
-20
-30
5.630
5.635
5.640
5.645
5.650
5.655
Time from Start, seconds

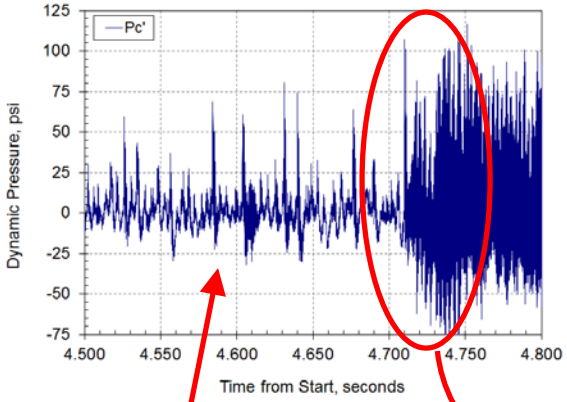
Really Bad Chug



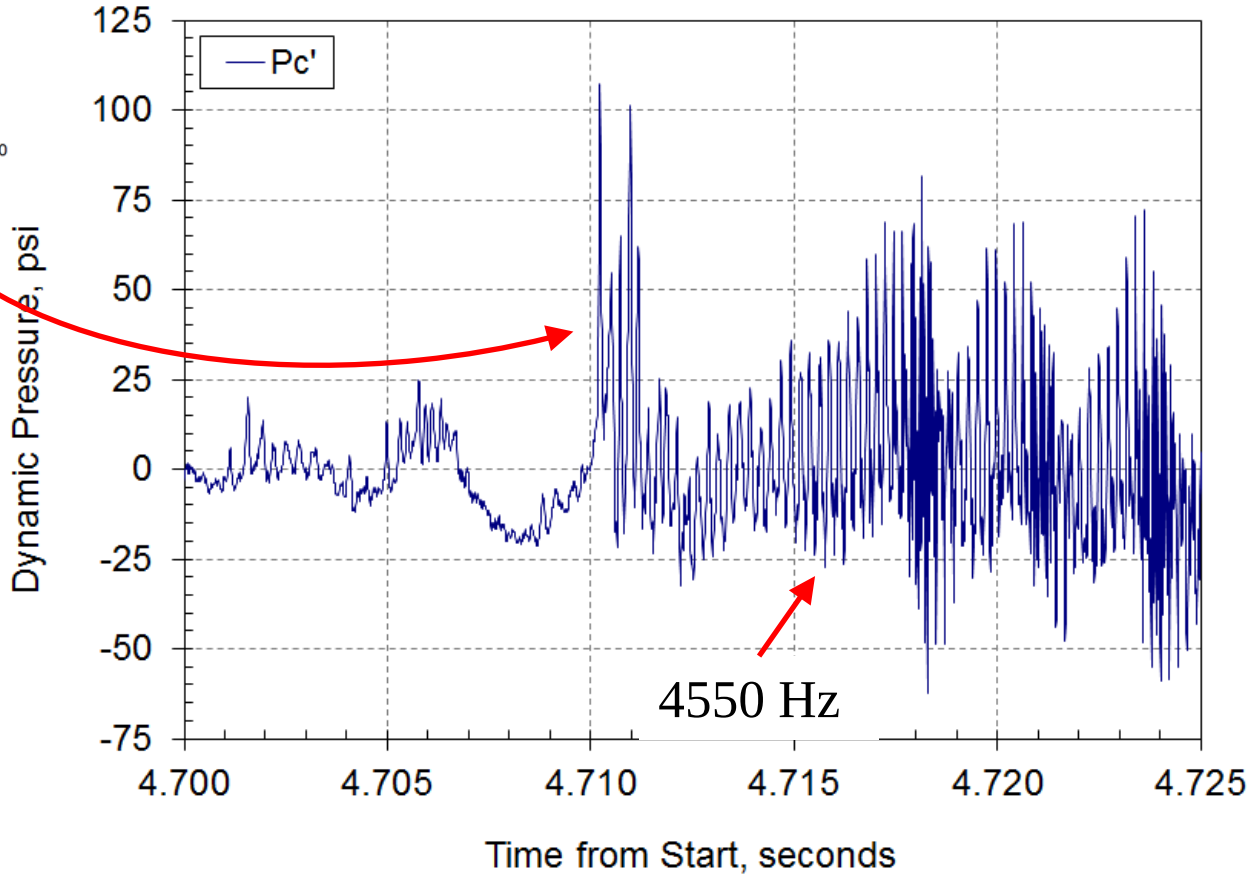




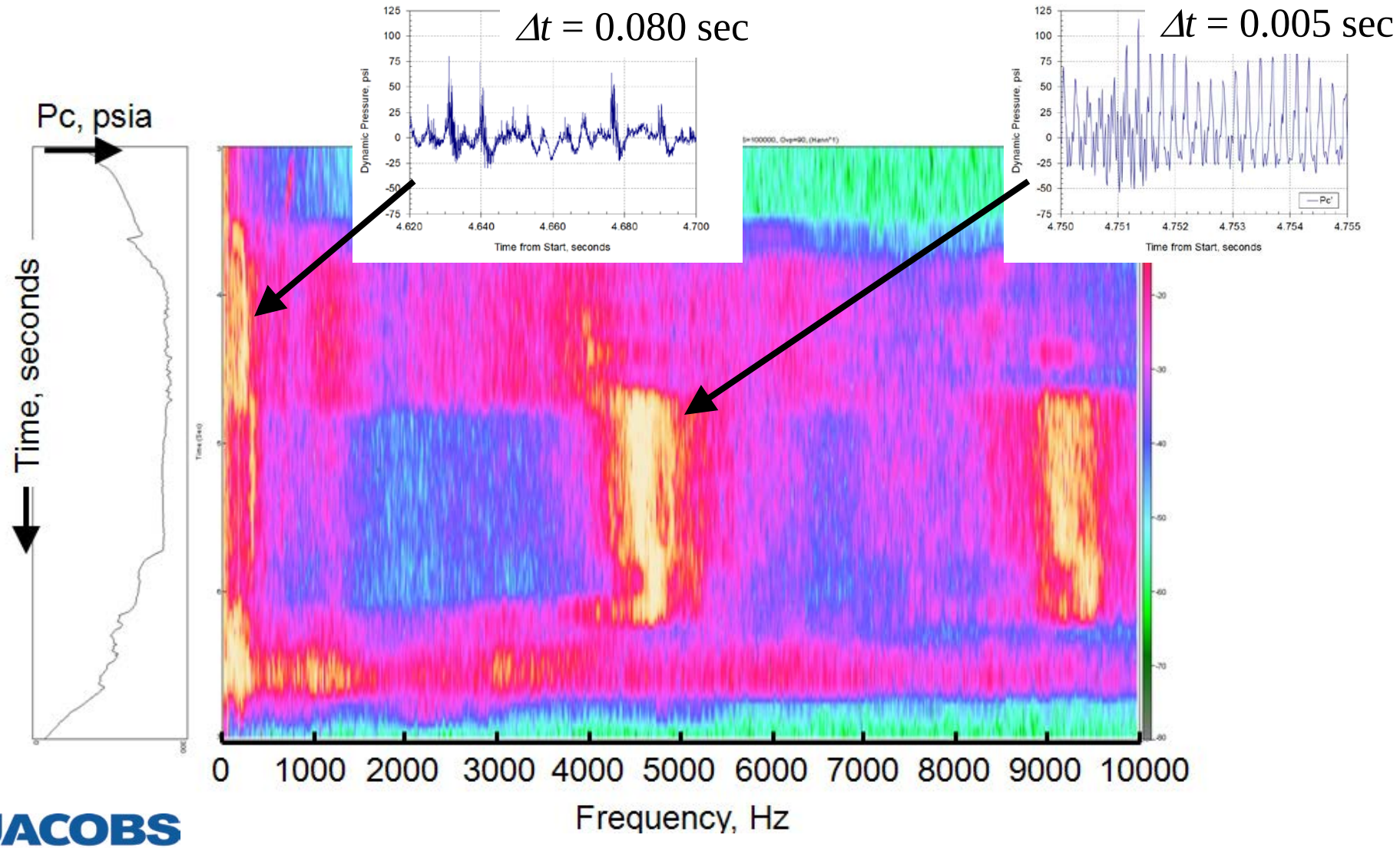
Really Bad Chug



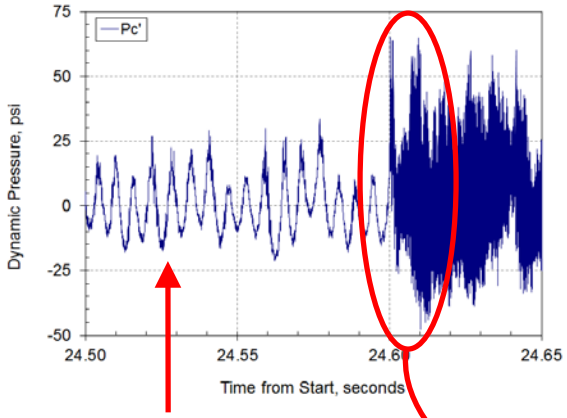
chug at 210 Hz



Really Bad Chug

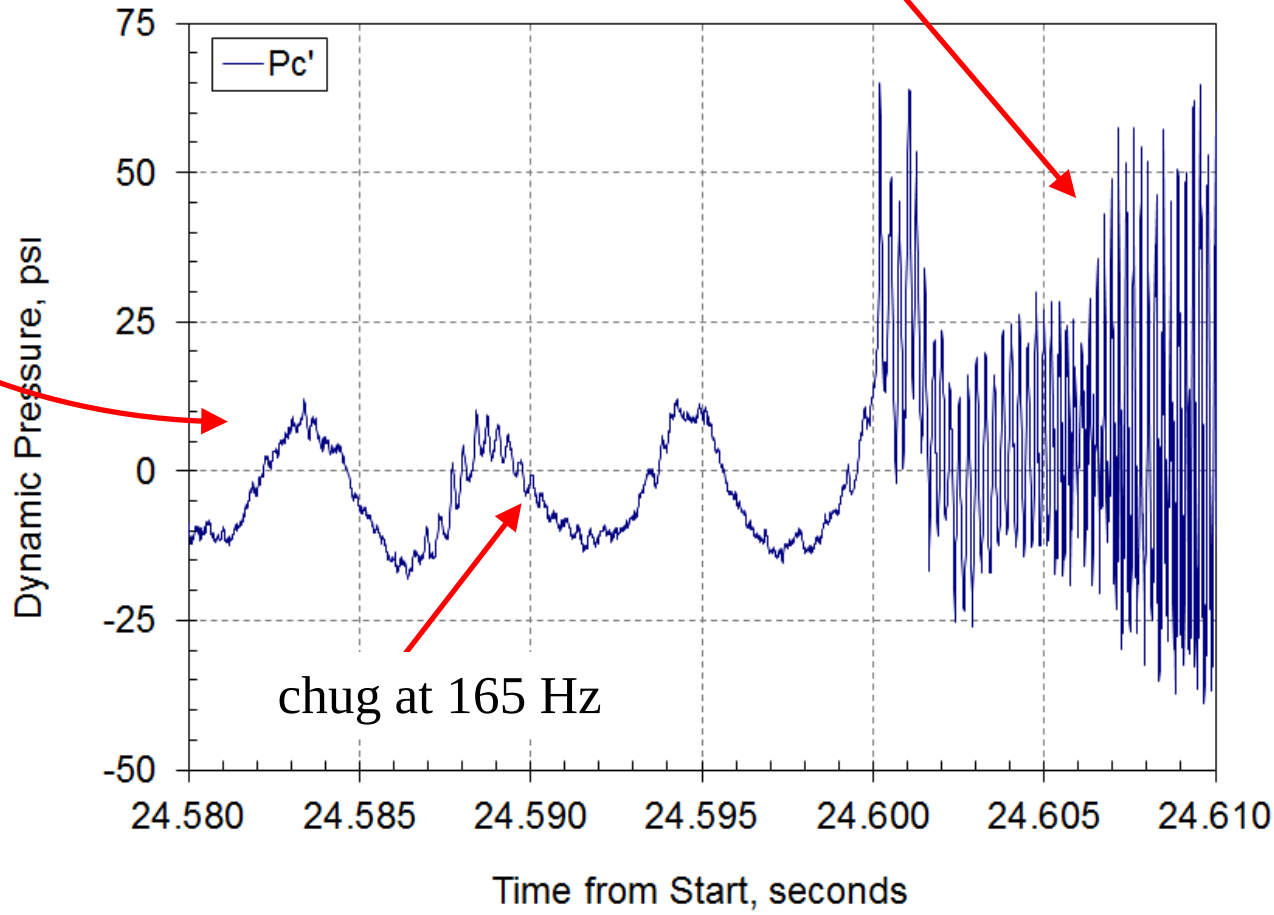


More Really Bad Chug

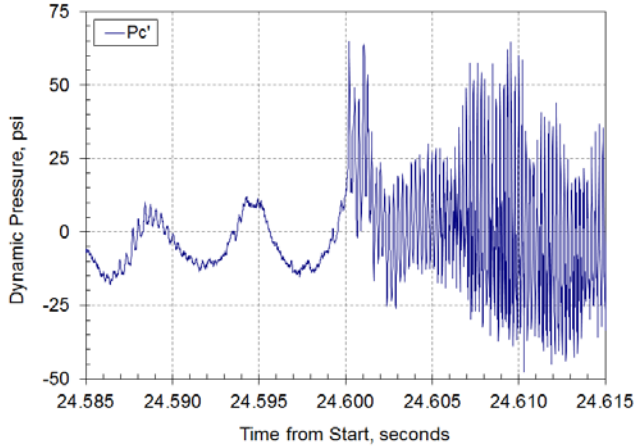


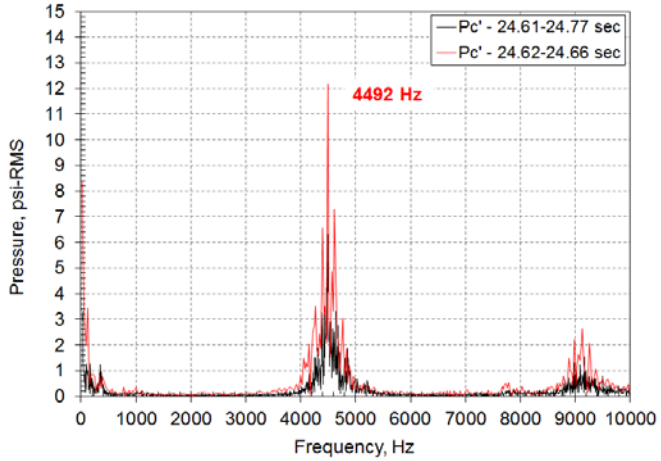
chug at 165 Hz

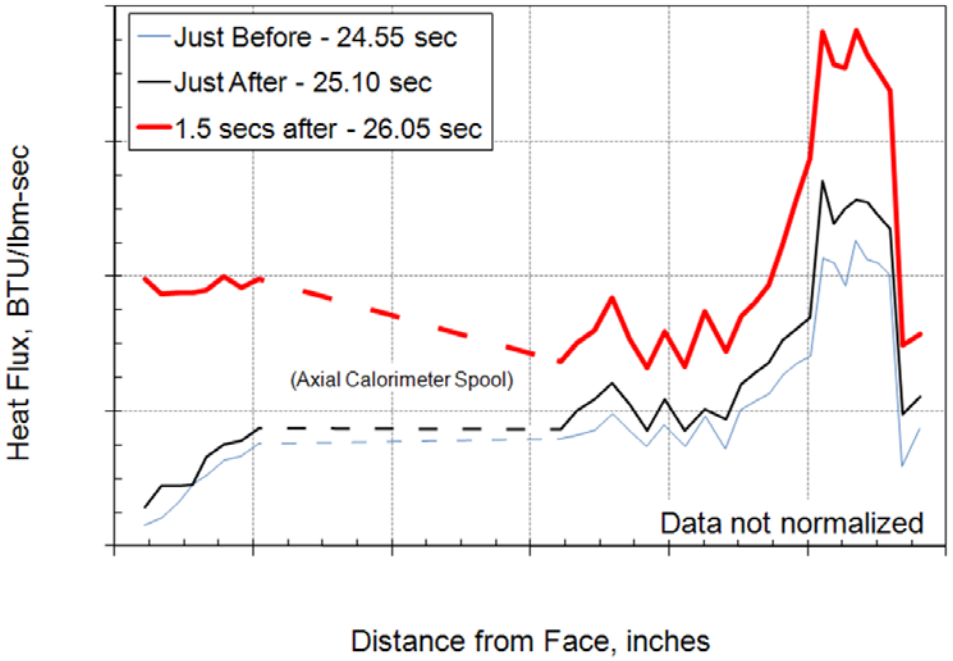
1T at 4490 Hz



More Really Bad Chug







- 4490 Hz is 89% of equilibrium f_{1T}
- Factor of 11 increase in head-end heat flux
- Factor of 1.8 increase in throat heat flux

…very likely the 1T mode

Really Really Bad Chug

Damage to injector element inserts

Buzz

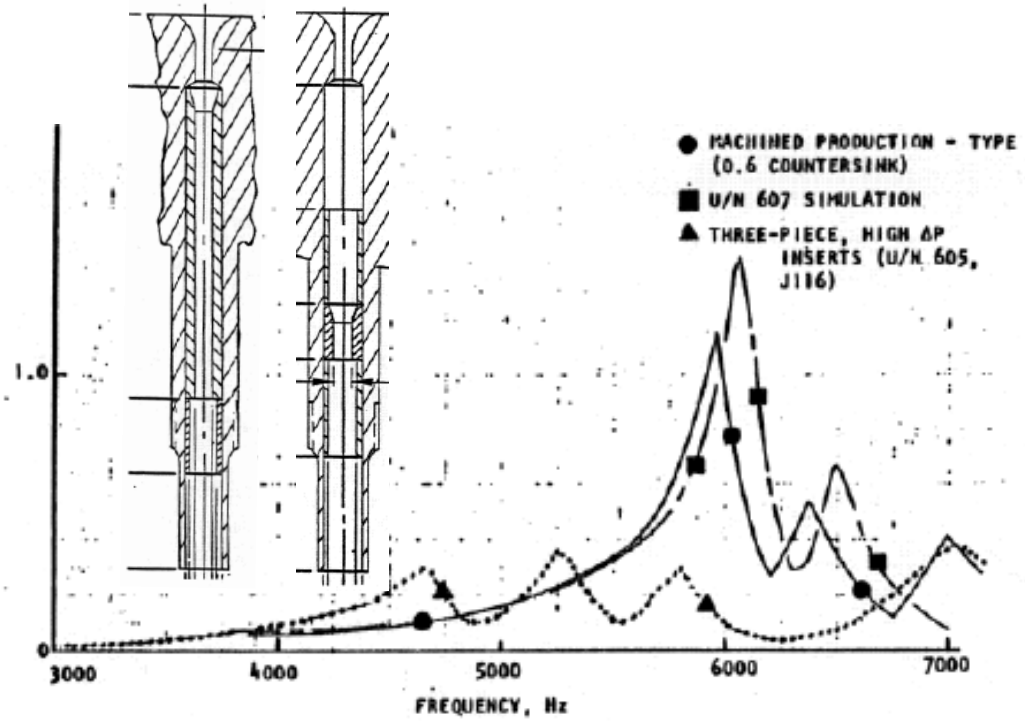
- An “intermediate frequency” combustion instability, displaying
  - wave motion in the combustion chamber although often not corresponding exactly to an acoustic mode
  - growing coherence from combustion noise, with slowly increasing amplitude
  - sometimes wave motion in the injector manifolding or feed systems
- Often misunderstood and misdiagnosed
- Two different types have been observed based on the driving source
  - coaxial element oxidizer post “organ pipe” modes
    - often coupling to transverse acoustic modes
  - injector Helmholtz resonance mode
    - coupling to longitudinal acoustic modes

"Buzz" Associated with "Organ-Pipe" Resonances of the Coaxial Oxidizer Tube

- Instability in J-2S engine development
  - interacting with dynamics of the element "recess" region
  - lightly coupled to 3T chamber acoustic mode
- Instability in late 1980s LO_2/gCH_4 test program
  - coupled to 1T chamber acoustic mode

Complex "Organ Pipe" Buzz During J-2S Development

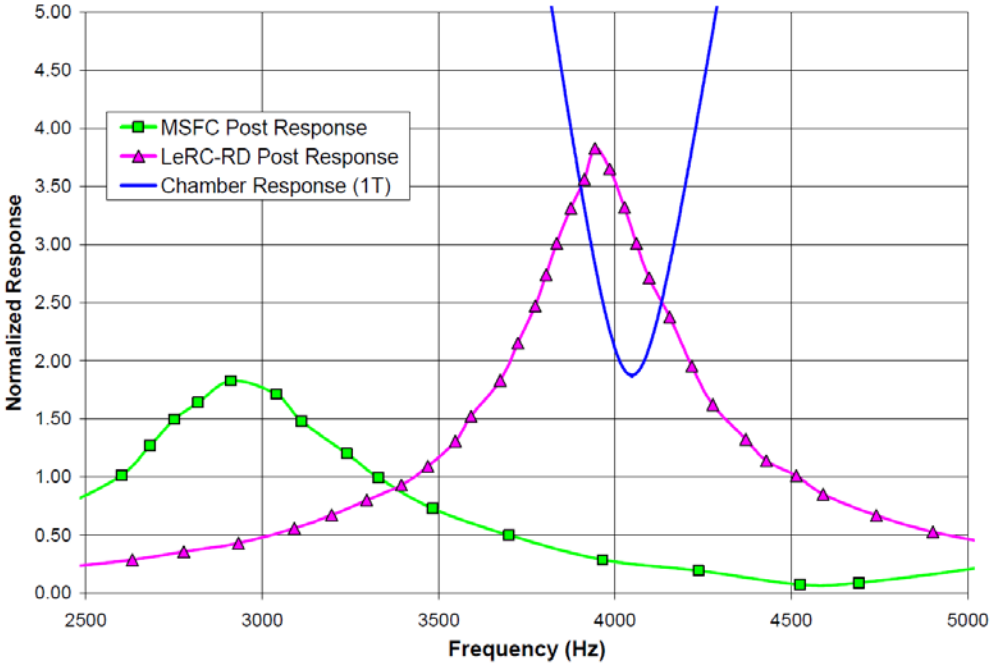
- Somewhat random oscillations, displaying characteristics of both acoustic instability and feed system-coupled instability
- Instability at 3T mode registered combustion chamber pressure oscillations ~150 psi-ptp, vibrations ~70 to 1000 g-RMS
- Modeling showed influence of oxidizer post, element recess, and chamber modes
- Resolved by inserts into posts



- See:
  - Anon., "4400-Hz Vibration Investigation, Final Report," Rocketdyne Report R-8742, Contract NAS8-25156, Canoga Park, CA, June 30, 1971.
  - Hutt, J.J., and Rocker, M., "High-Frequency Injection-Coupled Combustion Instability," Chapter 12, Liquid Rocket Engine Combustion Instability, V. Yang and W. Anderson, editors, Progress in Astronautics and Aeronautics, Volume 169, 1995, pp. 345-355.

"Organ Pipe" Buzz in Late 1980s

- Instability at 1T mode registered combustion chamber pressure oscillations ~300 psi-RMS, injector vibrations ~70 to 200 g-RMS
- LO_2/gCH_4 testing had otherwise been stable
- Modeling showed influence of organ pipe mode between two designs, one stable, one unstable

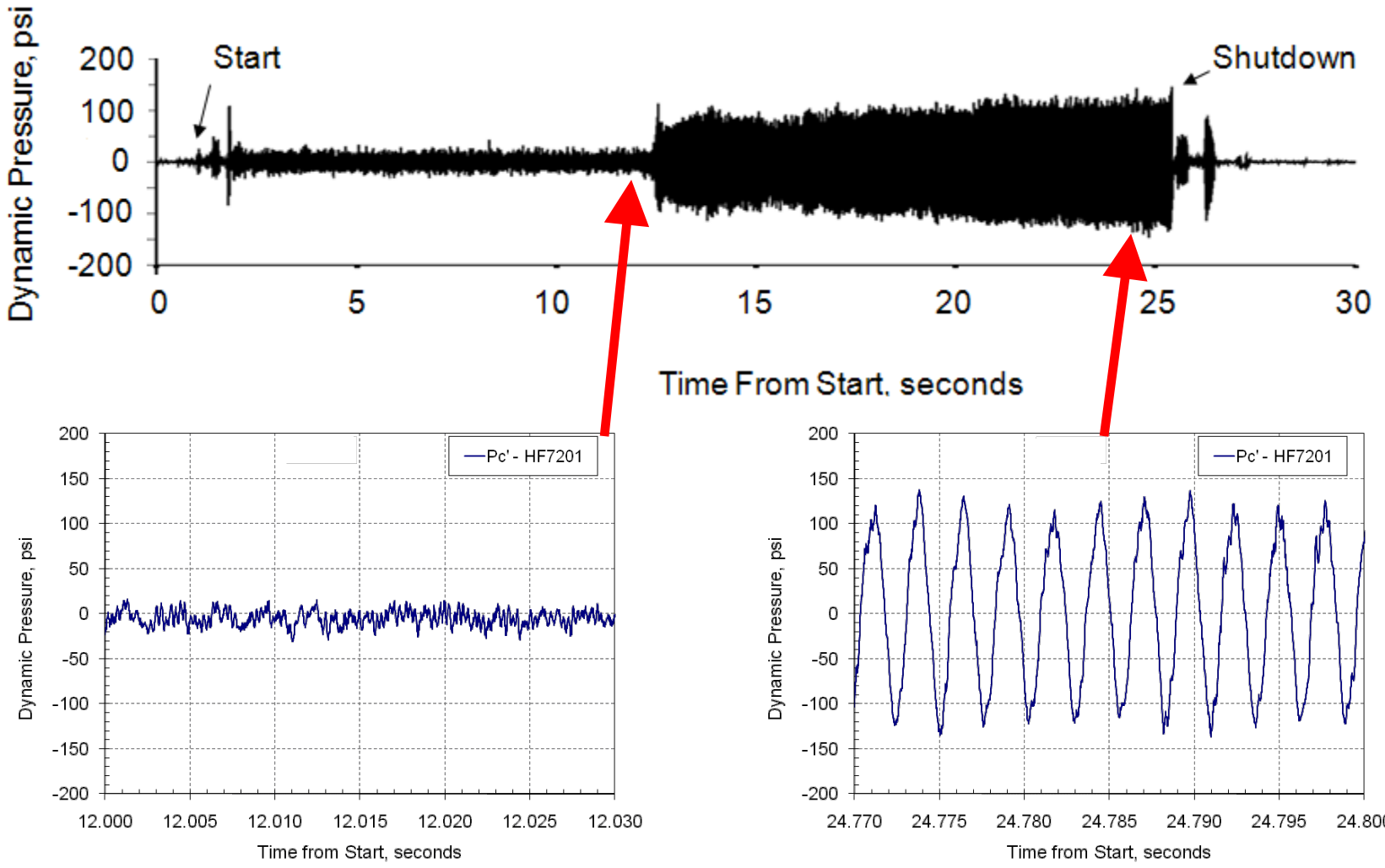


- See:
  - Jensen, R.J., Dodson, H.C., and Claflin, S.E., "LOX/Hydrocarbon Combustion Instability Investigation," NASA CR-182249, Rocketdyne Report RI/RD 89-179, Contract NAS3-24612, July 1989.
  - Aithal, S.M., Liu, Z., Jensen, R.J., Hinerman, T.D., and Lynch, E.D., "Nonlinear Injection Transfer Function Simulations for Liquid Propellants," AIAA Paper No. 2008-4742, July 2008.

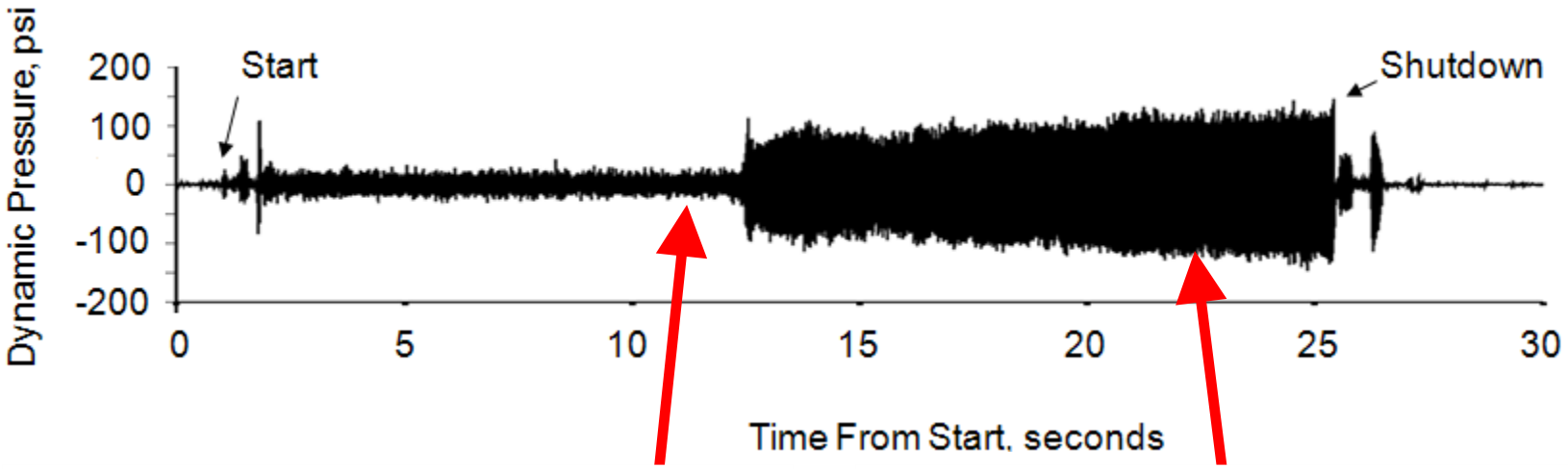
Another Form of "Buzz" Combustion Instability

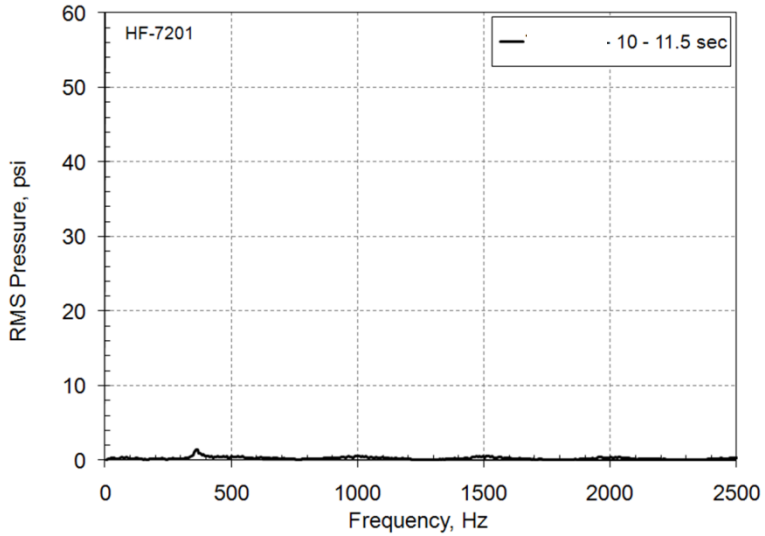
- Another type apparently provided issues for some older engines
  - Apollo Service Propulsion Module SPS engine
  - Shuttle Orbital Maneuvering System OMS
- This type has came back in many recent test programs
  - Gas generating combustion devices situated in long combustion chambers/ducts
  - Lots of arguments about what it was or wasn't
  - … but it definitely was combustion instability
- Injector Helmholtz resonance mode coupled to longitudinal chamber acoustic modes

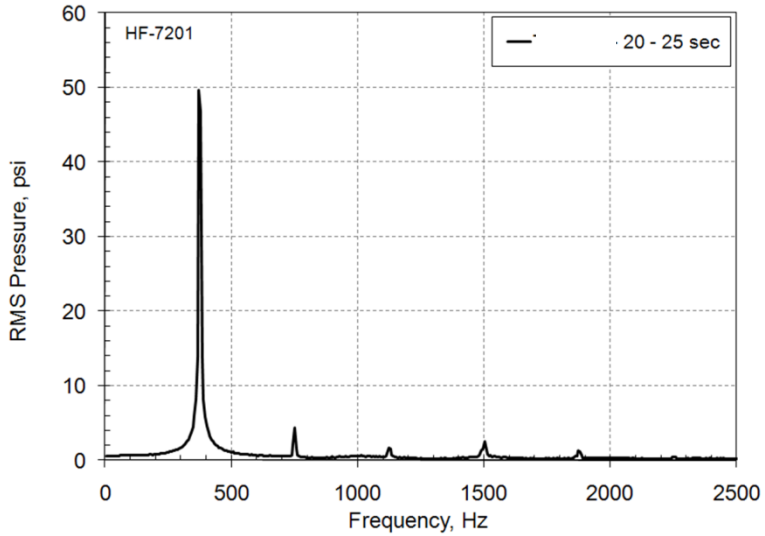
Combustion Instability Near 1L Acoustic Chamber Mode Appeared "Suddenly"



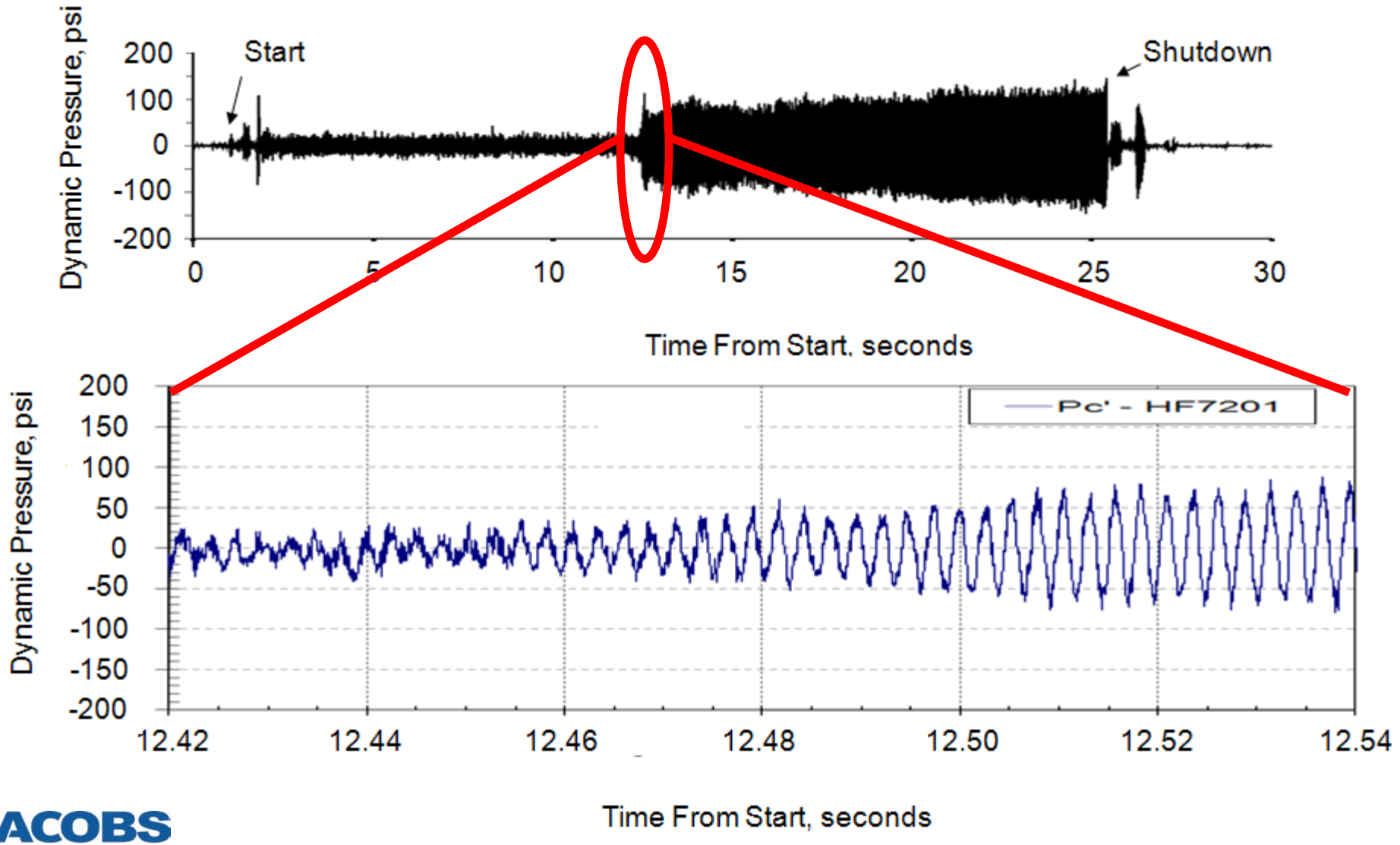
Very Discrete





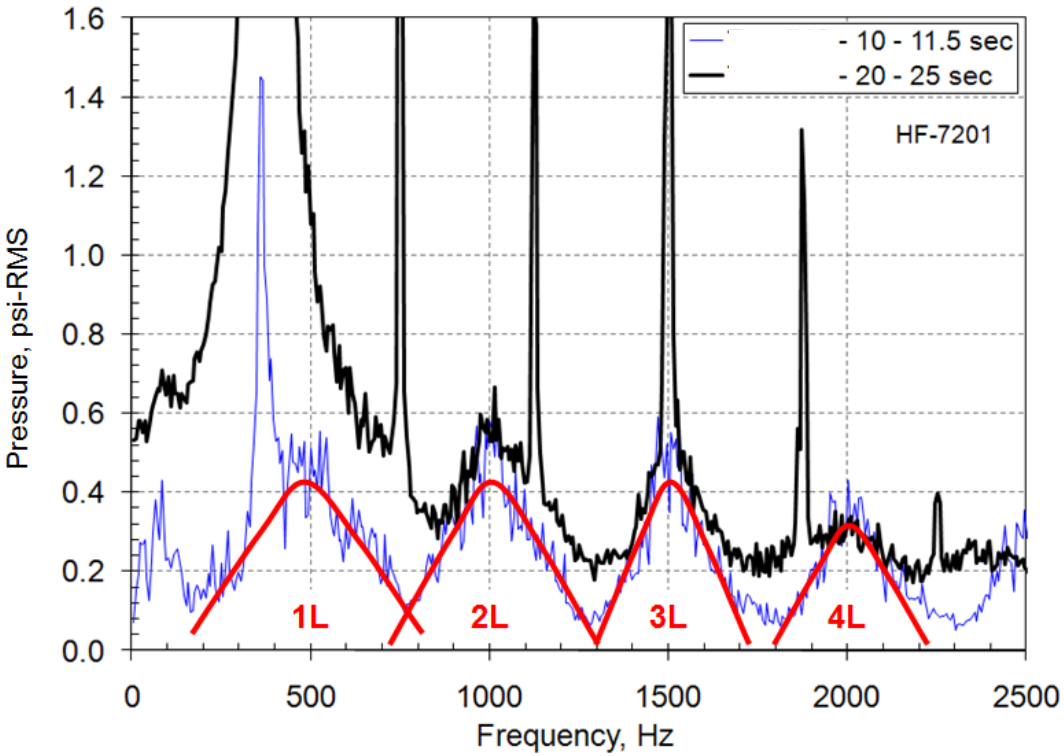


Slow Growth During Transition to Instability

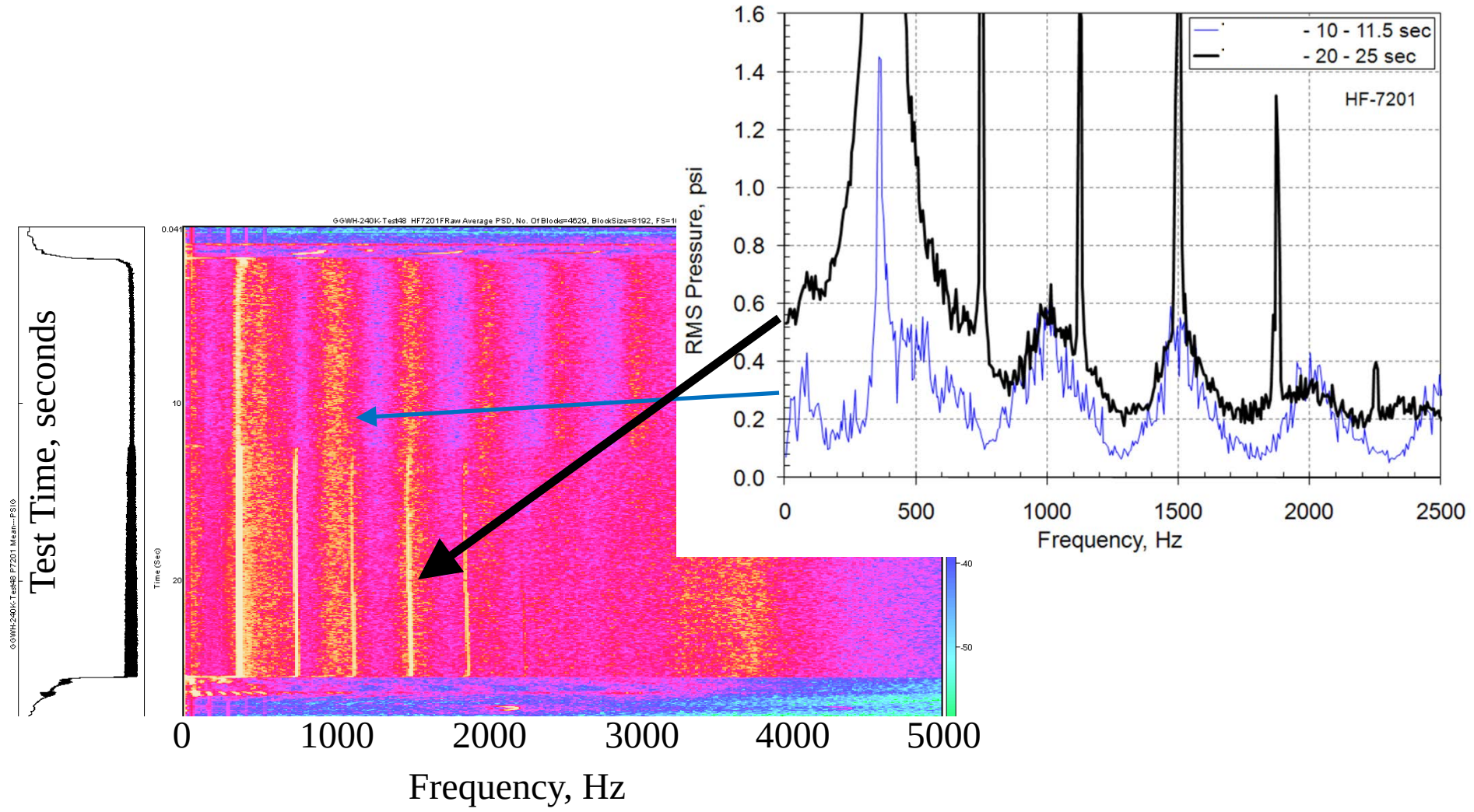


Instability of the 1L Mode but Not Exactly *at* the 1L Mode

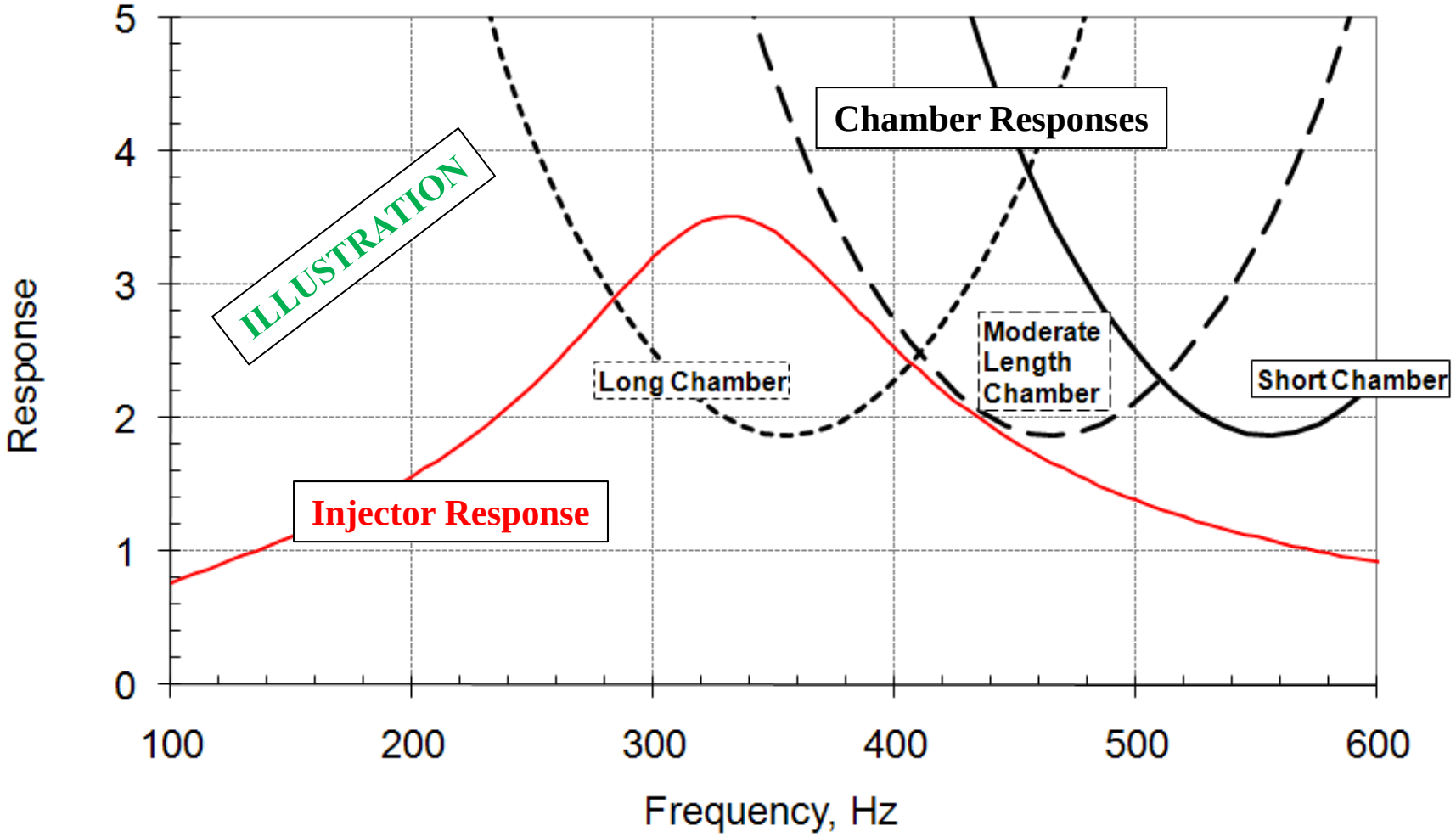
- Unstable at 378 Hz
- 1L mode frequency
  - early in test observe f_{1L} ~ 500 Hz
  - observe higher order modes are same later in test
  - All chamber modeling suggests f_{1L} ~ 500 Hz



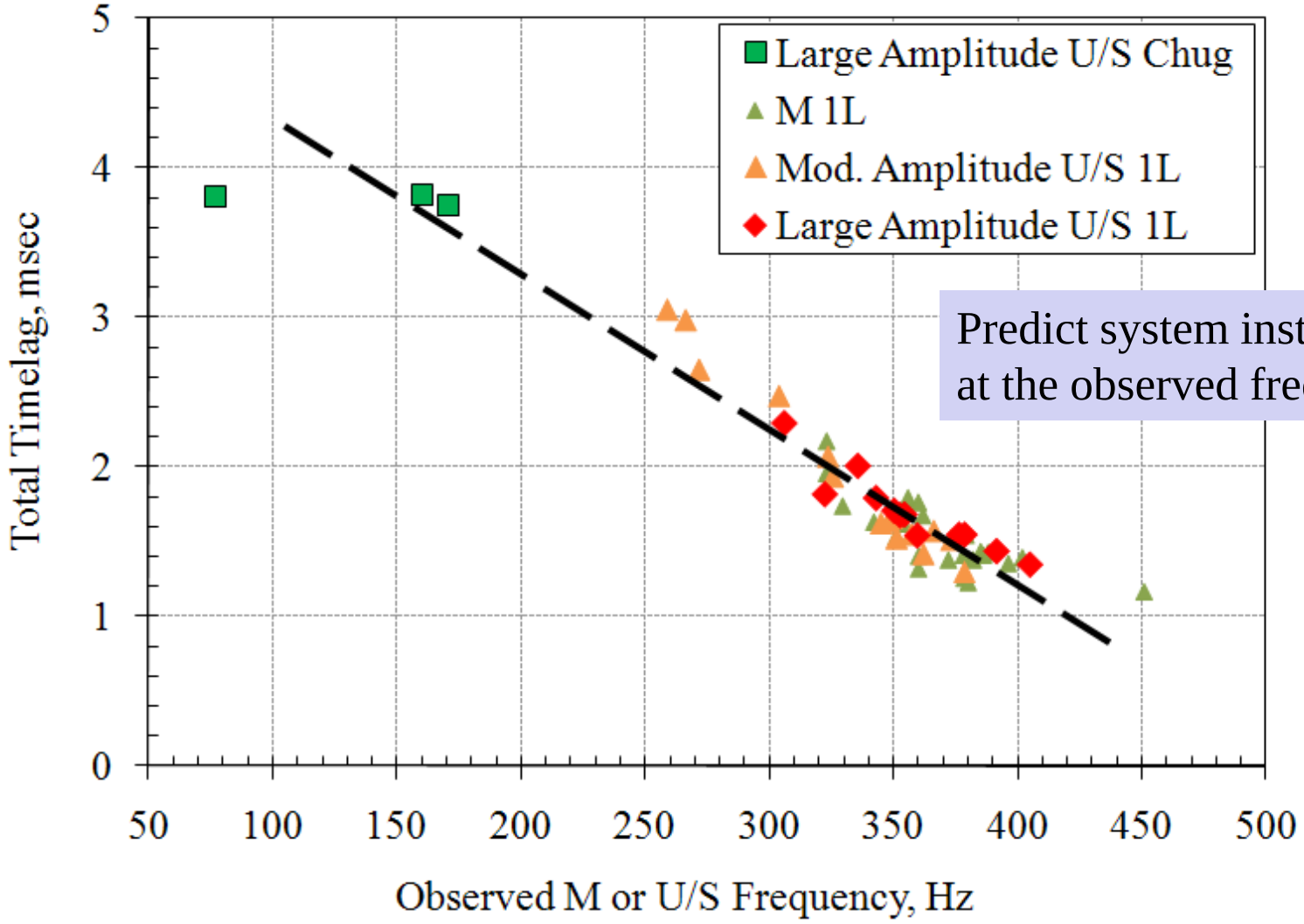
Frequency of Instability was Present Early in Test Prior to "Instability"



General Transfer Function Analytical Formulation



Total Timelag Problem



Predict system instability at the observed frequency

Summary

- Chug happens…
  - On almost every program… on almost every start or shutdown transient.
  - Vibration levels can be bad. Things get broken.
  - Modeling is getting pretty good. Use it !
- Buzz is happening … again …
  - Coupling to transverse acoustic modes associated with coaxial element oxidizer post organ pipe modes
  - Coupling to longitudinal acoustic modes associated with injector Helmholtz mode
  - Vibration levels can be bad. Things get broken.
  - Modeling capability isn't bad… but still needs work…
  - Some people still need convincing

Motivating Comments from Years of Doing This

- Compile your design and test data for every program you work on
  - Keep at it throughout your career
  - Data are your blood – don't let your data get away from you
- Use your compiled data for continued analytical and empirical investigations
  - Don't let unanswered questions stay unanswered
  - Determine not only what happened, but why
- *The few that are unstable are more useful than the many that are stable*
  - Thanks Ross!

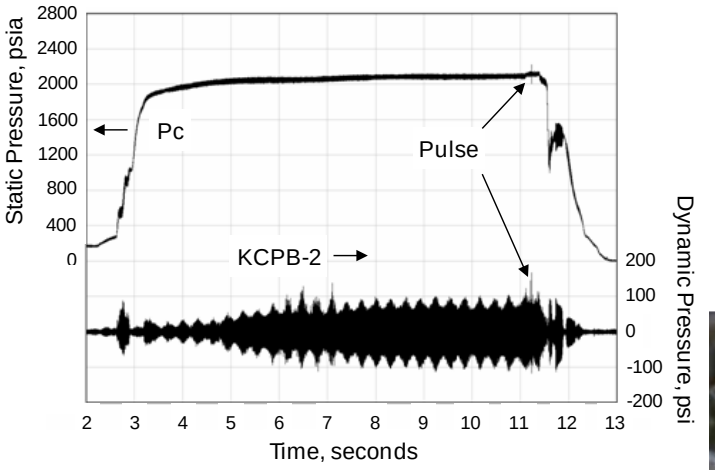
Final

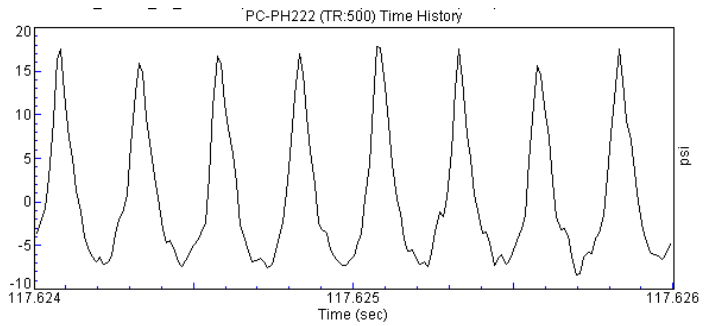
- Keep aware…. don't let this happen to you

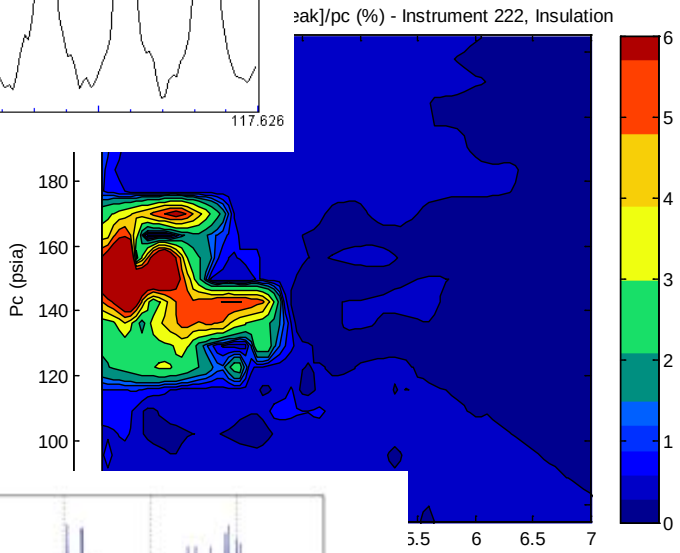
Backup

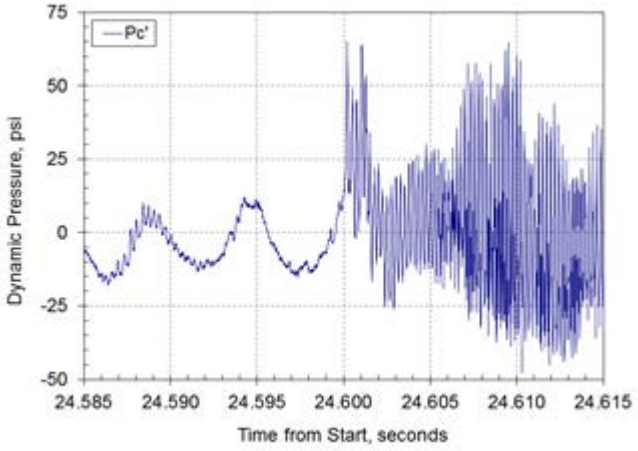
Marshall Space Flight Center

The Problem: Dynamics Happens (and we don't always know why)









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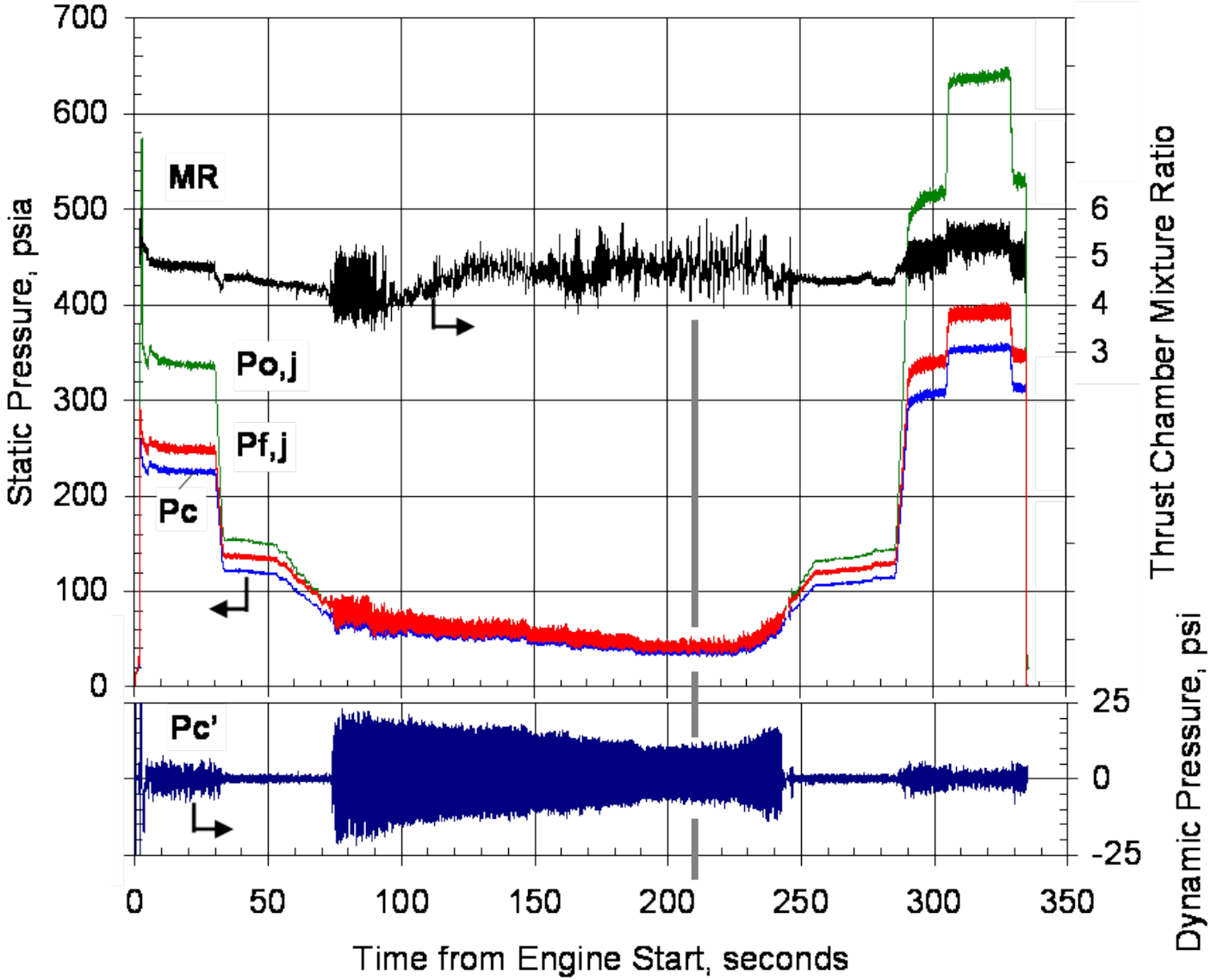
Reasons for Occurrence of Combustion Instability

- Large combustion chamber diameters
- Long chamber lengths
- Insufficient injector pressure drops
- Fluid dynamic conditions inside combustion chamber susceptible to oscillations
  - Atomization, vaporization, mixing, reaction
- Injector geometrical features create potential for oscillations
- Propellant combination is capable of producing “pops”
- Start transient produces different transient temperatures, pressures, and flow rates that could create a “pop

Reasons for Occurrence of Combustion Instability, continued

- Development program did not include sufficient testing to understand margins
  - i.e., you did not do enough to find out what your margins are
- Operating with insufficient margin after development
  - i.e., you know where the margins are and you operate too close to them
- Propellant combination is capable of producing “pops”
- Start transient produces different transient temperatures, pressures, and flow rates than examined during development program
- Change in manufacturing processes (even if dimensional characteristics are not changed)

MR Excursions with Chug



More Bad Chug