Miniature Thermoacoustic Engines in the High Audio and Low Ultrasonic Ranges

Myra Flitcroft and
O.G. Symko
University of Utah

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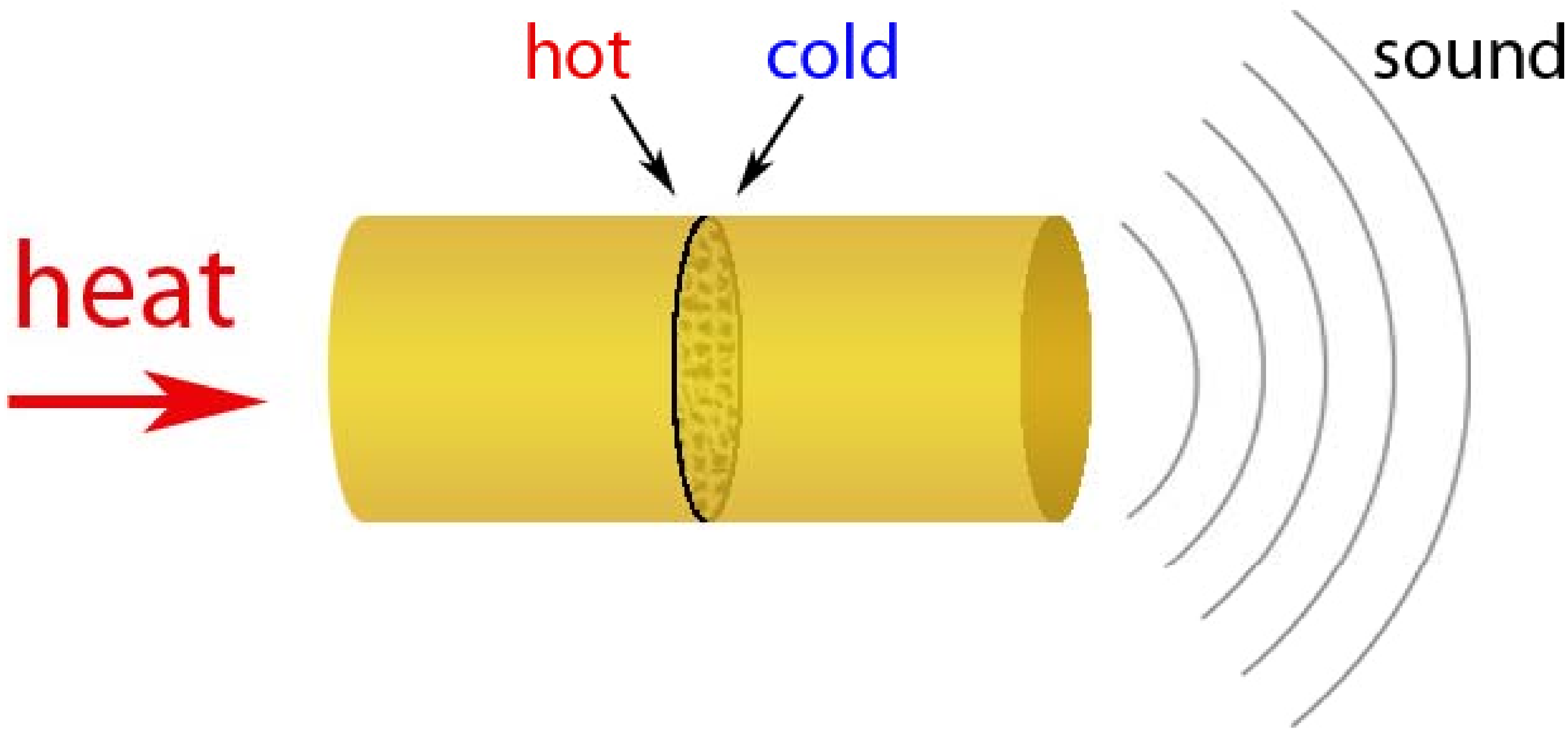
Outline

- Introduction / motivation
- Theory – thermoacoustics
- Experimental details
- Single engine performance
- Theory - synchronization
- Synchronization observations
- Conclusions

Introduction

Thermoacoustic engines convert input heat to sound



Threshold behavior

- As the temperature gradient builds up, parcels of air diffuse along stack from the hot to cold side
- When parcels reach the cold side, they compress quickly, generating many frequencies
- One frequency is reinforced through positive feedback by the resonator
- As the gradient increases, there will be enough ‘pops’ to sustain oscillation – a standing wave is set up

Thermocoustic effects

Glass blowing

Taconis oscillations

Thermoacoustic engines – either prime movers or refrigerators

Luminosity oscillations in variable stars

Thermoacoustic applications

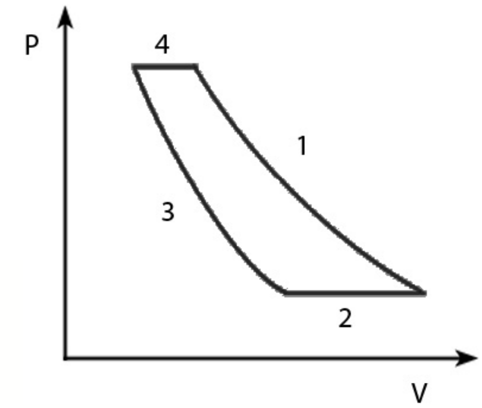
Green energy:

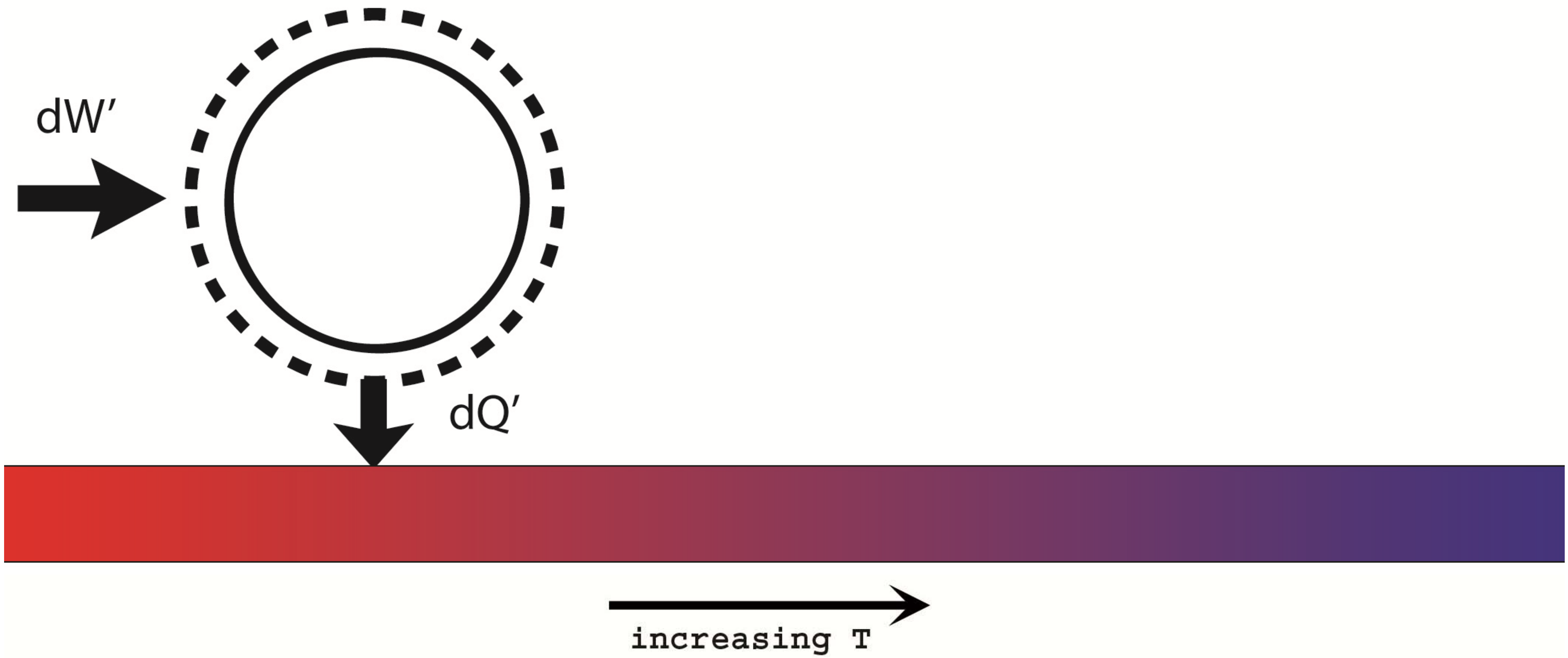
Clean refrigeration

Energy harvesting

http://www.acoustics.org/press/147th/thermoacoustics.htm

Thermoacoustic Cycle





Motivation

- Thermoacoustic engines have conventionally operated at frequencies of 100 – 500 Hz.
- However, theory predicts that higher frequency engines have a higher power density. They can be assembled into multiple engine arrays for higher power output.
- Arrays of miniature engines can be used for energy conversion at small scales.

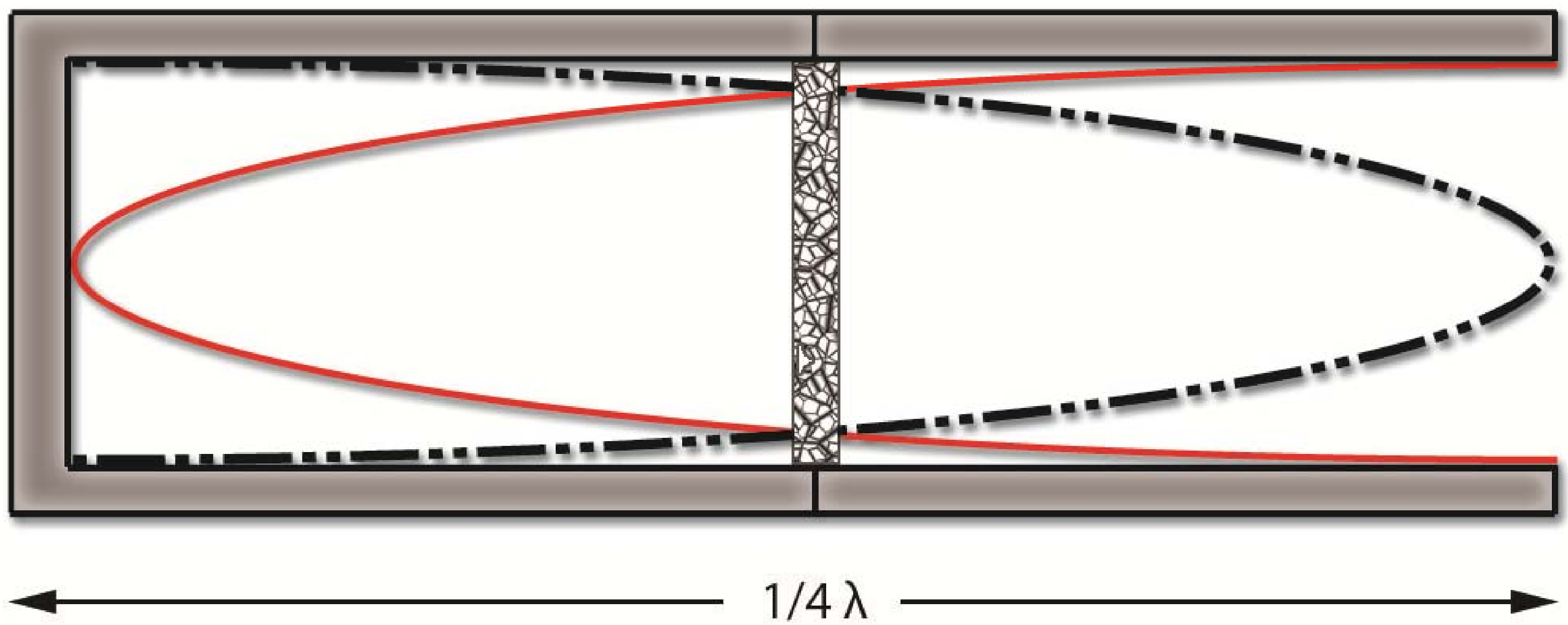
Motivation

- Advantages of higher frequency engines
  - Smaller engines → smaller volumes → higher power density
  - Lower masses → short response time
  - Piezoelectric power density increases with frequency
  - Many units can be combined to form an array → MEMS

Goals

- Reduce thermoacoustic engines length scales from mid-audio to ultrasonic range, by first building 10 kHz range devices and then further reducing to 20 kHz range engines
- Observe in-phase synchronization between a pair of ultrasonic engines

Quarter wave resonator

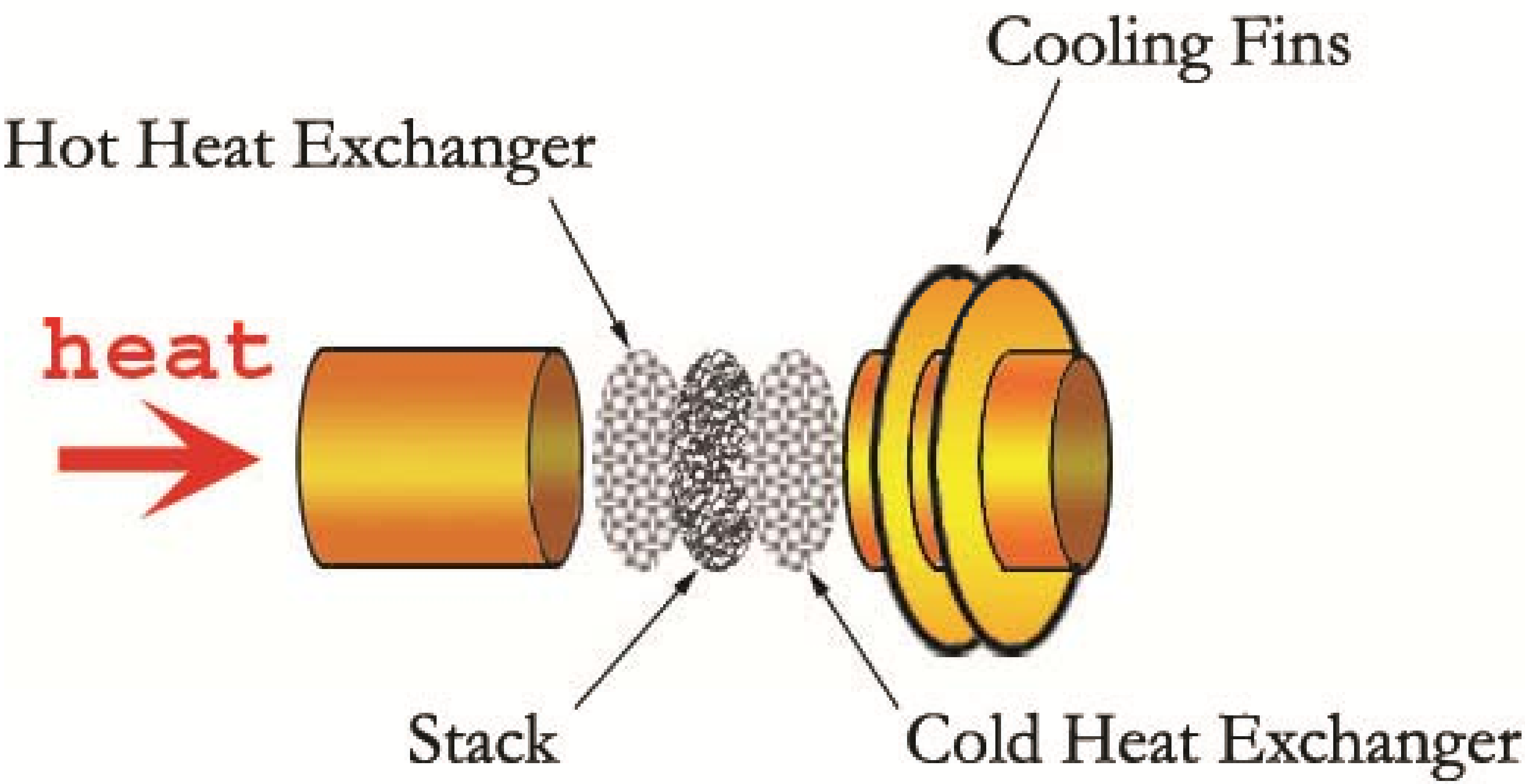


$$p_1 = P_A \sin\left(\frac{x}{\lambda}\right)\cos(\omega t)$$

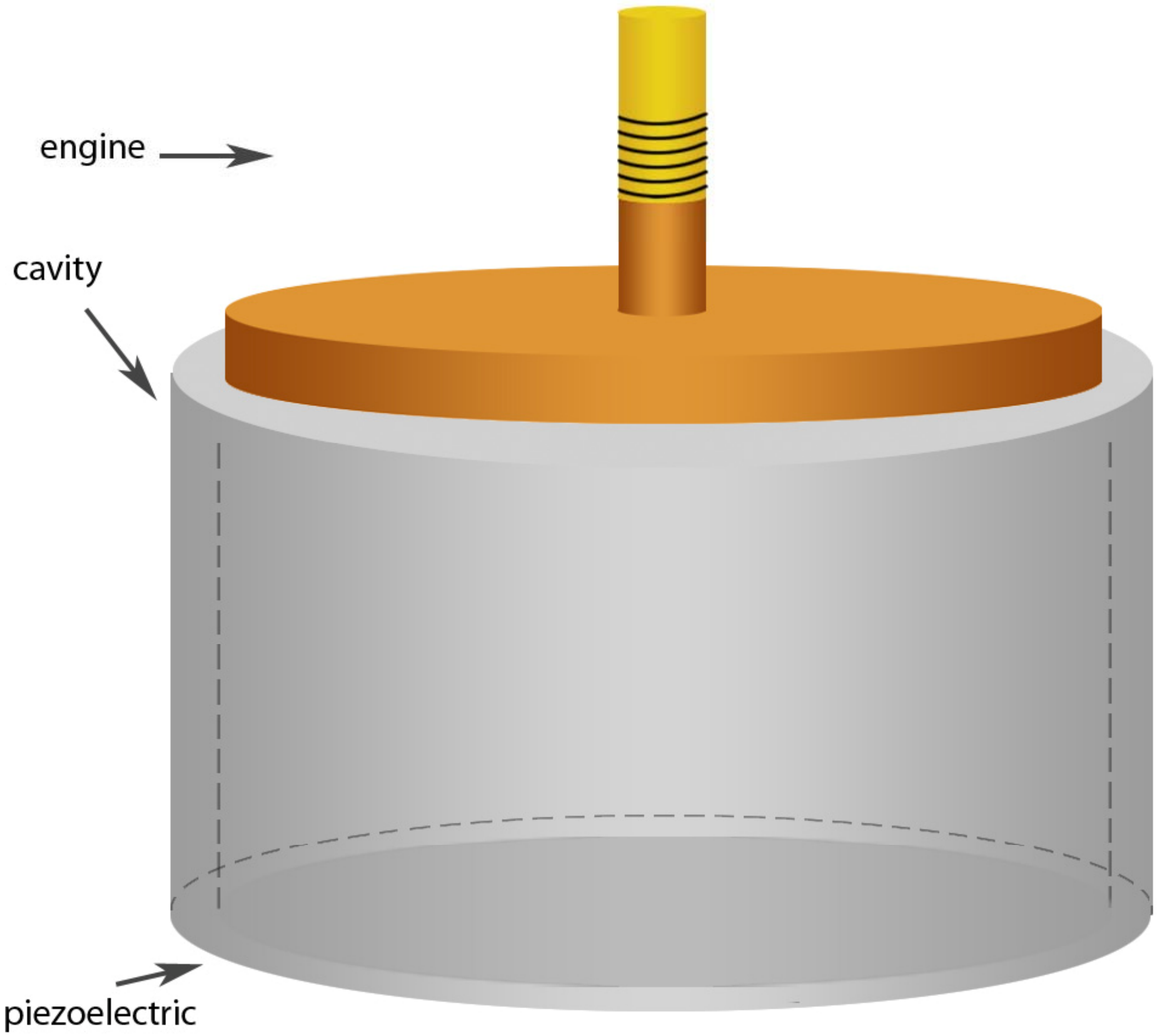
$$u_1 = \frac{P_A}{\rho_m a}\cos\left(\frac{x}{\lambda}\right)\sin(\omega t)$$

$$I \sim p_1(x,t)u_1(x,t)$$

Engine Components



Cavity



- provides positive feedback
- piezoelectric transducer can be attached
- thermal anchor
- allows for pressurization or the use of different gases

Linear Thermoacoustics

- Thermal penetration depth $\delta_\kappa = \sqrt{\dfrac{2\kappa}{\omega}}$

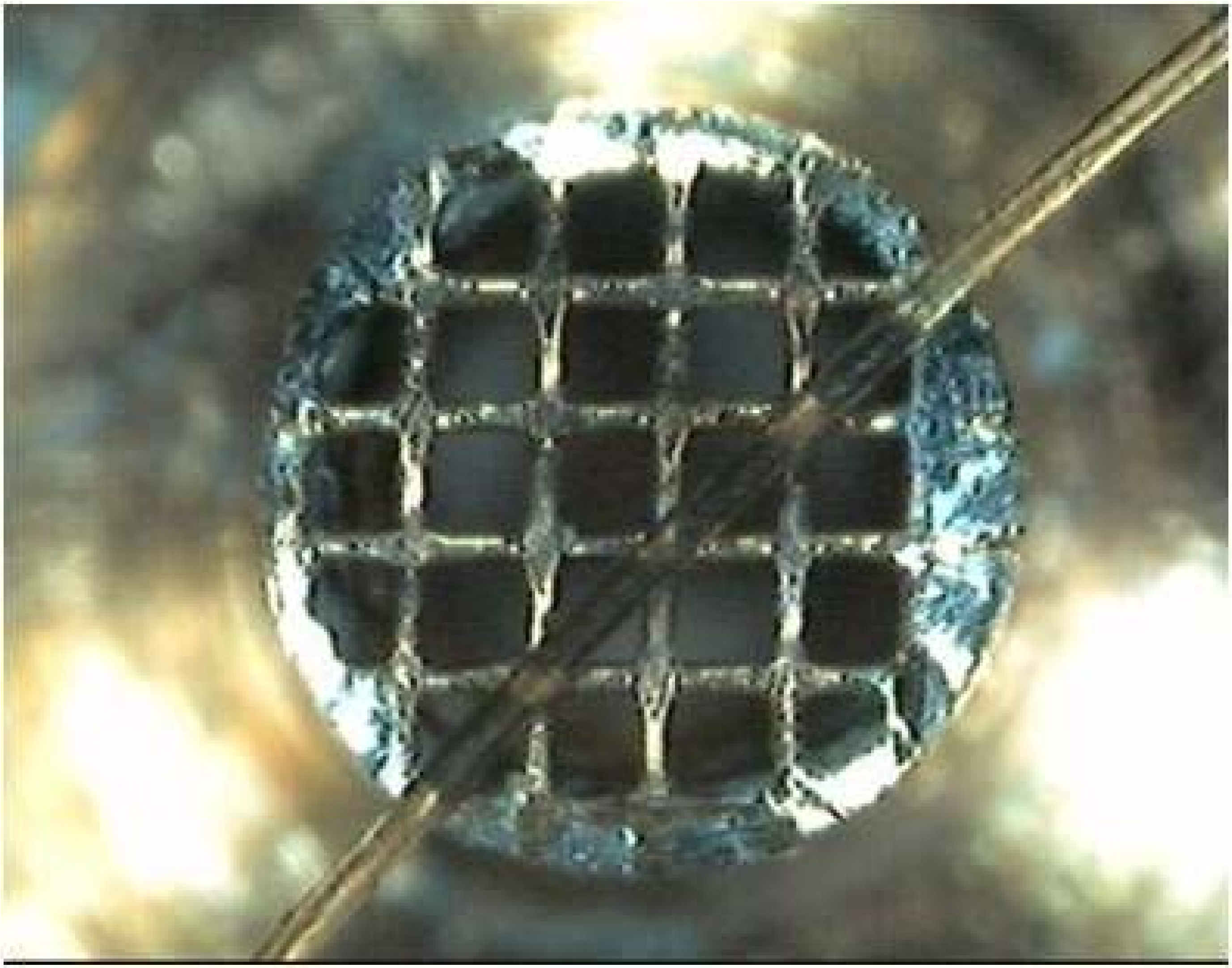
- Critical temperature gradient

$$\nabla T_{critical} = \frac{(\gamma - 1)}{T_m \beta} \frac{T_m}{\lambda} \tan\left(\frac{x}{\lambda}\right) \qquad \Gamma = \frac{\nabla T}{\nabla T_{crit.}}$$

- Acoustic power density

$$\frac{Acoustic\ Power}{Volume} = \frac{1}{2} \frac{\Pi \delta_\kappa \Delta x\, T_m \beta^2 \omega^2}{\pi^2 r^2 a \rho_m c_p} p_1{}^2 (\Gamma - 1)$$

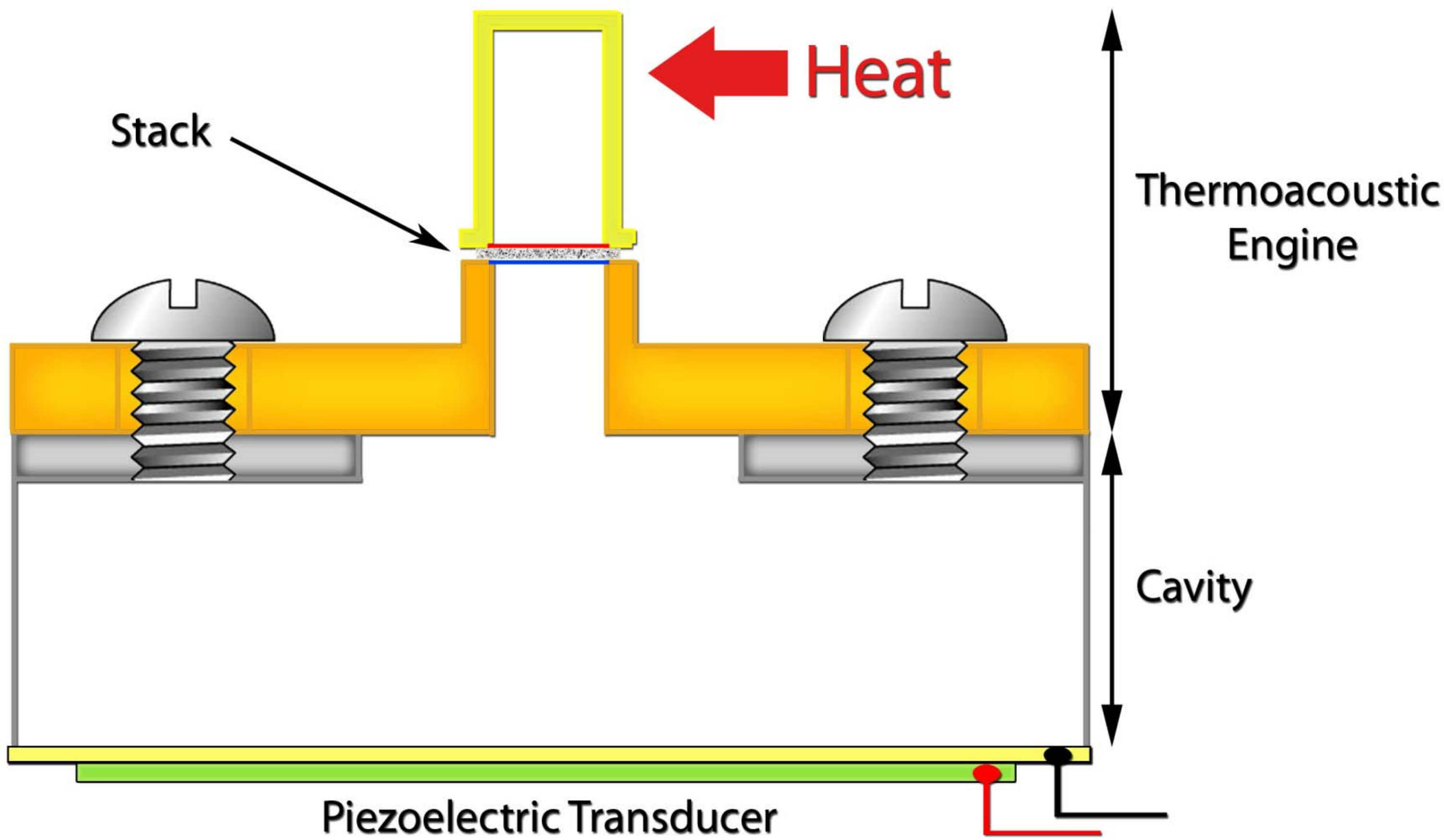
Assembly challenges



Experimental Details

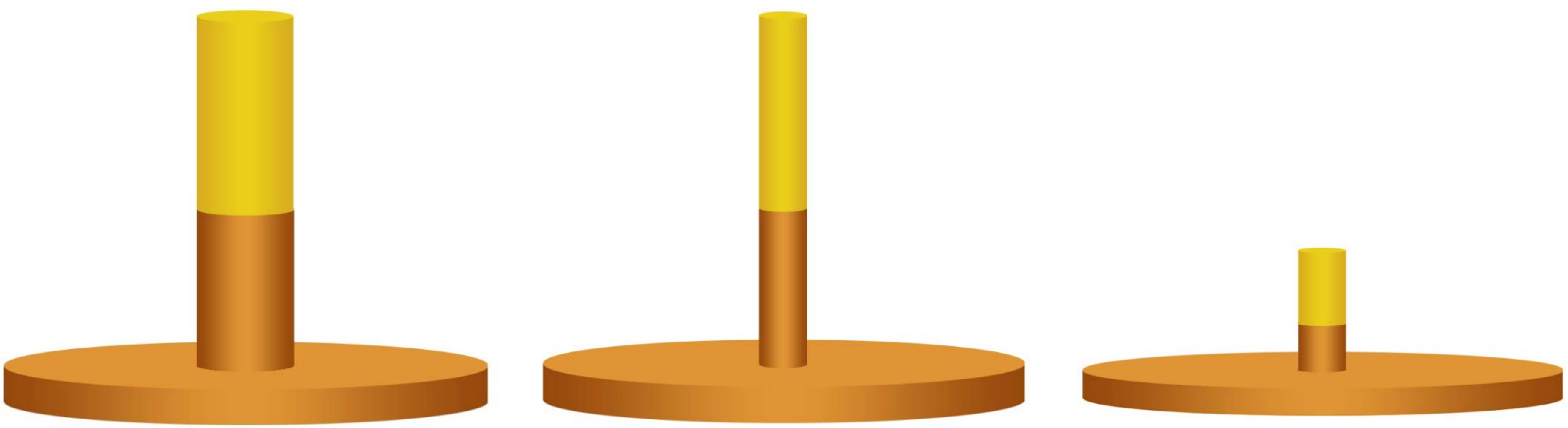
- Heat was injected using heater wires.
- Temperature measurements were made with thermocouples read by a USB DAQ module.
- Pressure measurements were made with a piezoelectric transducer read by a PCI DAQ board.
- All measurements were recorded using NI Signal Express and analyzed with NI DIAdem.

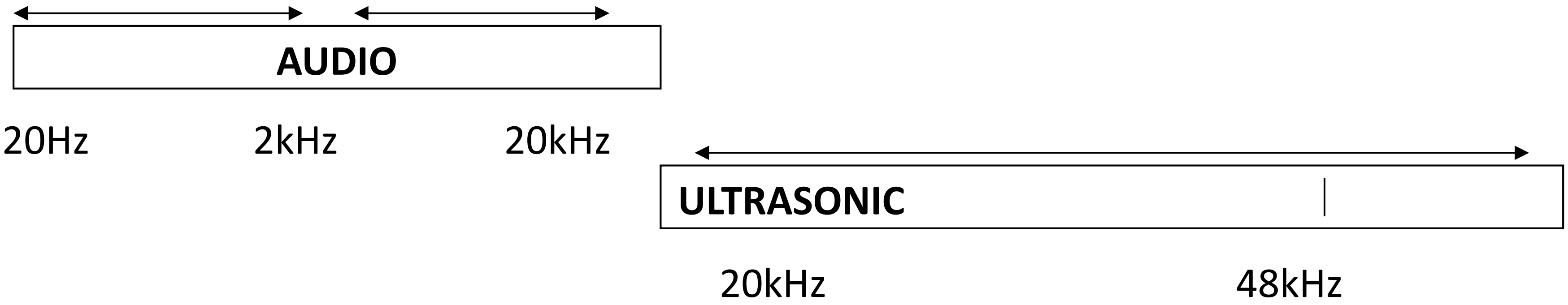
Experimental details

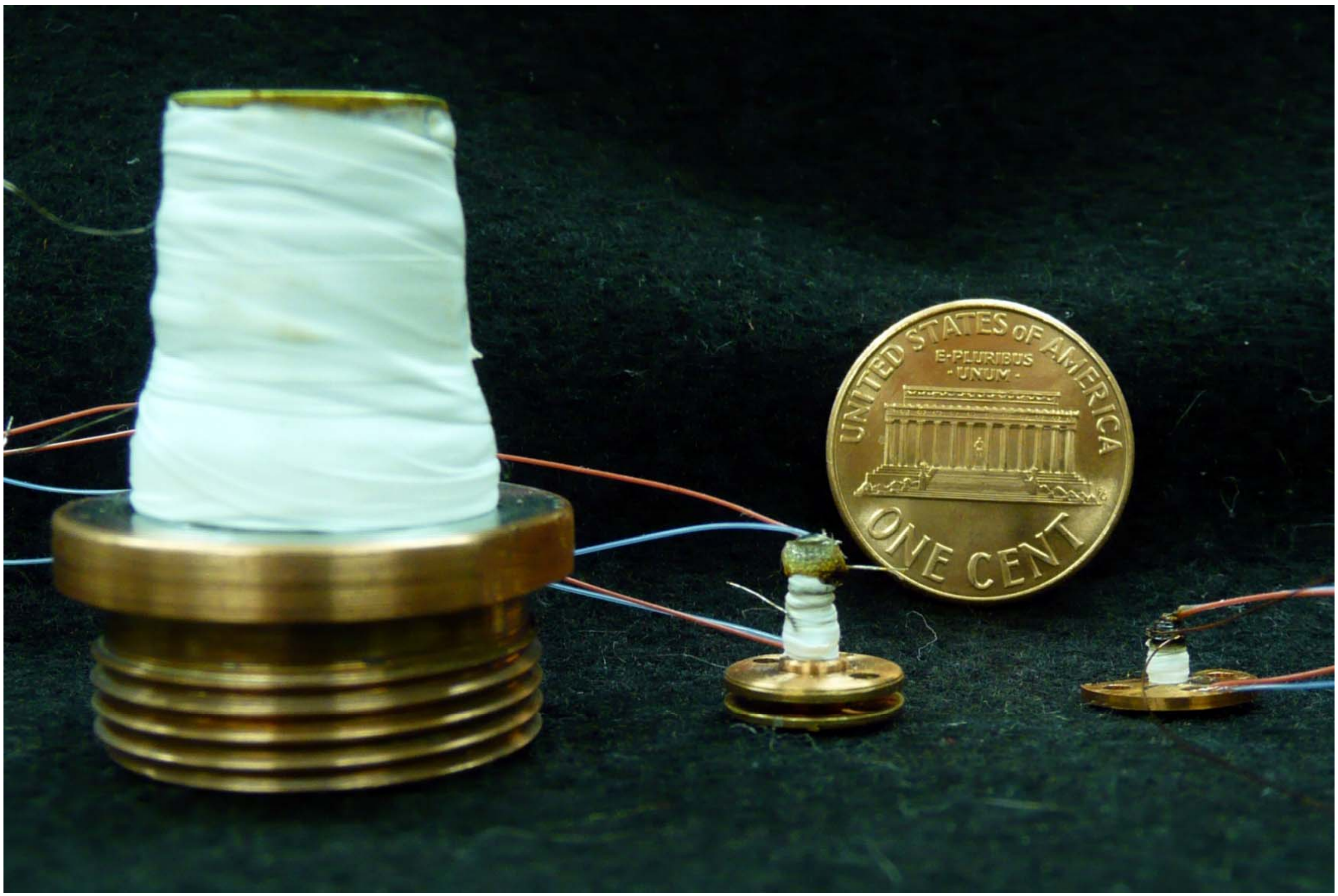


Single Engines

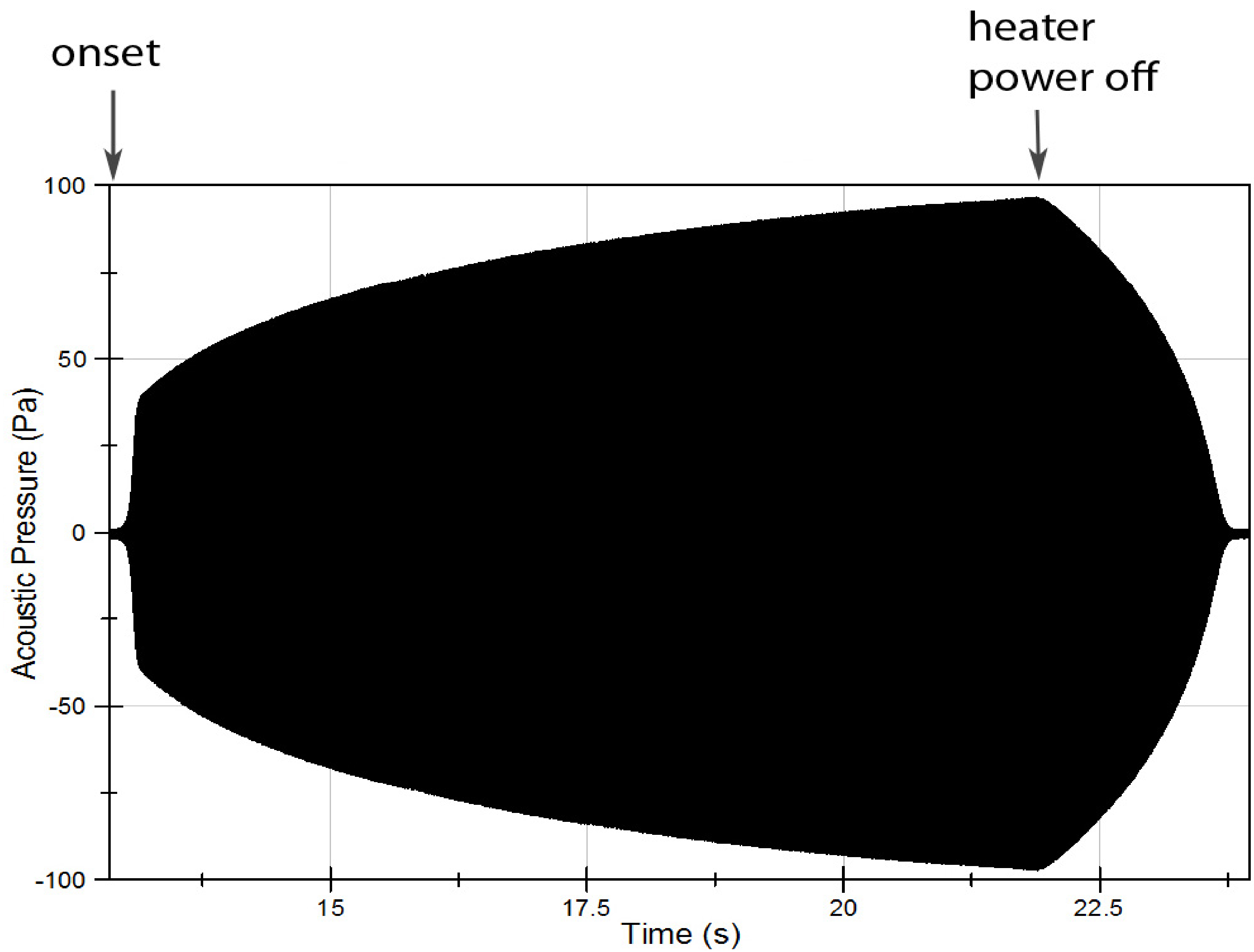
- 10 kHz range – 8.6 mm long, with 1 and 2 mm diameters
- 20+ kHz range – 3.4 mm long with 1 mm diameter



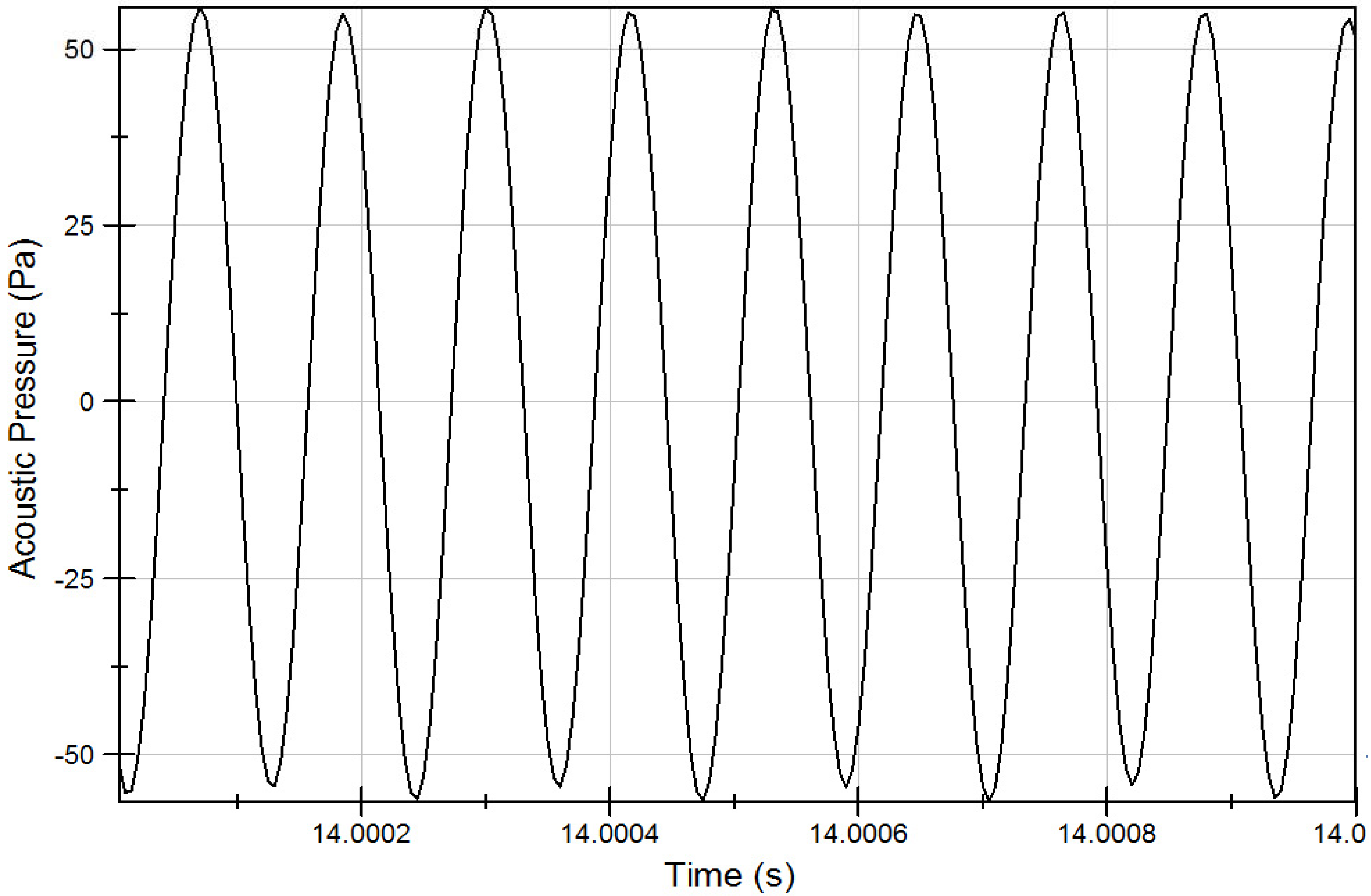

AUDIO
20Hz
2kHz
20kHz
ULTRASONIC
20kHz
48kHz


UNITED STATES OF AMERICA
E PLURIBUS UNUM
ONE CENT

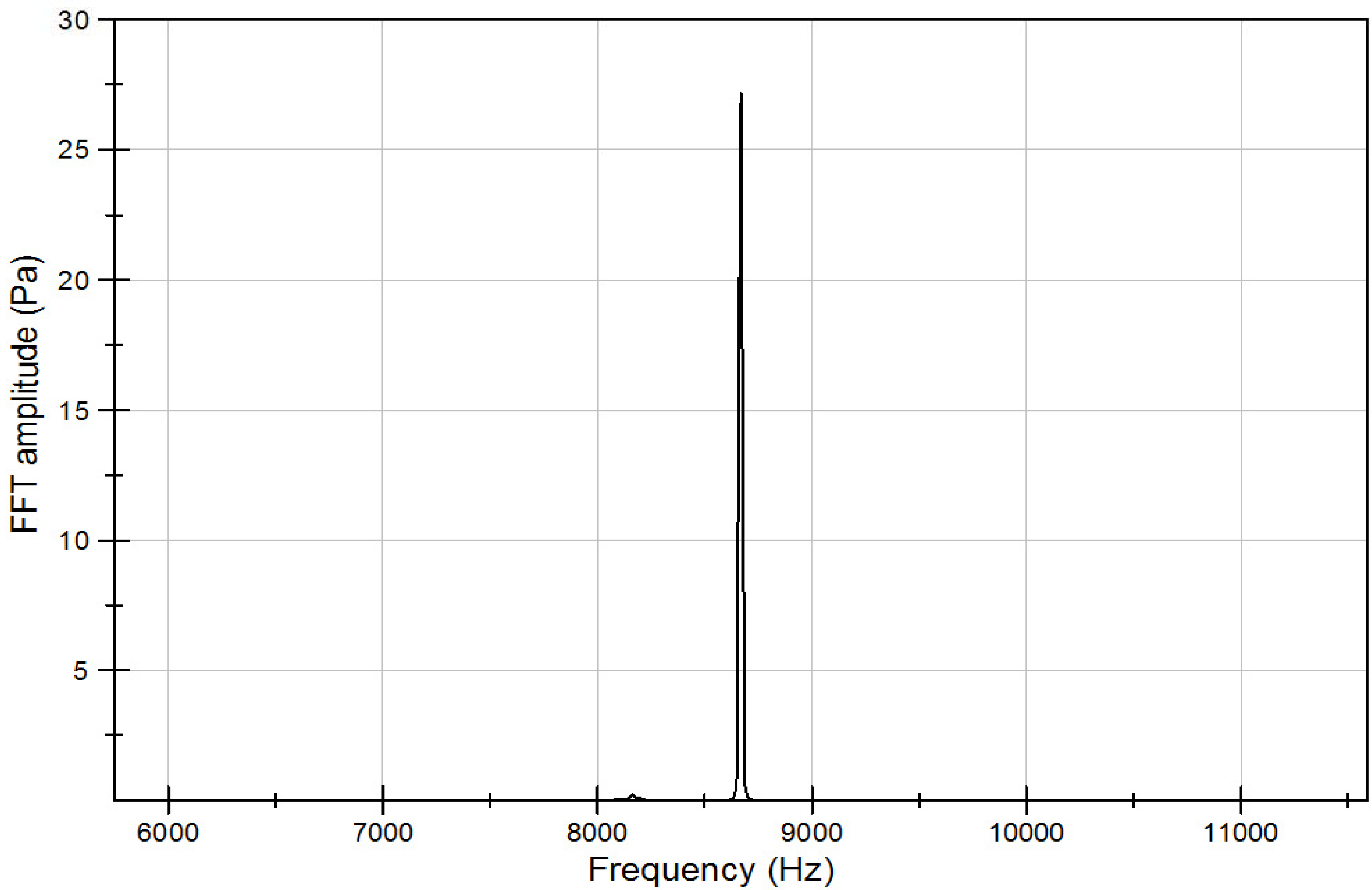
10 kHz (2mm) engine run



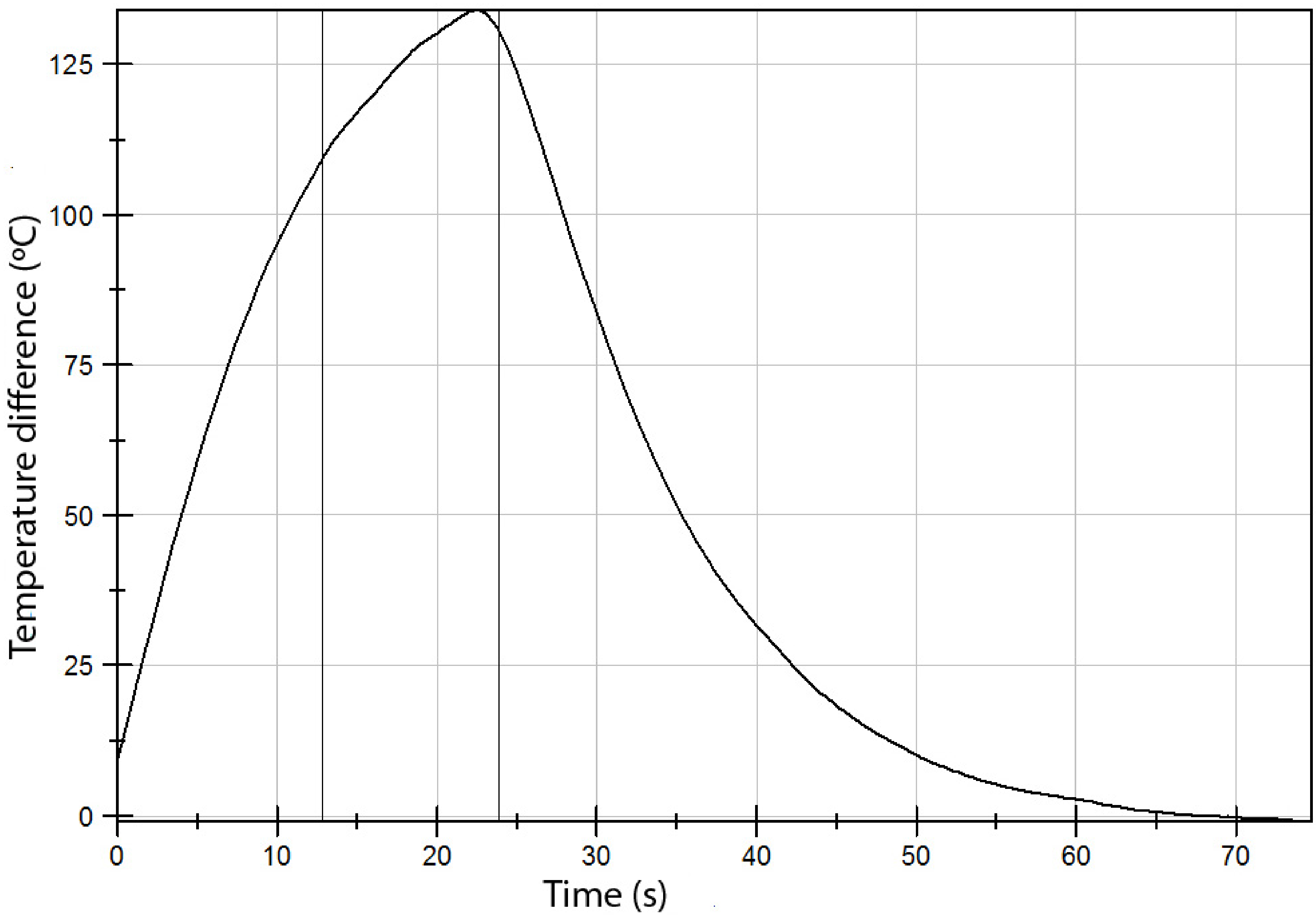
10 kHz engine run



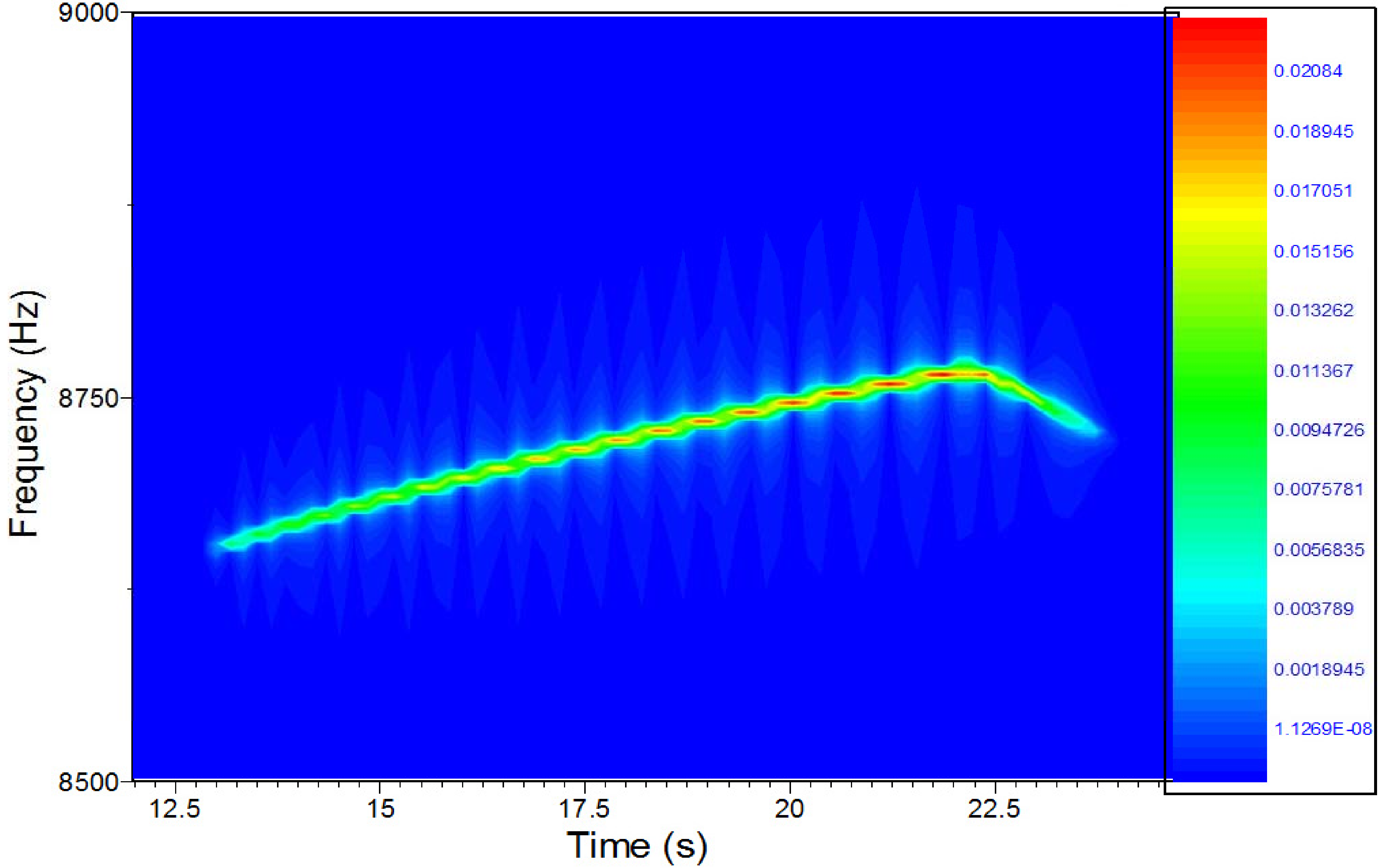
10 kHz engine run



10 kHz engine run

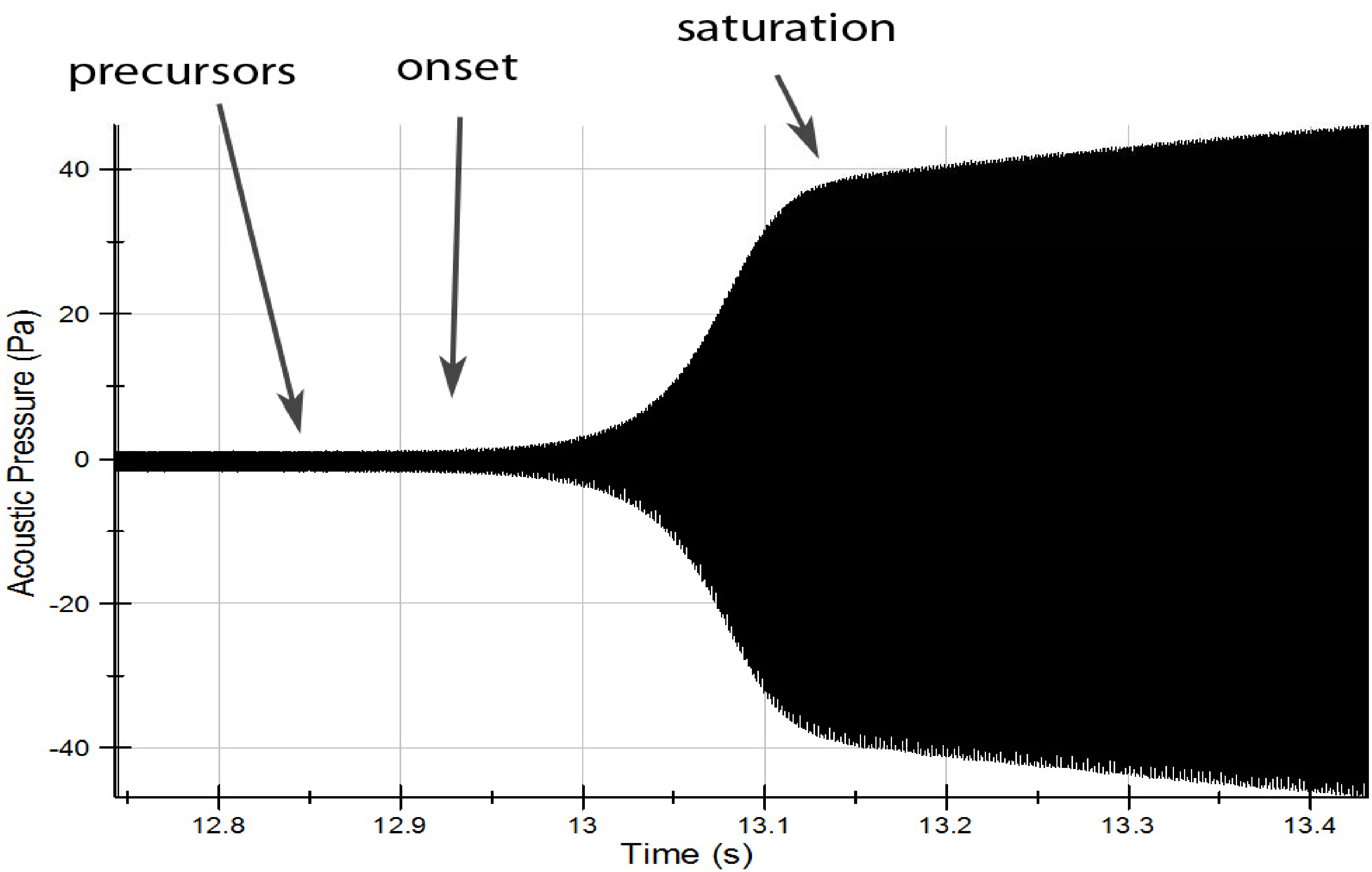


10 kHz JTFA



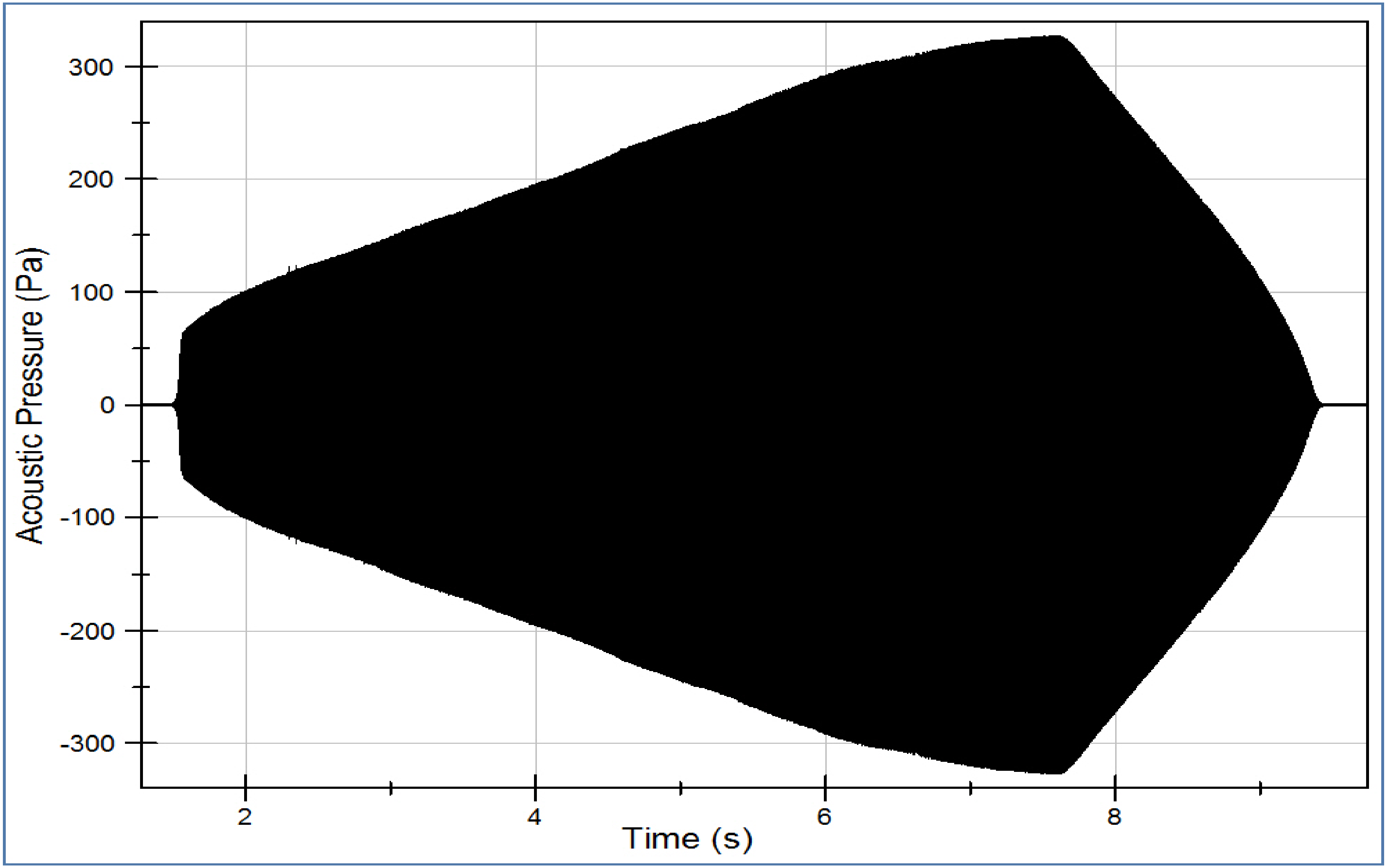
9000
8750
8500
Frequency (Hz)
12.5
15
17.5
20
22.5
Time (s)
0.02084
0.018945
0.017051
0.015156
0.013262
0.011367
0.0094726
0.0075781
0.0056835
0.003789
0.0018945
1.1269E-08

Onset

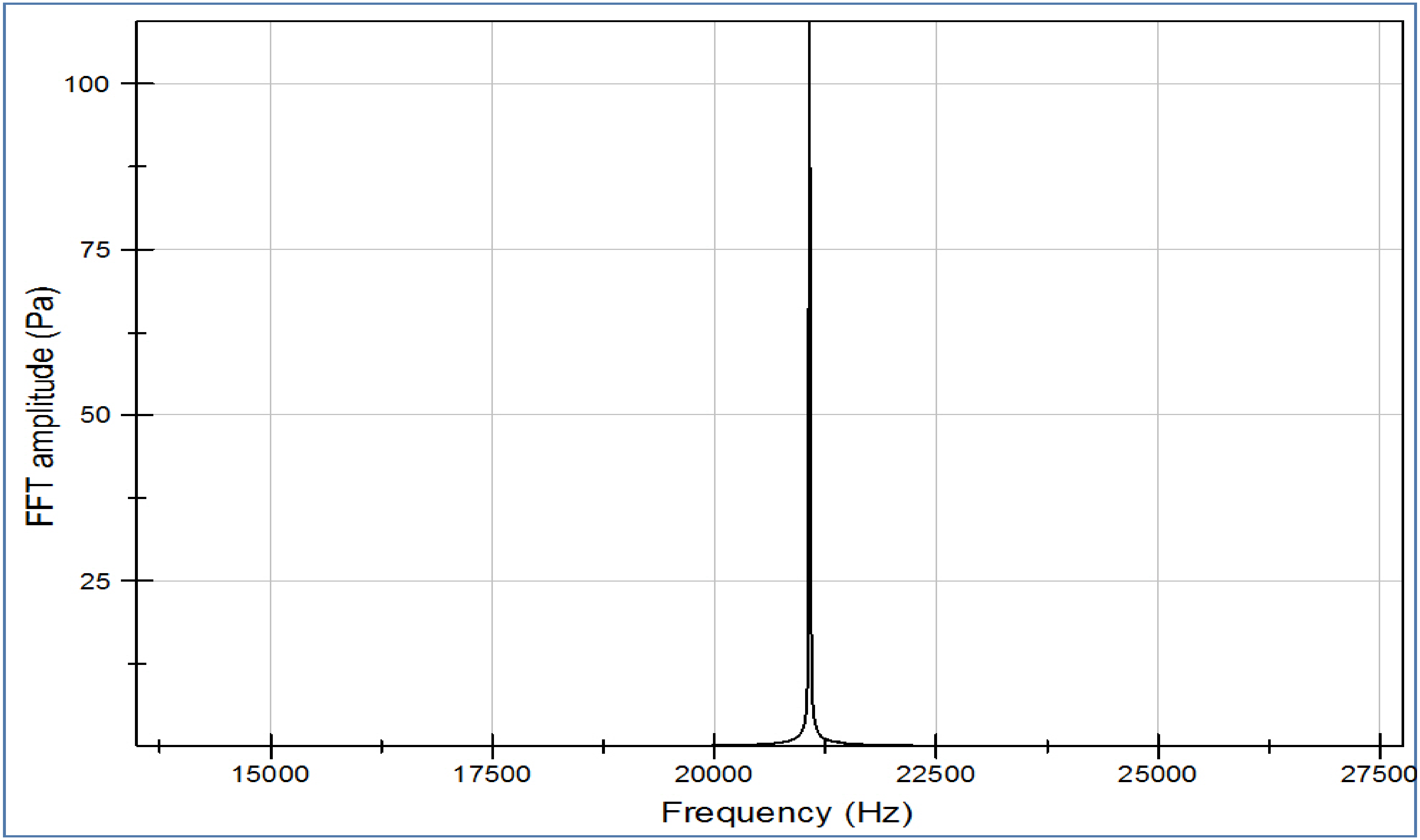


saturation
precursors
onset
40
20
0
-20
-40
Acoustic Pressure (Pa)
12.8
12.9
13
13.1
13.2
13.3
13.4
Time (s)

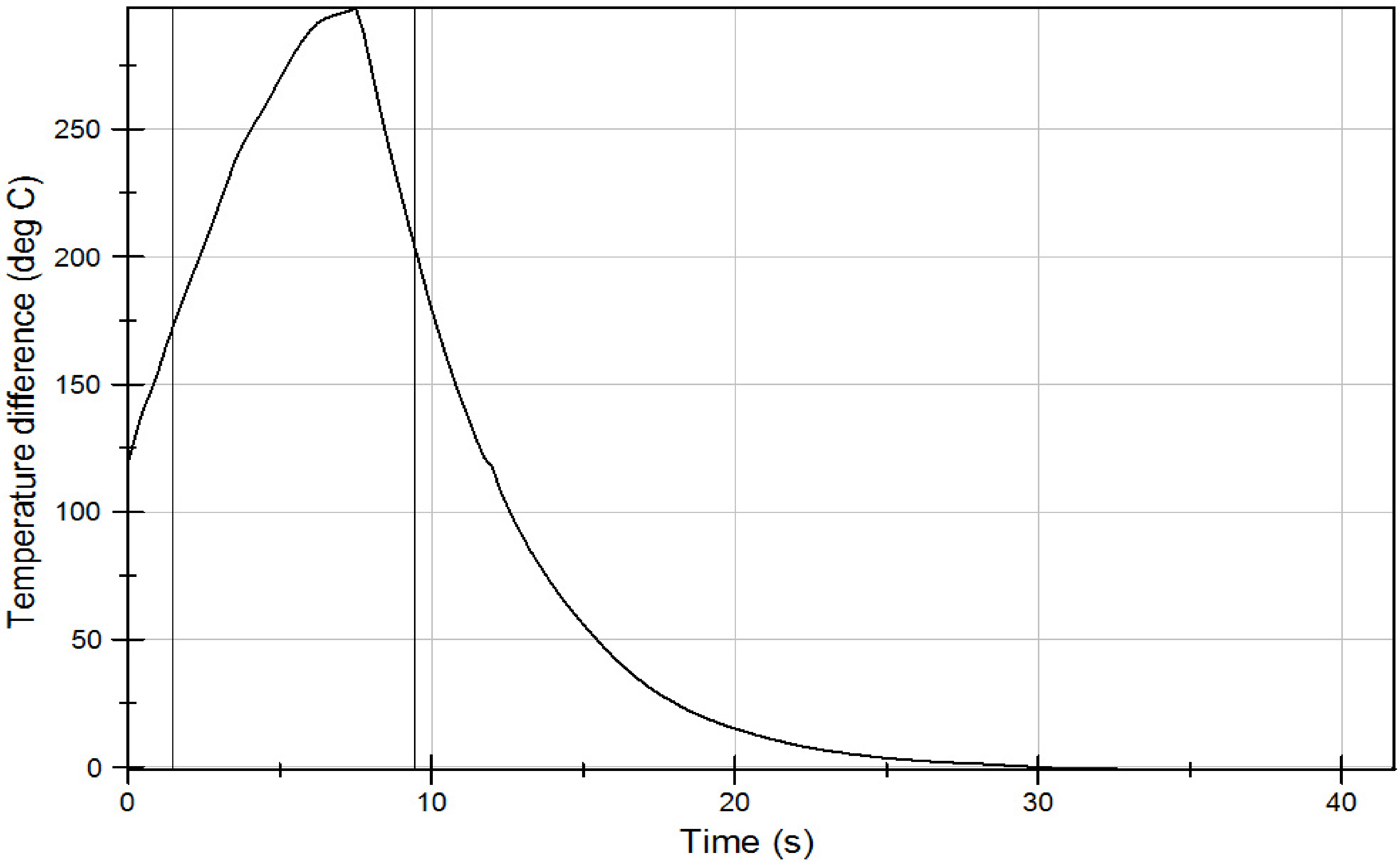
Ultrasonic engine run



Ultrasonic engine run



Ultrasonic engine run



Engine characteristics

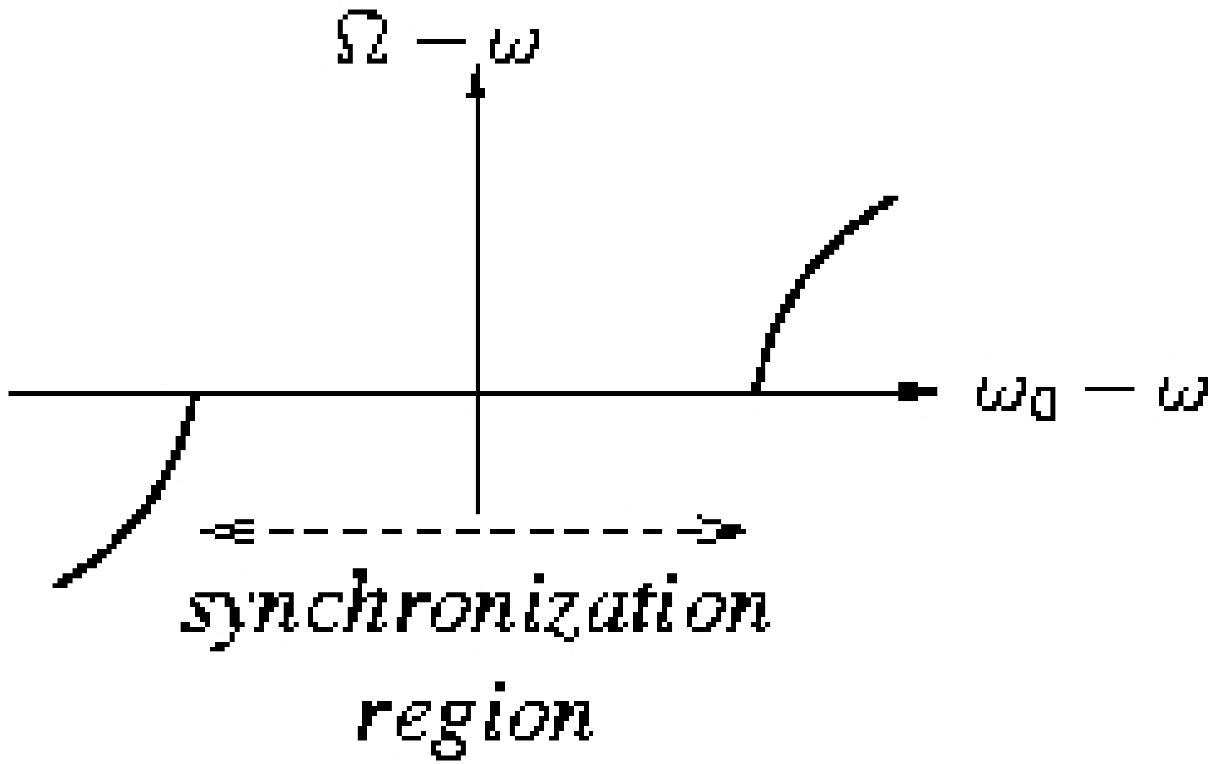
Engine	Frequency (kHz)	Onset delta T (ºC)	Max. Pressure Amplitude (Pa)	Onset time (s)
10 kHz 1mm	8.7-9.9	130-180	99	.23-.65
10 kHz 2mm	8.1-9.0	110-160	414	.23-.52
ultrasonic, 1mm	20.0-23.5	180-260	335	.10-.25

Self-sustained oscillators

- have an energy source, but are not driven
- oscillator's vibration affects the source's vibration
- the phase of oscillations is random
- intrinsically non-linear
- other examples are lasers, electronic oscillators, many clocks, and biological systems.

- An important characteristic of self-sustained oscillators is that they can be synchronized.

Synchronization

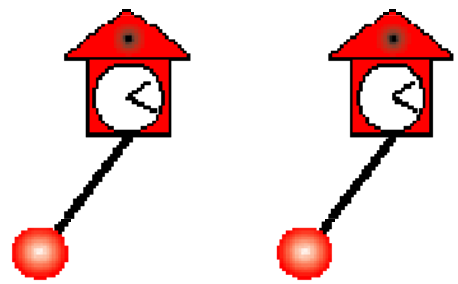


Courtesy of Arkady and Pikovsky, 2007, scholarpedia.org

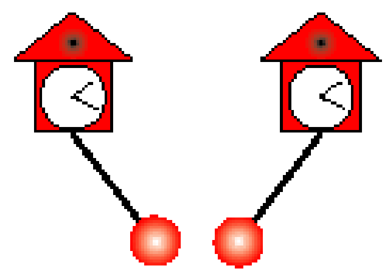
Synchronization

- In the synchronization region, the oscillators become phase-locked, generally either:

In-phase $\psi \sim 0$

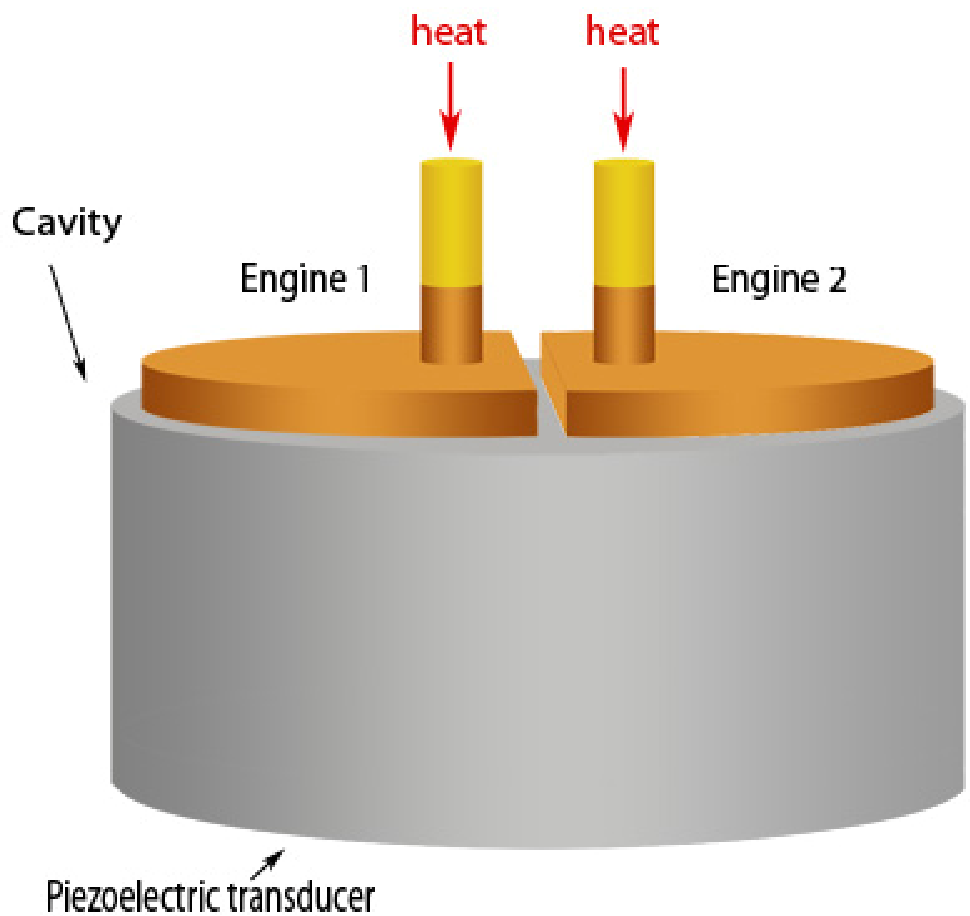


Or anti-phase $\psi \sim \pi$

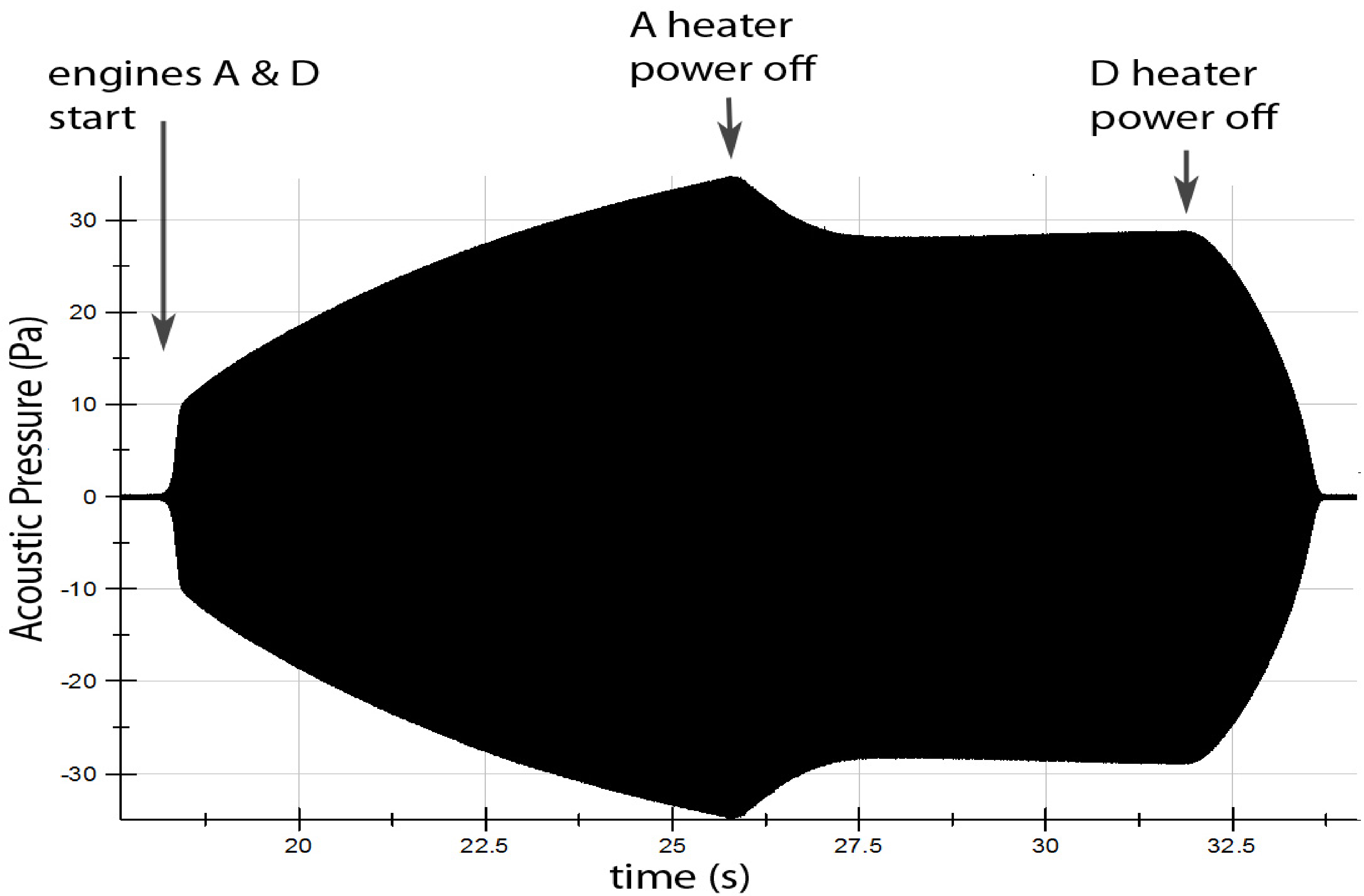


Courtesy of Arkady and Pikovsky, 2007, scholarpedia.org

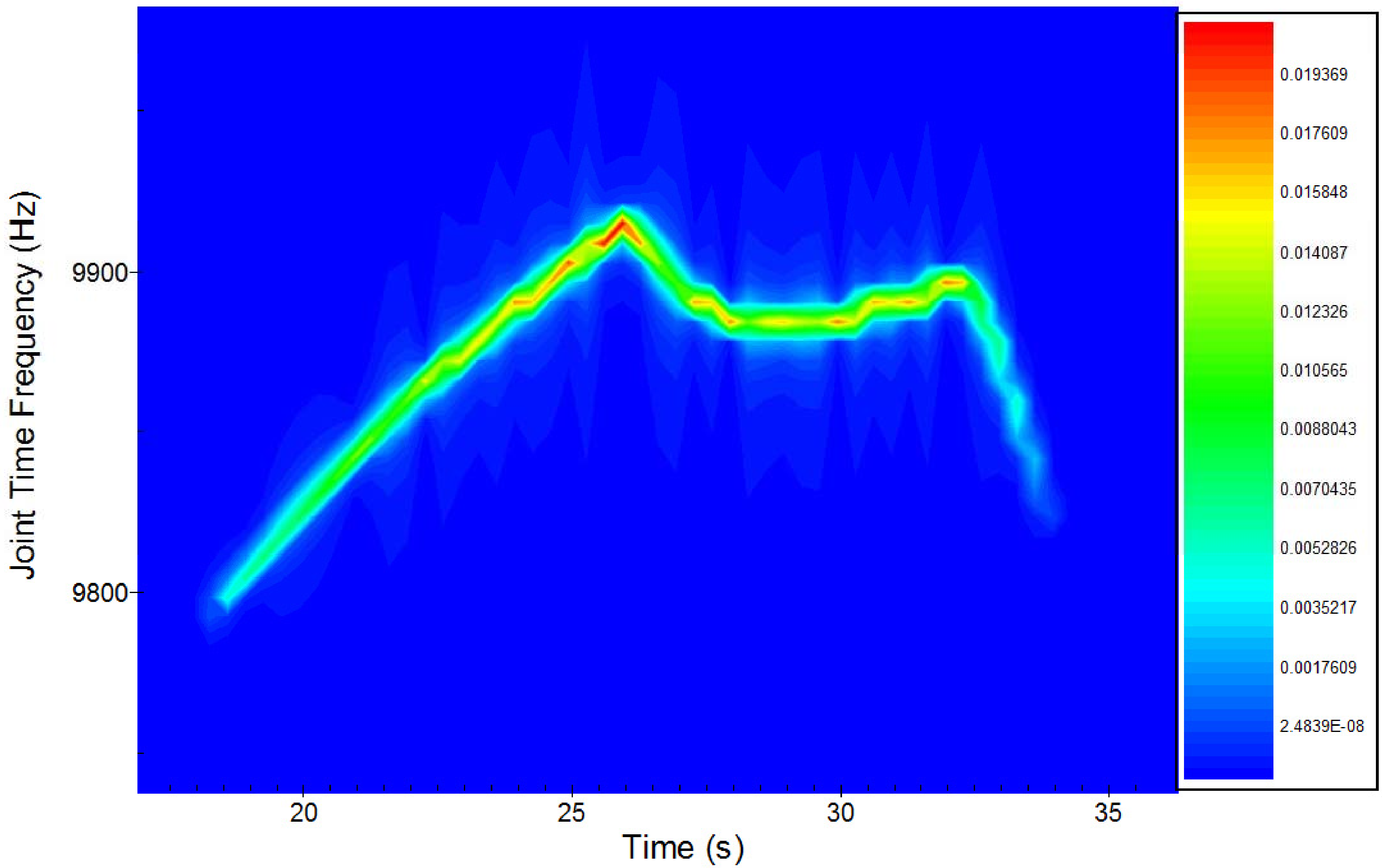
Synchronization set up



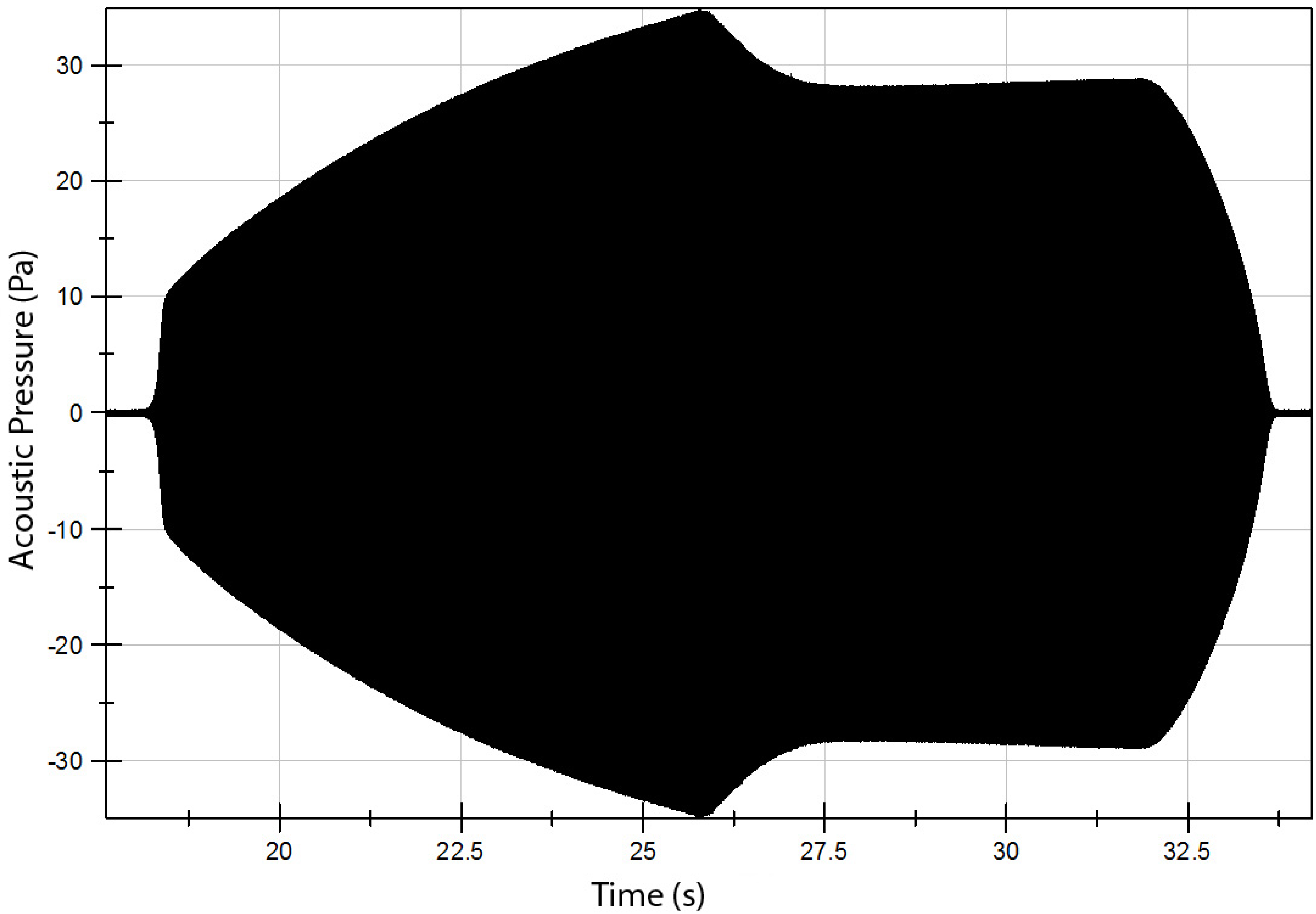
10 kHz synchronization



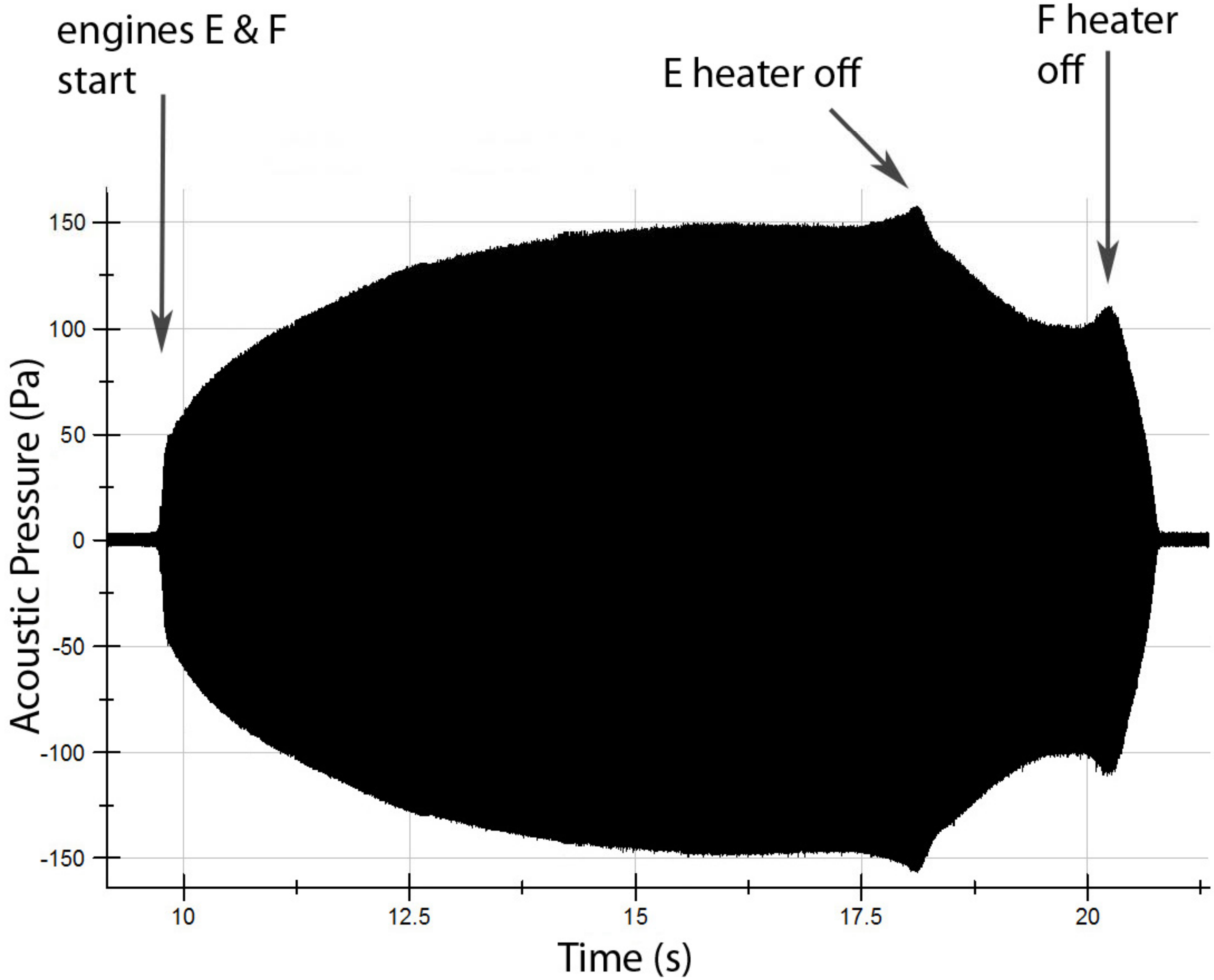
10 kHz synchronization JTFA



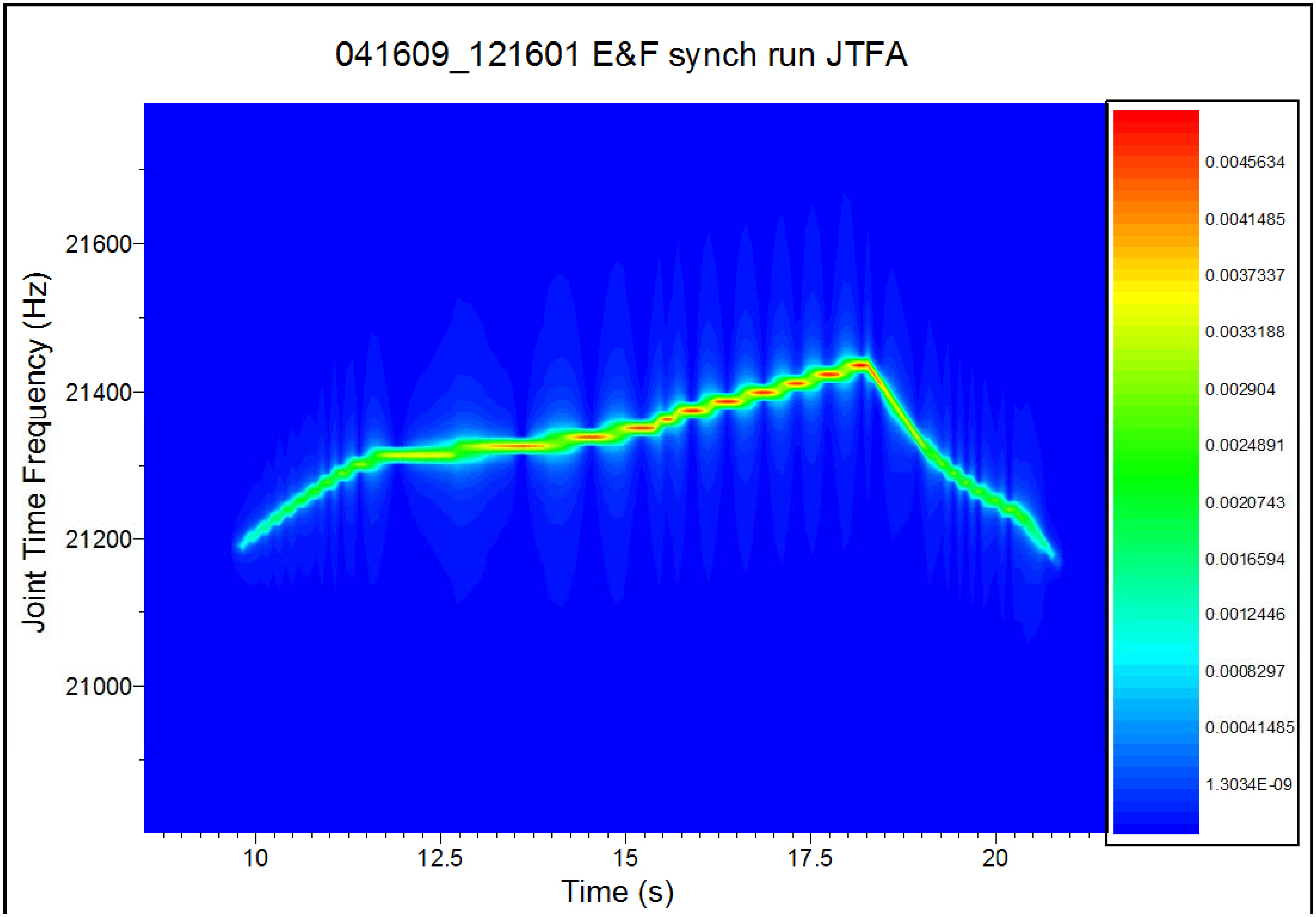
10 kHz amplitude comparison



21 kHz synchronization



21 kHz synchronization JTFA



Conclusions

- Designed, assembled, and studied engines in 10 kHz and low ultrasonic ranges.
- Engine performance scaled as expected with frequency.
- In-phase synchronization was observed at both frequency ranges.
- Opened the field to MEMS technology for fabrication of the devices in large arrays.

Thank you!