Delayed acoustic self-feedback control of limit cycle oscillations in a turbulent combustor

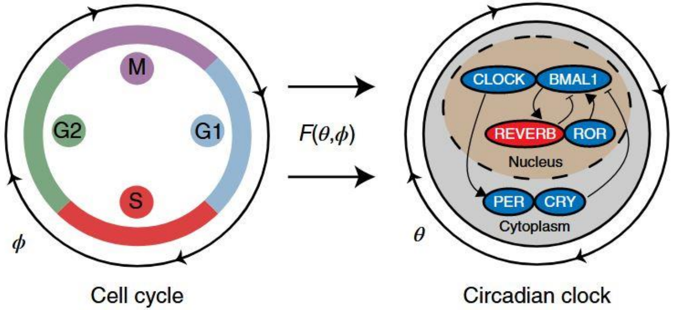
Ankit Sahay, Abhishek Kushwaha, Samadhan A. Pawar, Midhun P. R., Jayesh M. Dhadphale, R. I. Sujith

Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai, India

Funding agencies:
IoE Initiative, Department of Science and Technology, Gov. of India

NODYCON 2023, ROME, JUNE 18-22, 2023

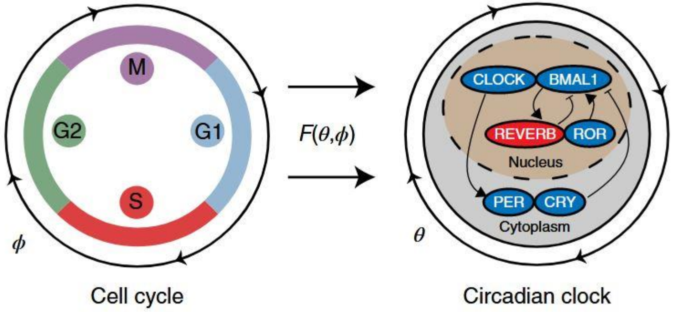
Oscillations in daily life



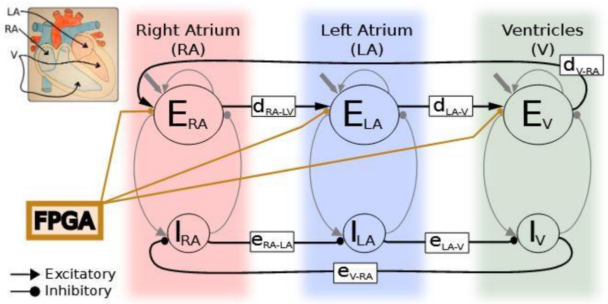
Circadian rhythm cycle

Droin *et al*. Nature Physics **15**, 2019,

Oscillations in daily life



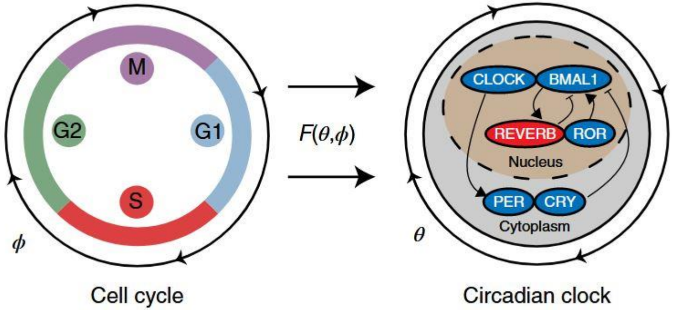
Circadian rhythm cycle



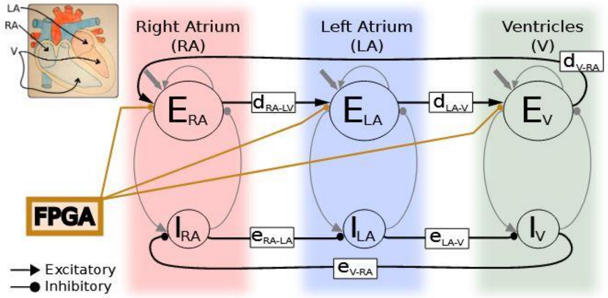
Cardiac pacemaker dynamics

Droin *et al*. Nature Physics **15**, 2019,
Qian *et al*. Nature Communications **7**, 2016

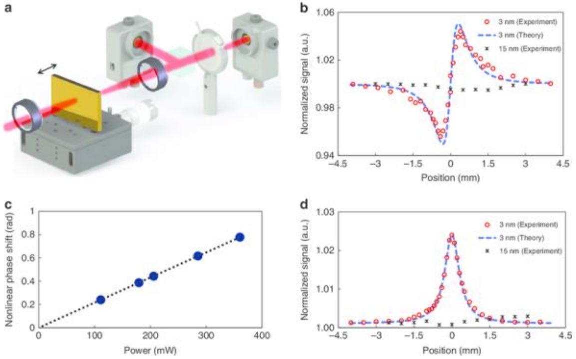
Oscillations in daily life



Circadian rhythm cycle



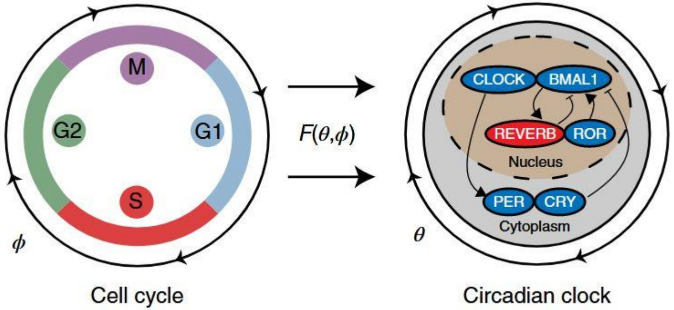
Cardiac pacemaker dynamics



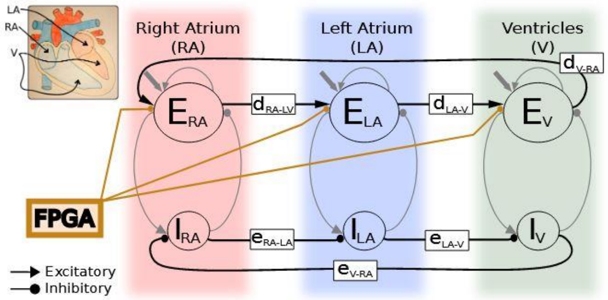
Laser oscillators

Droin *et al*. Nature Physics **15**, 2019,
Qian *et al*. Nature Communications **7**, 2016
Krause *et al*. arXiv, 2021,

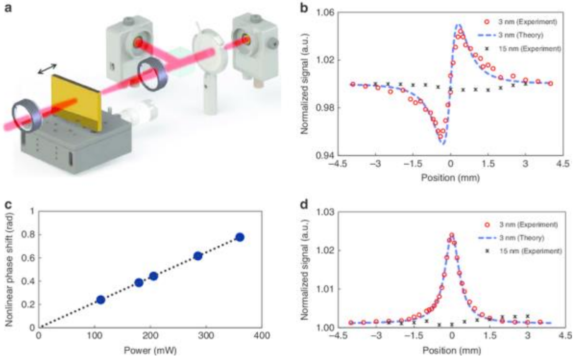
Oscillations in daily life



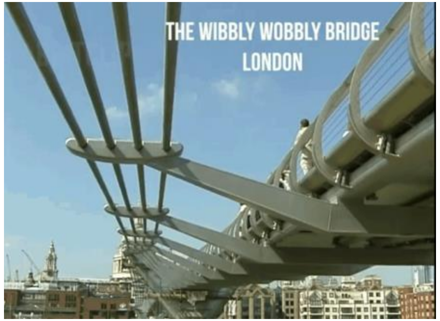
Circadian rhythm cycle



Cardiac pacemaker dynamics



Laser oscillators



Structural oscillations

Droin *et al*. Nature Physics **15**, 2019,
Qian *et al*. Nature Communications **7**, 2016
Krause *et al*. arXiv, 2021,
BritSync YouTube Channel

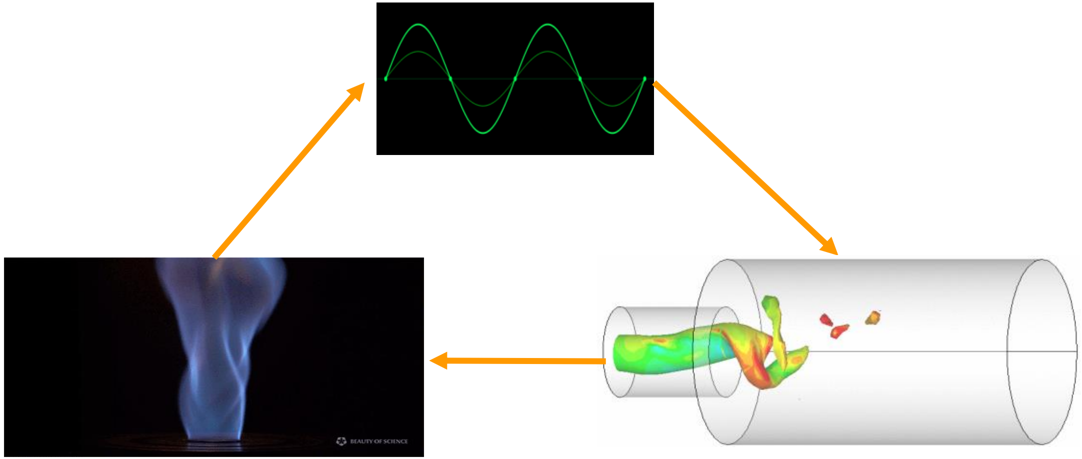
Oscillations can be detrimental too!

Wobbling bridge

Fluttering aircraft wings

Image source: vice.com (bridge), makeagif.com (flutter)

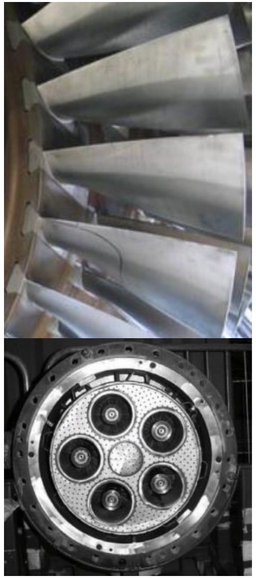
Thermoacoustic instability

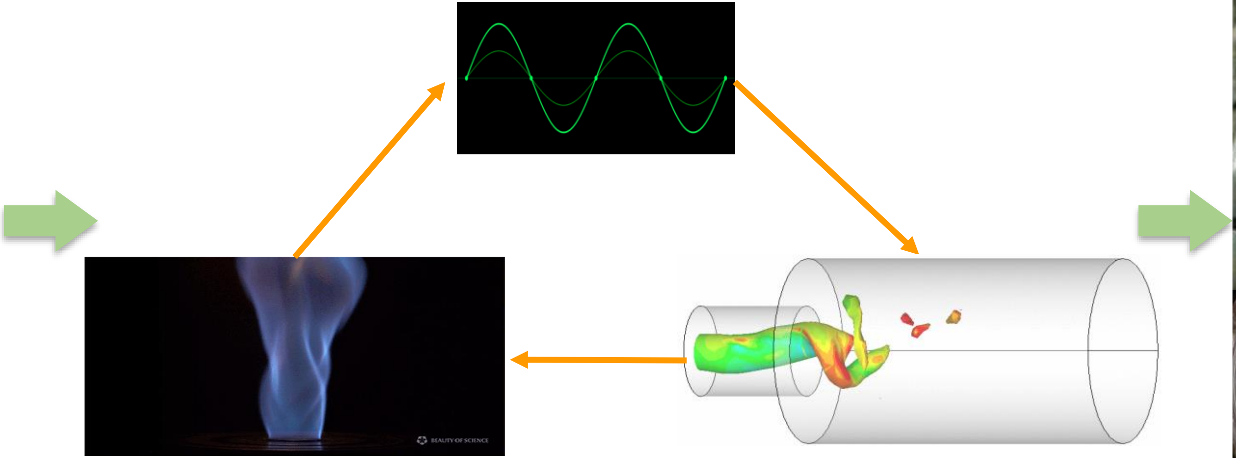


Thermoacoustic instability occurs due to positive feedback between flame, flow and heat release rate

GIF courtesy: Stephanie Mann (standing wave), Beauty of Science (flame), https://engineering.purdue.edu/CFDLAB/projects/combustor.html

Structural damage to combustors





Thermoacoustic instability can cause structural damage to gas turbine and rocket engine combustors

GIF courtesy: Stephanie Mann (standing wave), Beauty of Science (flame), https://engineering.purdue.edu/CFDLAB/projects/combustor.html,
Image courtesy: Goy, et al. Monitoring Combustion Instabilities: E. ON UK's experience. Progress in Astronautics and Aeronautics. Ed. Lieuwen and Yang (2005).

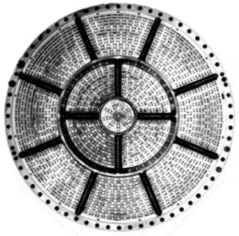
…and even compromise space missions!

Video link: https://www.youtube.com/watch?v=DjWiuMIGVEs.
Youtube channel: Eyes to the Sky

Ways to control thermoacoustic instability

Passive Controls:

Helmholtz resonator



Baffles

Advantages:

Cheap, simple components, reliable, low power requirements

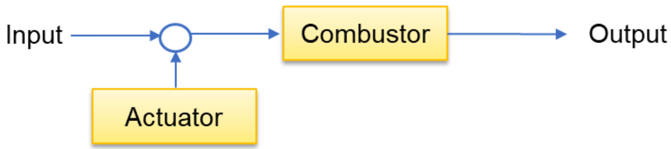
Limitations:

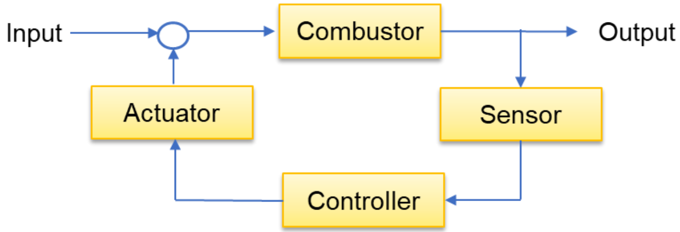
Restricted range of operation, difficult to modify or replace

Image source: Wikimedia Commons (user: Brian0918), Kraemer and Wheelock. Rocketdyne: Powering Humans into Space, *AIAA* (2006)

Ways to control thermoacoustic instability

Active Controls:





Advantages:

Wide operative range, fast response, easy to replace

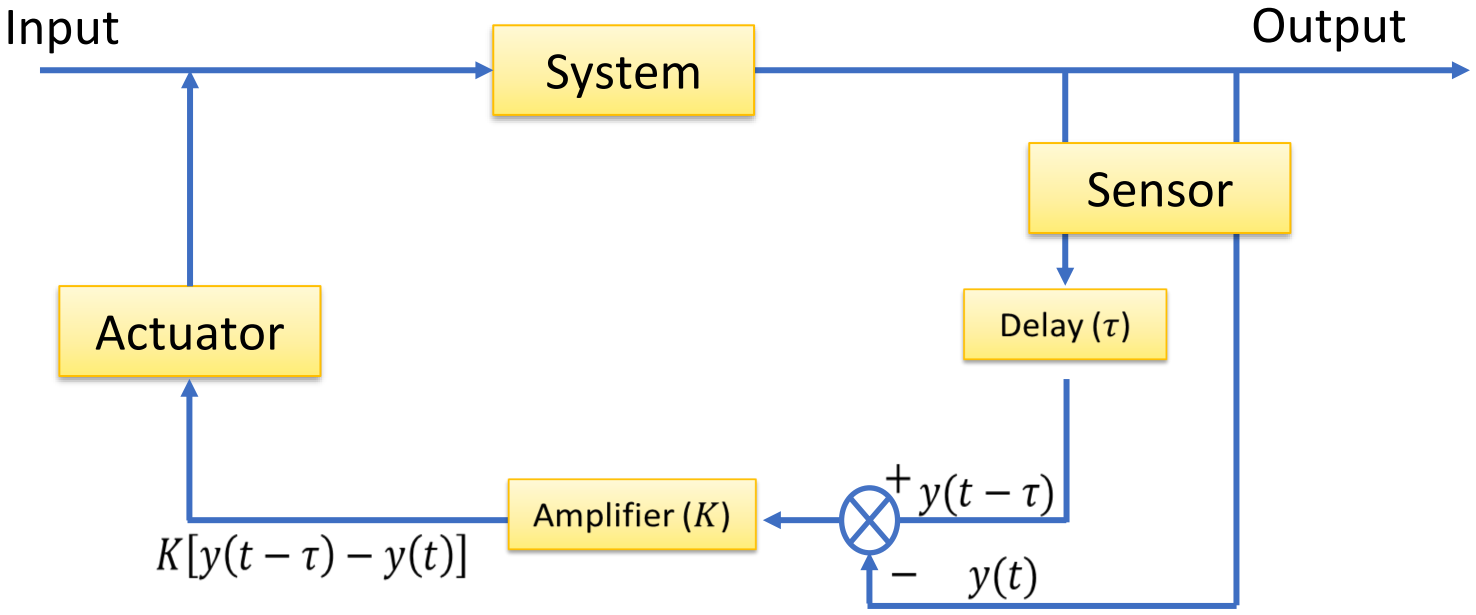
Limitations:

High power requirements, complex components, unreliable

Delayed feedback control

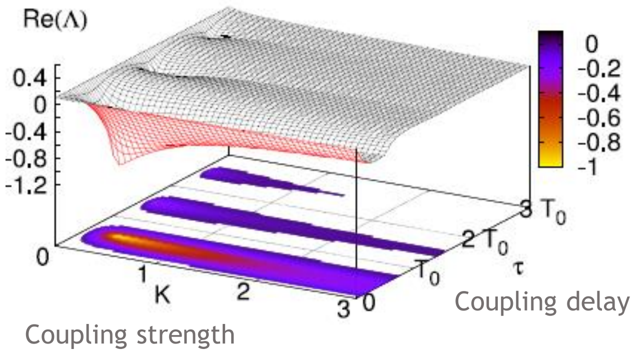
Delayed feedback control has been used to quench limit cycle oscillations in various systems.

Ways to control thermoacoustic instability



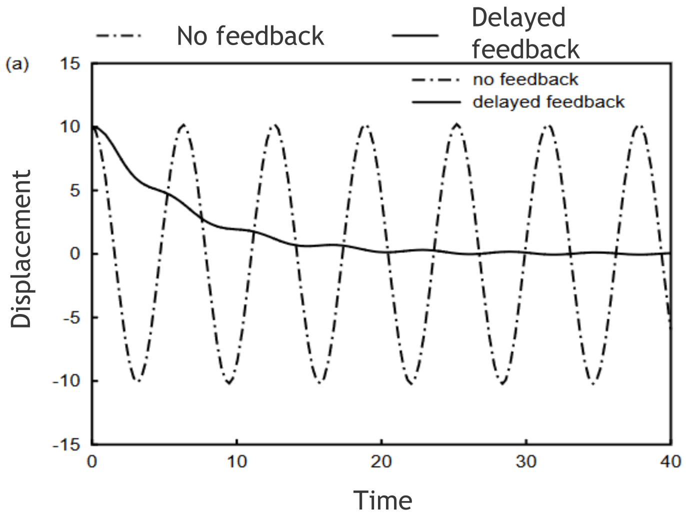
In delayed feedback, output signal measured a finite time ago is used to provide feedback to the system

Ways to control thermoacoustic instability



$$\dot{Z} = (\lambda + i\omega)Z + K[(Z(t-\tau) - Z(t)]$$

Delay feedback Stuart-Landau oscillator
[Hovel and Schöll (2005)]

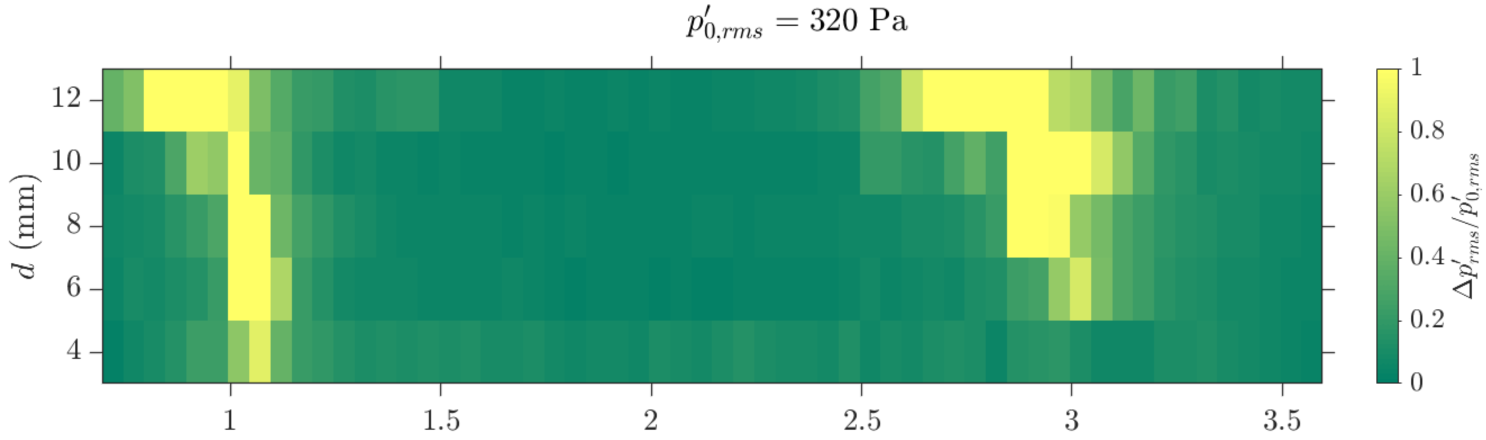


$$\ddot{x} - 0.8\sin(\dot{x}) + x = 0.8kx(t-\tau)$$

Delay feedback nonlinear oscillator
[Atay (2002)]

Delayed feedback has been used to quench oscillations in different oscillators

Ways to control thermoacoustic instability



Length of coupling tube/Length of Rijke tube

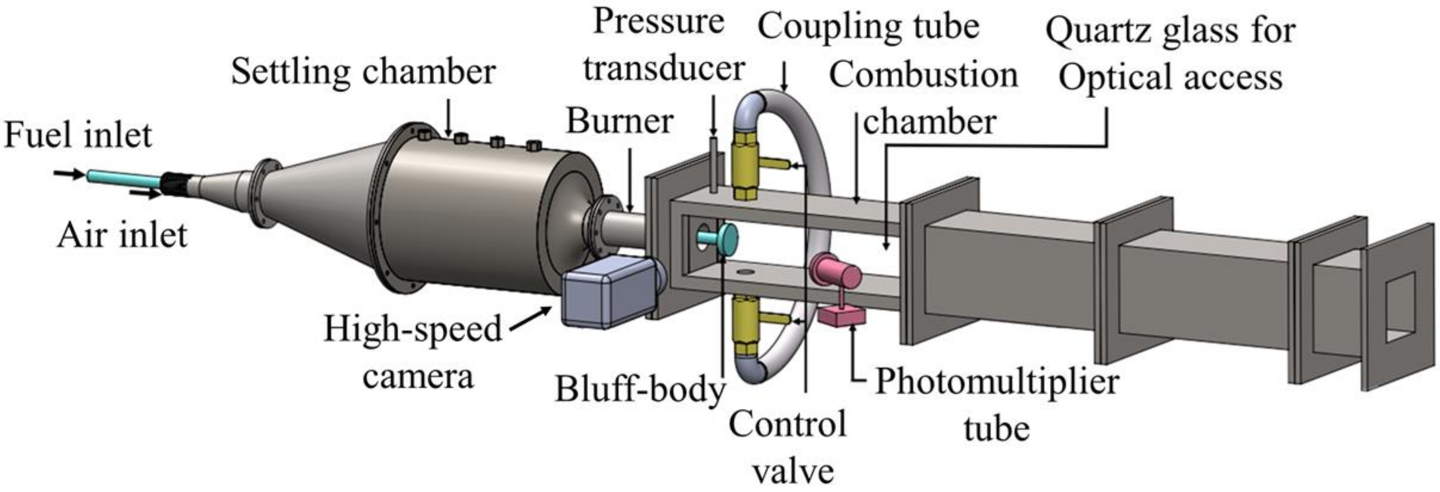
Rijke tube oscillator [Srikanth (2022)]

Delayed feedback has been used to quench thermoacoustic instability in a laminar prototypical thermoacoustic system.

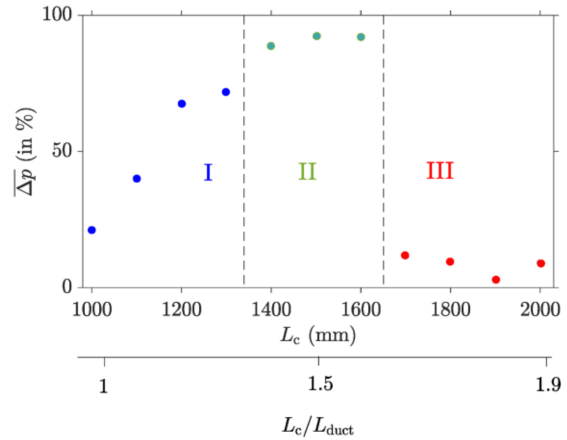
Ways to control thermoacoustic instability

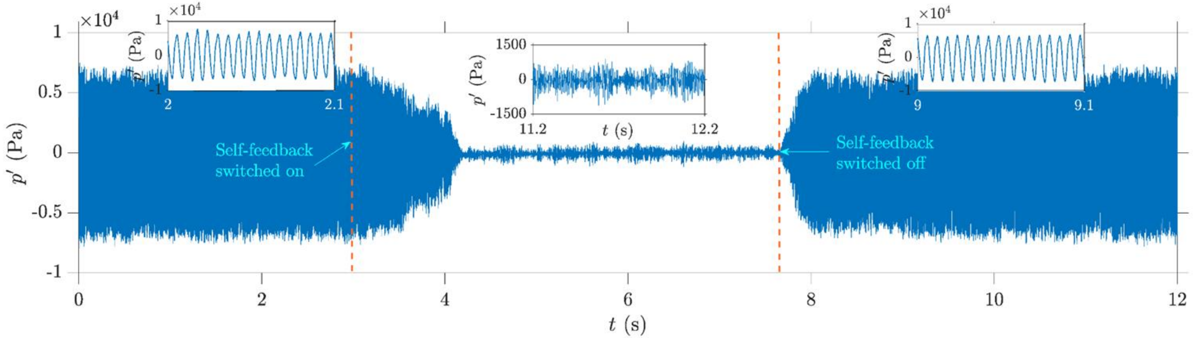
We propose a simple form of delayed feedback called self-coupling to quench thermoacoustic instability by disrupting the coupling between flame, flow, and heat release rate in turbulent thermoacoustic systems.

Turbulent combustor



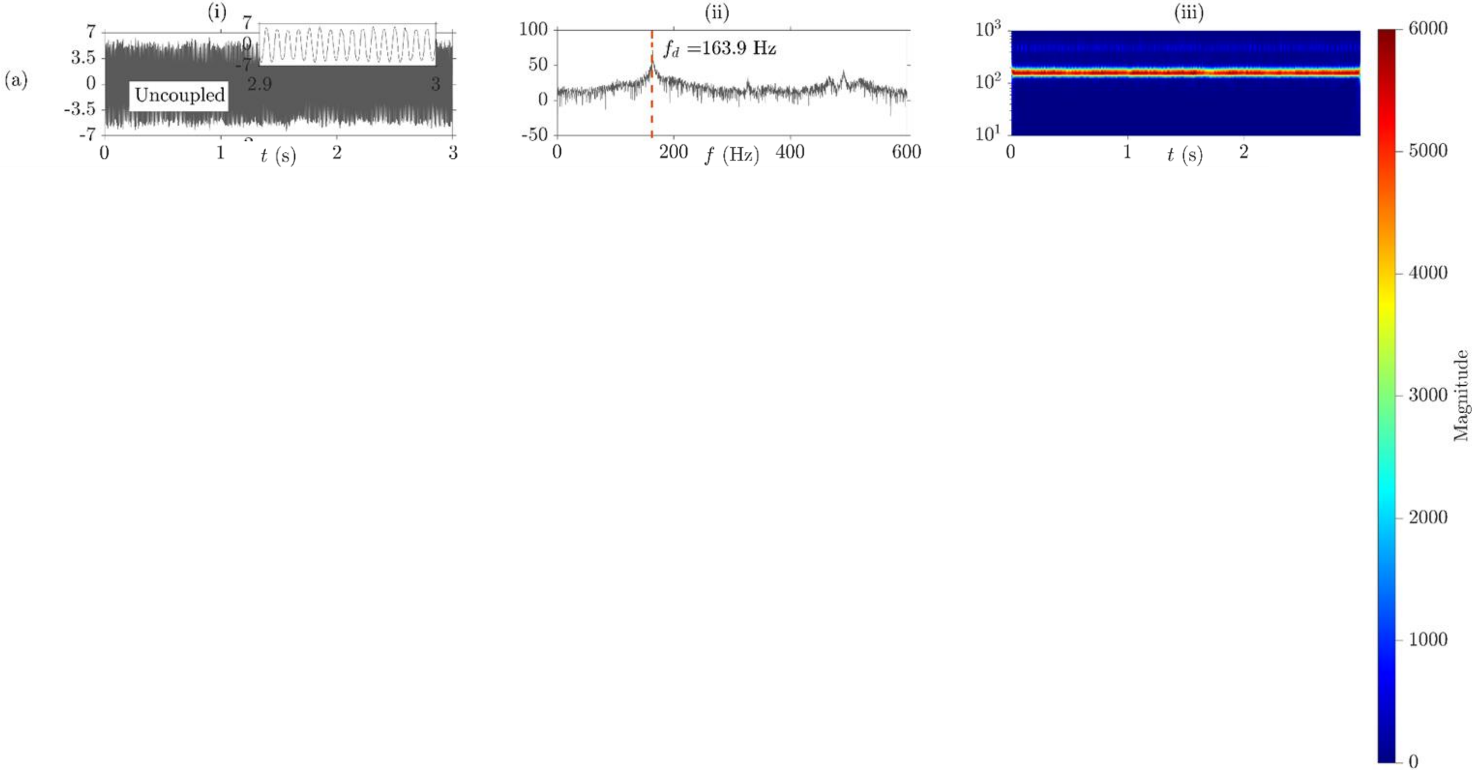
Suppression of thermoacoustic instability





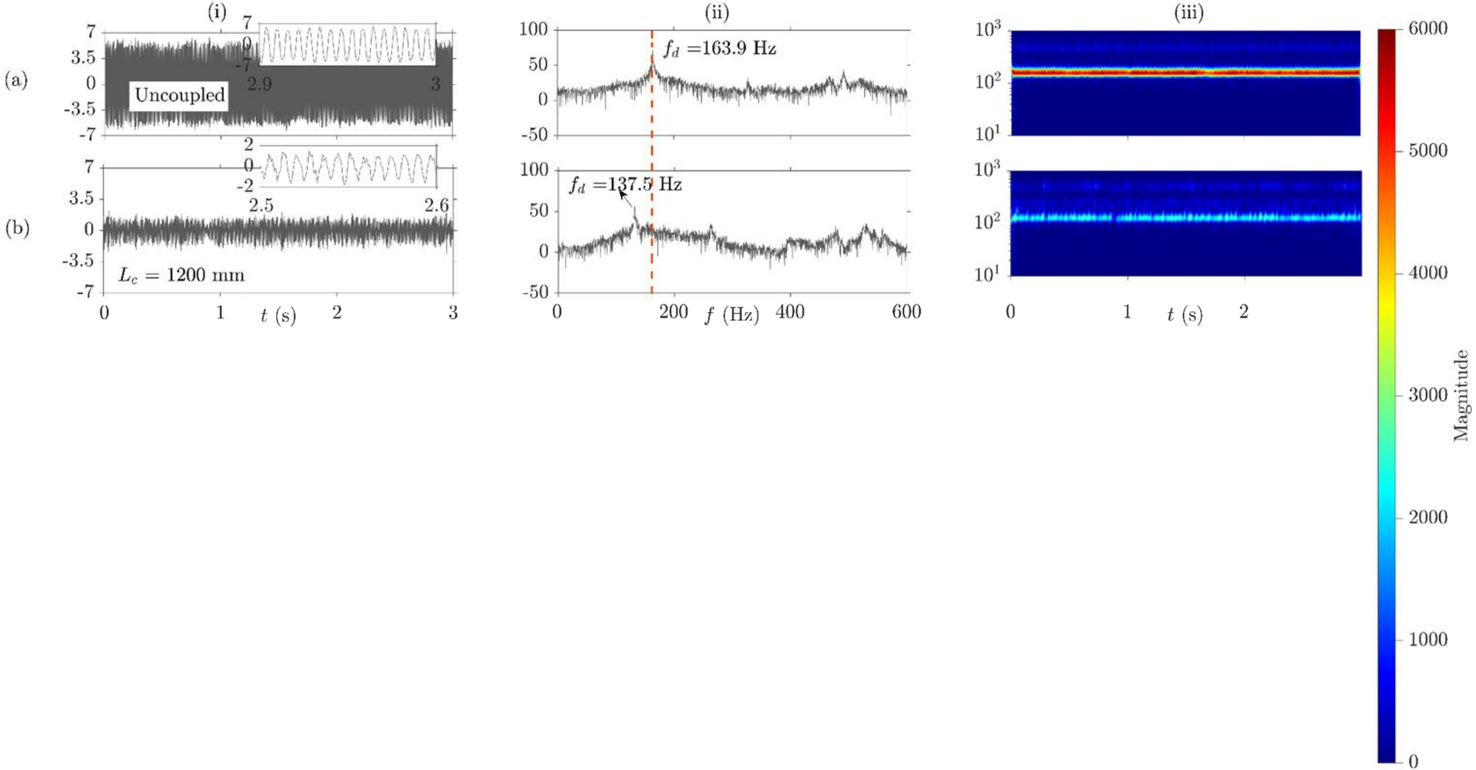
The magnitude of p' during the suppressed state is almost same as that observed during the steady state.

Transition through intermittency



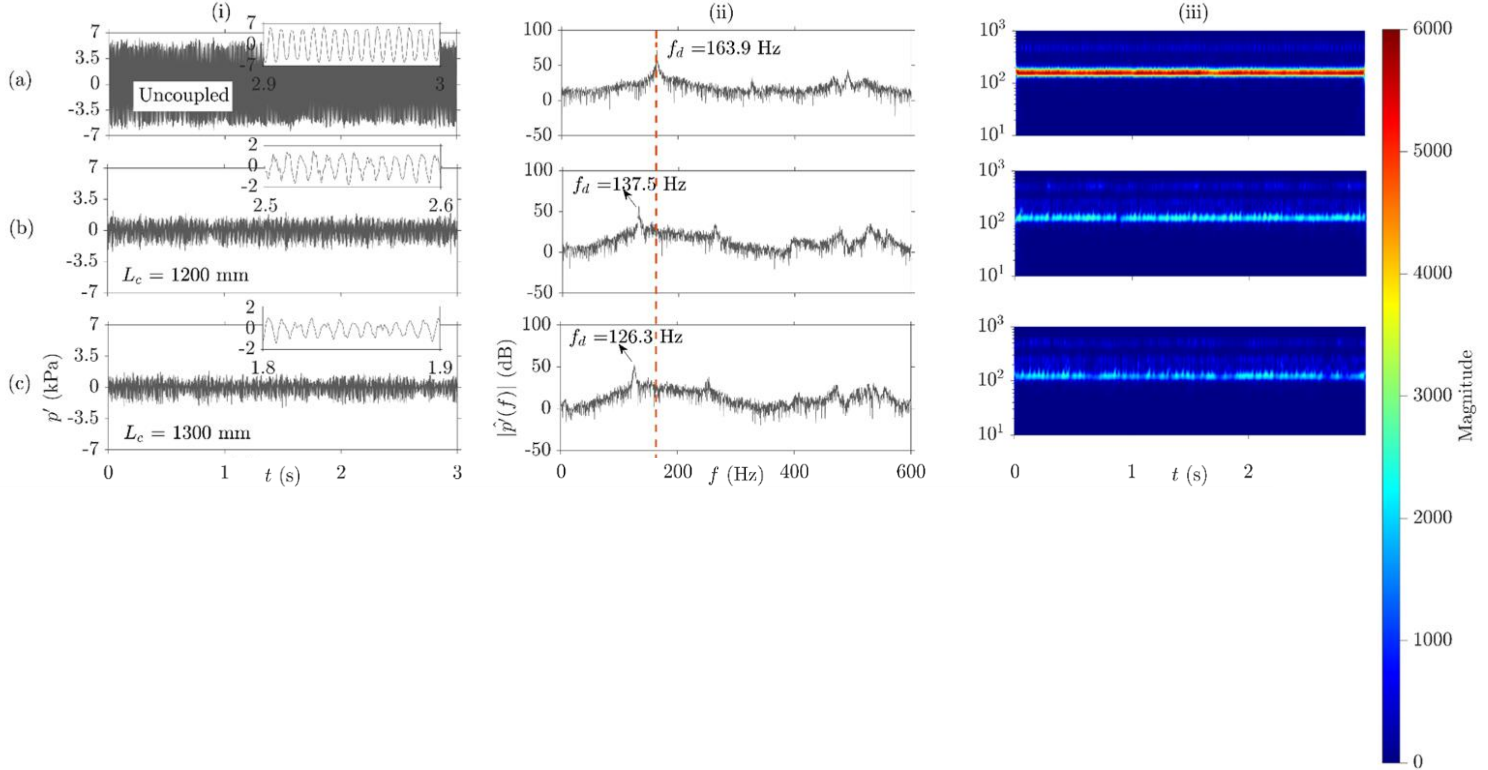
The dominant frequency corresponds to the acoustic frequency of the uncoupled combustor.

Transition through intermittency



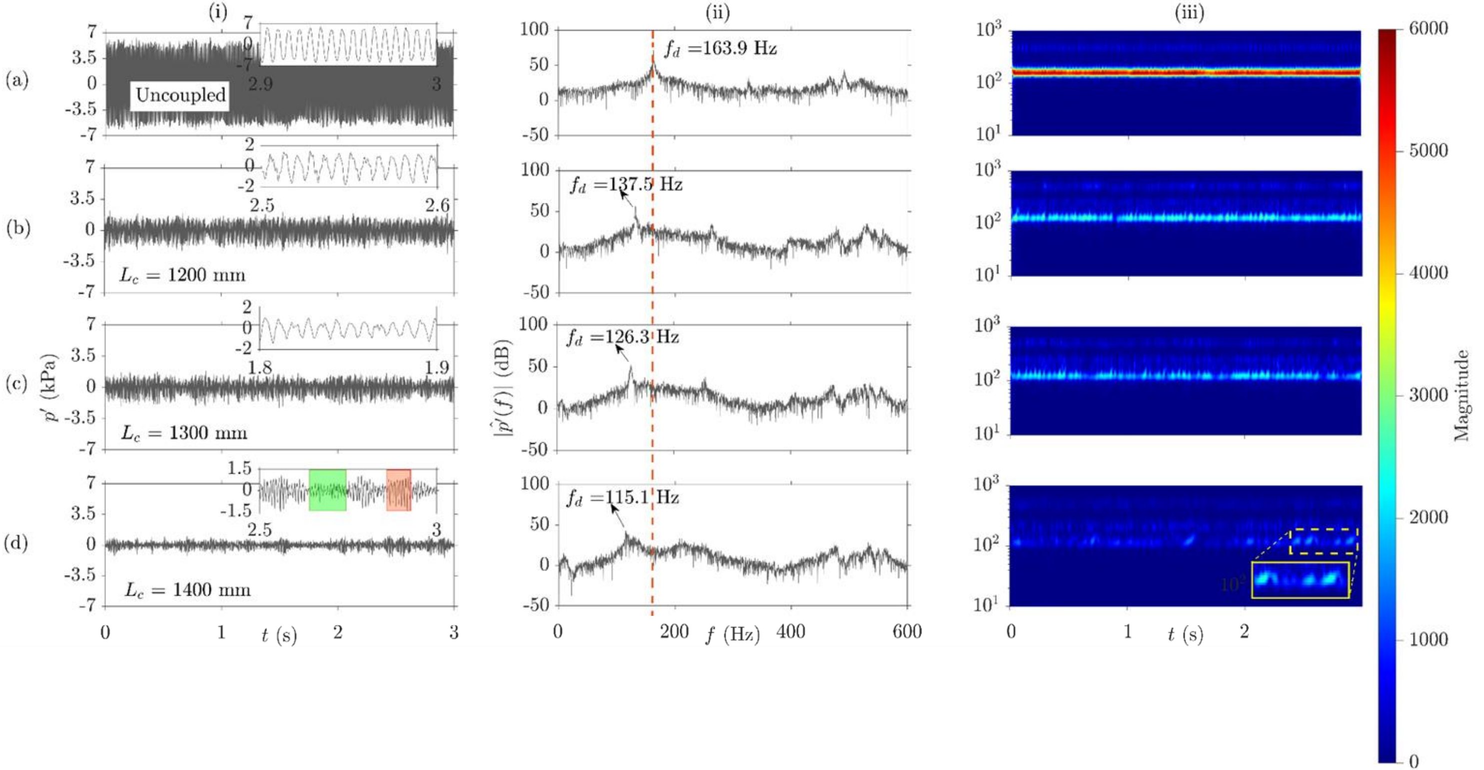
Introduction of self-coupling decreases the dominant frequency of the p' oscillations.

Transition through intermittency



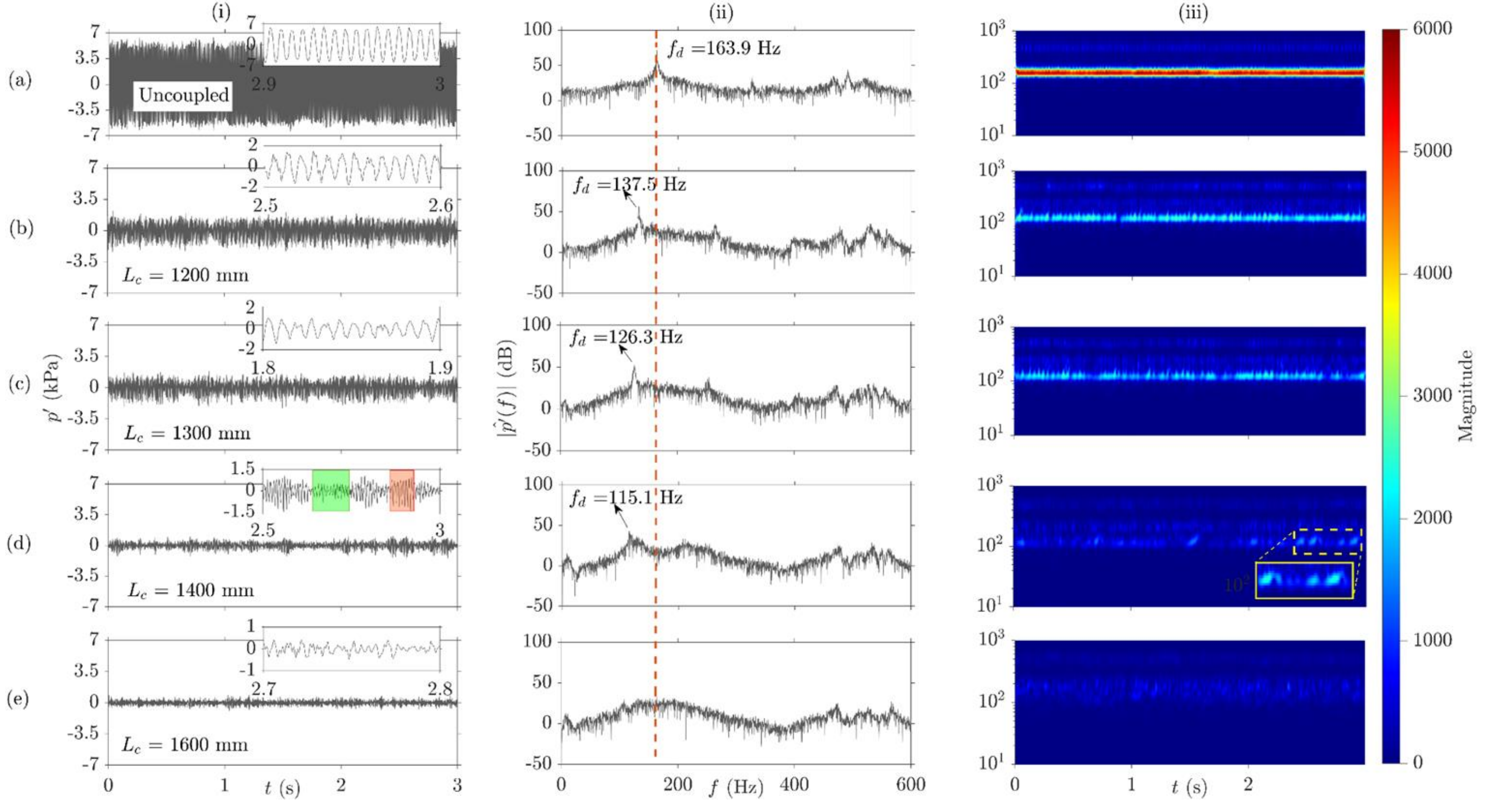
As the length of the self-coupling tube is increased, the dominant frequency of p' oscillations continue to decrease.

Transition through intermittency



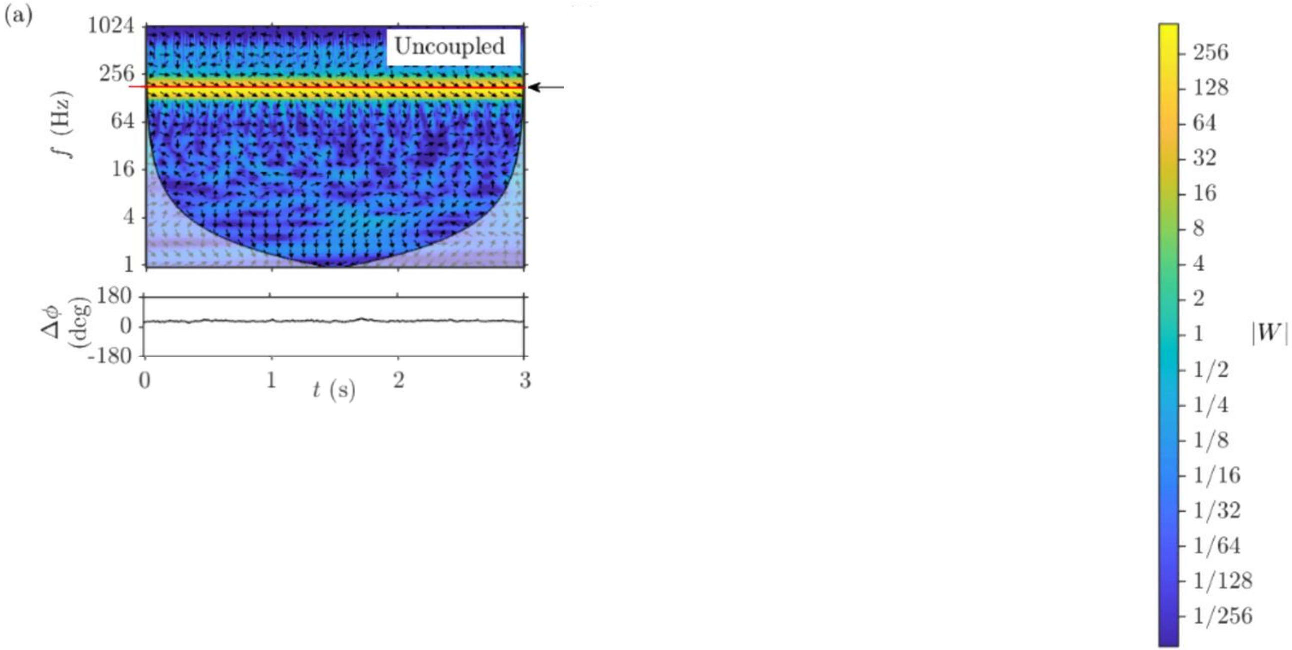
Intermittency is observed as the length of the self-coupling tube is increased.

Transition through intermittency



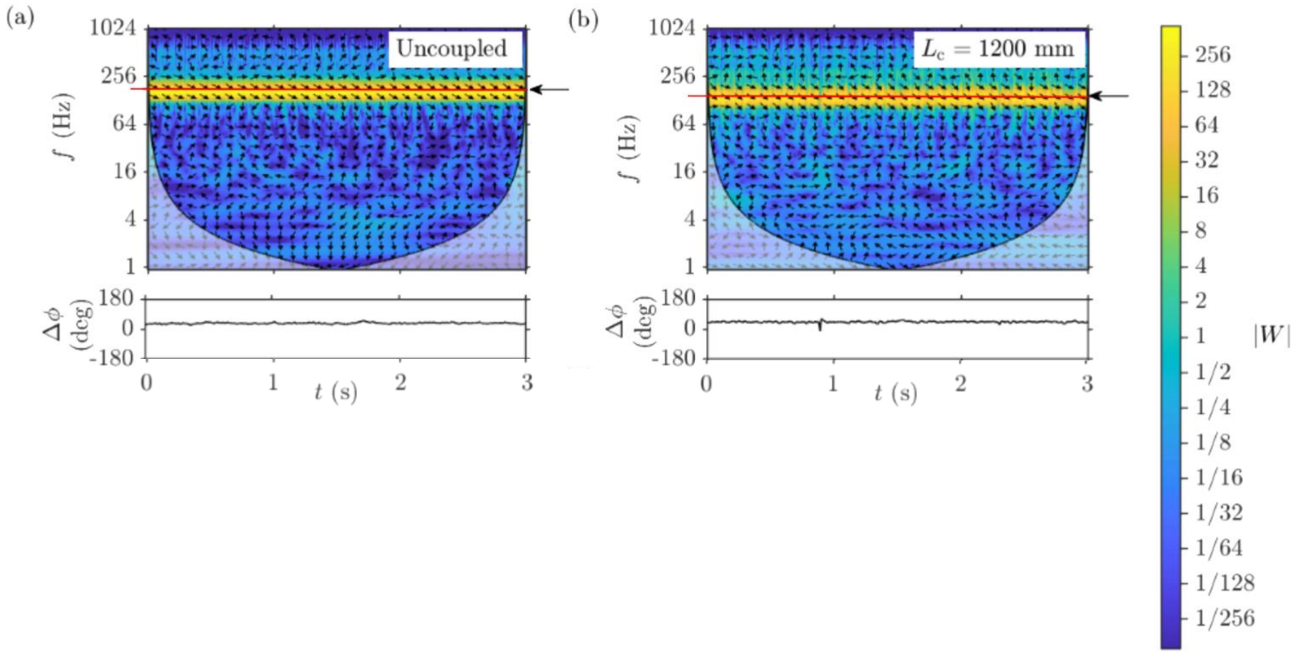
Maximum suppression is observed at $L_c = 1600$ mm.

Coupled behaviour of p' and $\dot{q}'$ oscillations



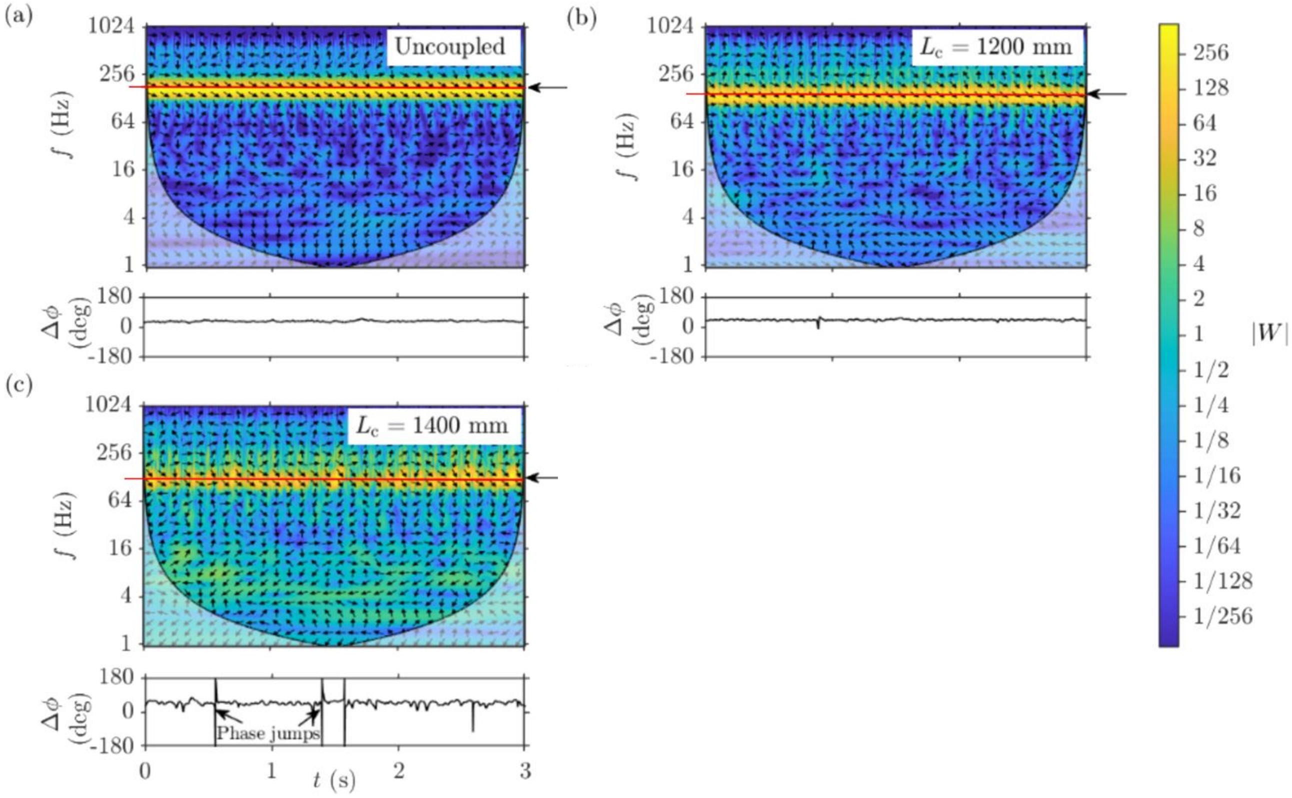
Phase synchronization between p' and $\dot{q}'$ exists during the state of thermoacoustic instability.

Coupled behaviour of p' and $\dot{q}'$ oscillations



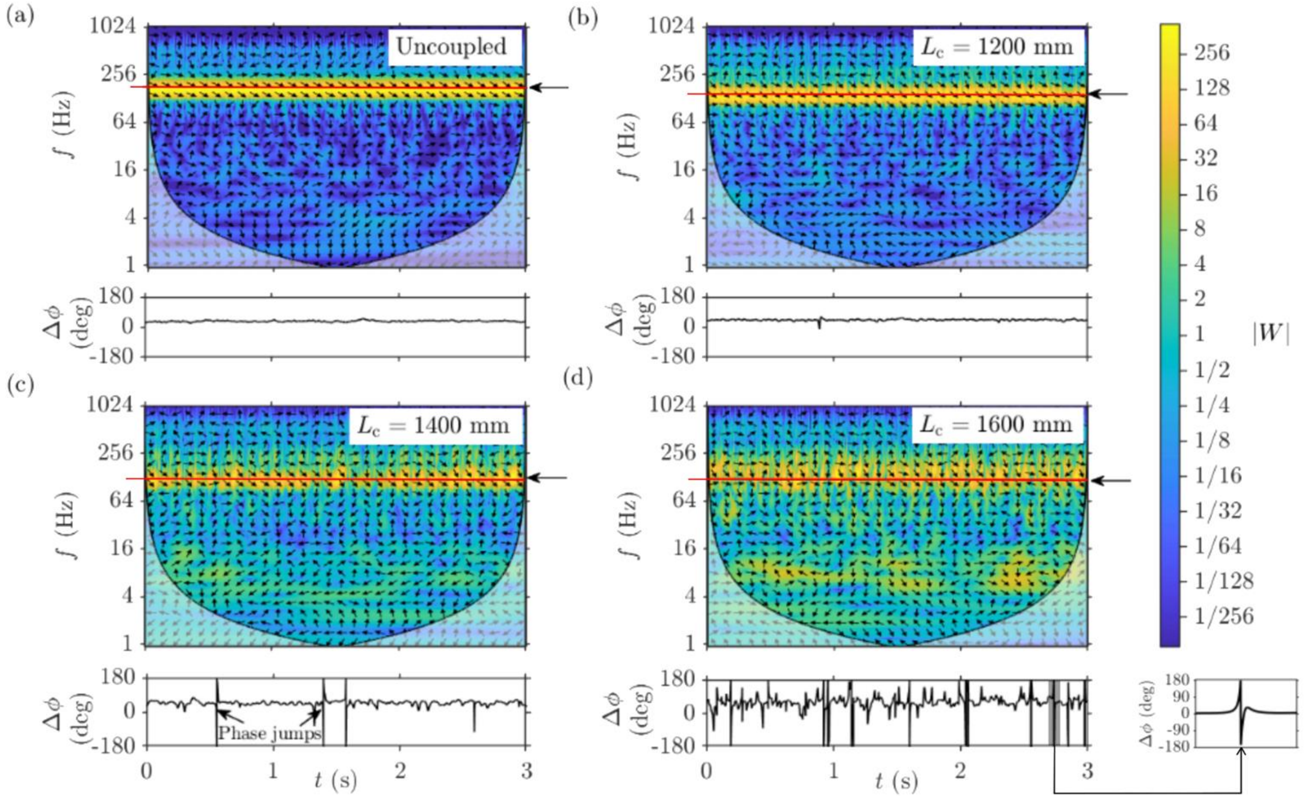
Phase synchronization between p' and $\dot{q}'$ exists for coupling under low values of coupling tube length.

Coupled behaviour of p' and $\dot{q}'$ oscillations



Discontinuities in the common frequency band of p' and $\dot{q}'$ oscillations as the length of self-coupling tube is increased.

Coupled behaviour of p' and $\dot{q}'$ oscillations



Increase in discontinuities in the common frequency band of p' and $\dot{q}'$ oscillations during maximum suppression.

Acoustic power sources and sinks

$$\int p'(t)\dot{q}'(x,y,t)$$

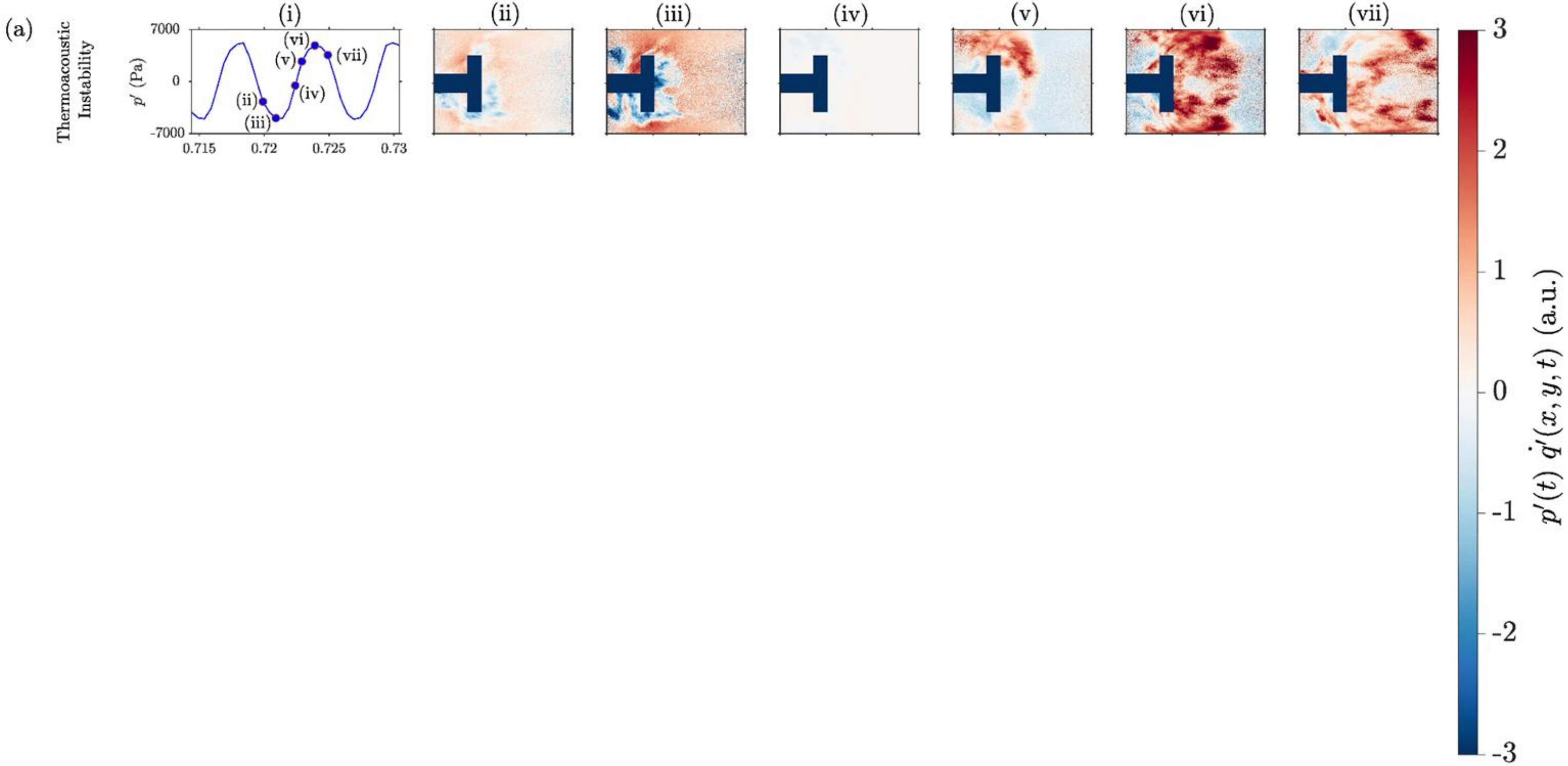
> 0 Acoustic power sources

< 0 Acoustic power sinks

Acoustic power sources and sinks

$$\int p'(t)\dot{q}'(x,y,t) \begin{cases} > 0 & \text{Acoustic power sources} \\ < 0 & \text{Acoustic power sinks} \end{cases}$$

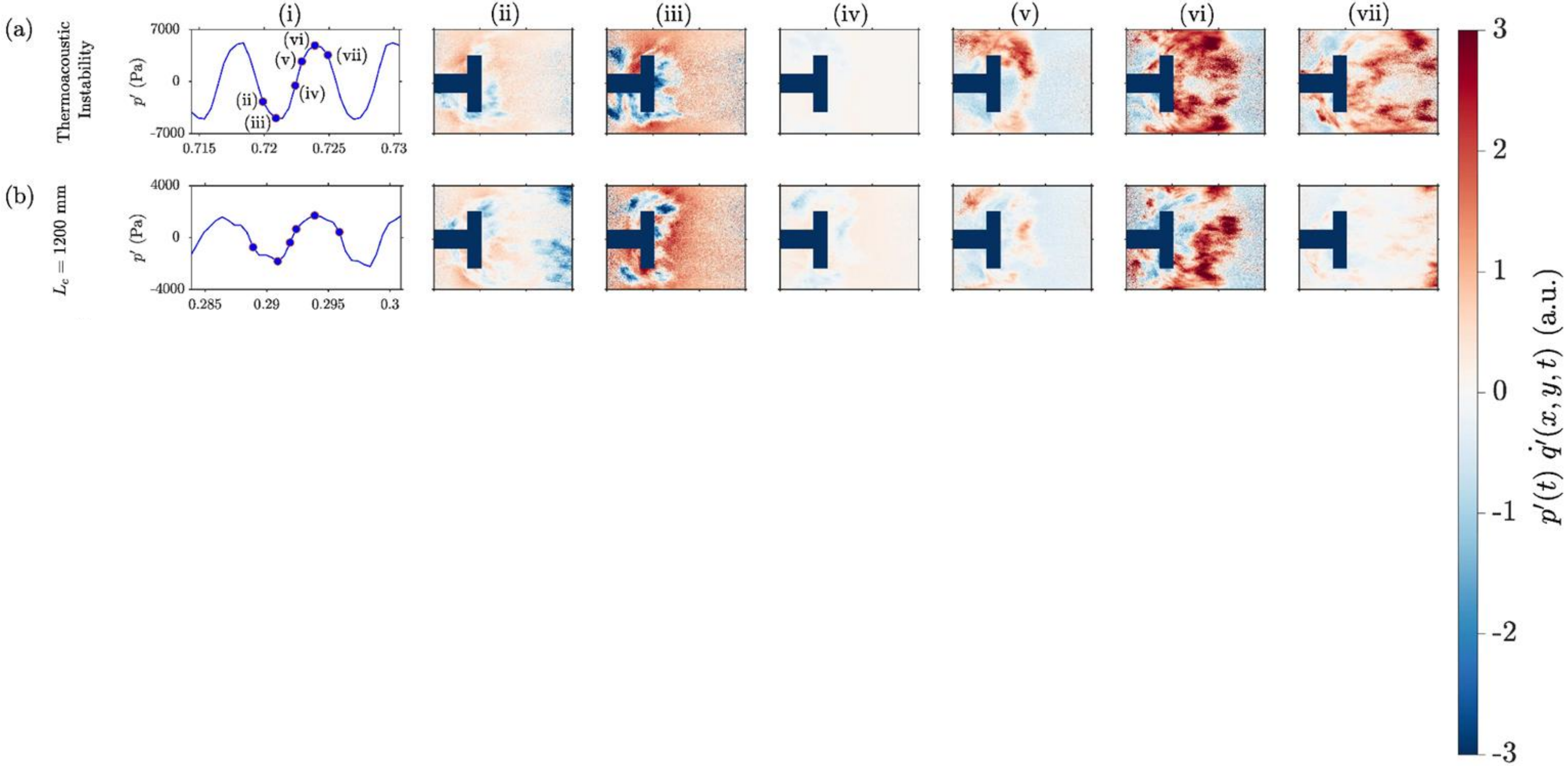
Acoustic power sources and sinks



Coherent production of acoustic power sources during thermoacoustic instability.

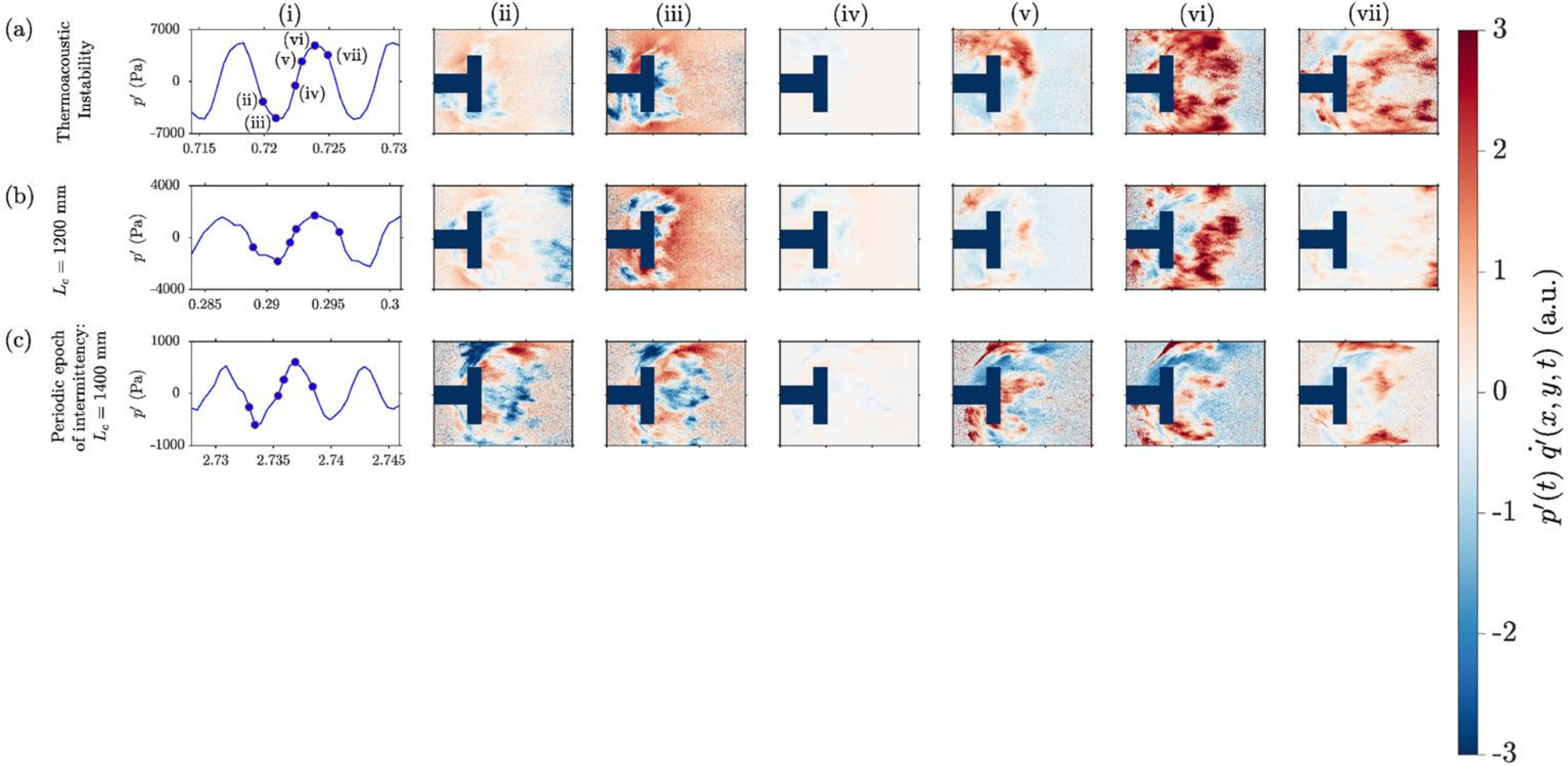
Third International Nonlinear Dynamics Conference

Loss of acoustic power structures



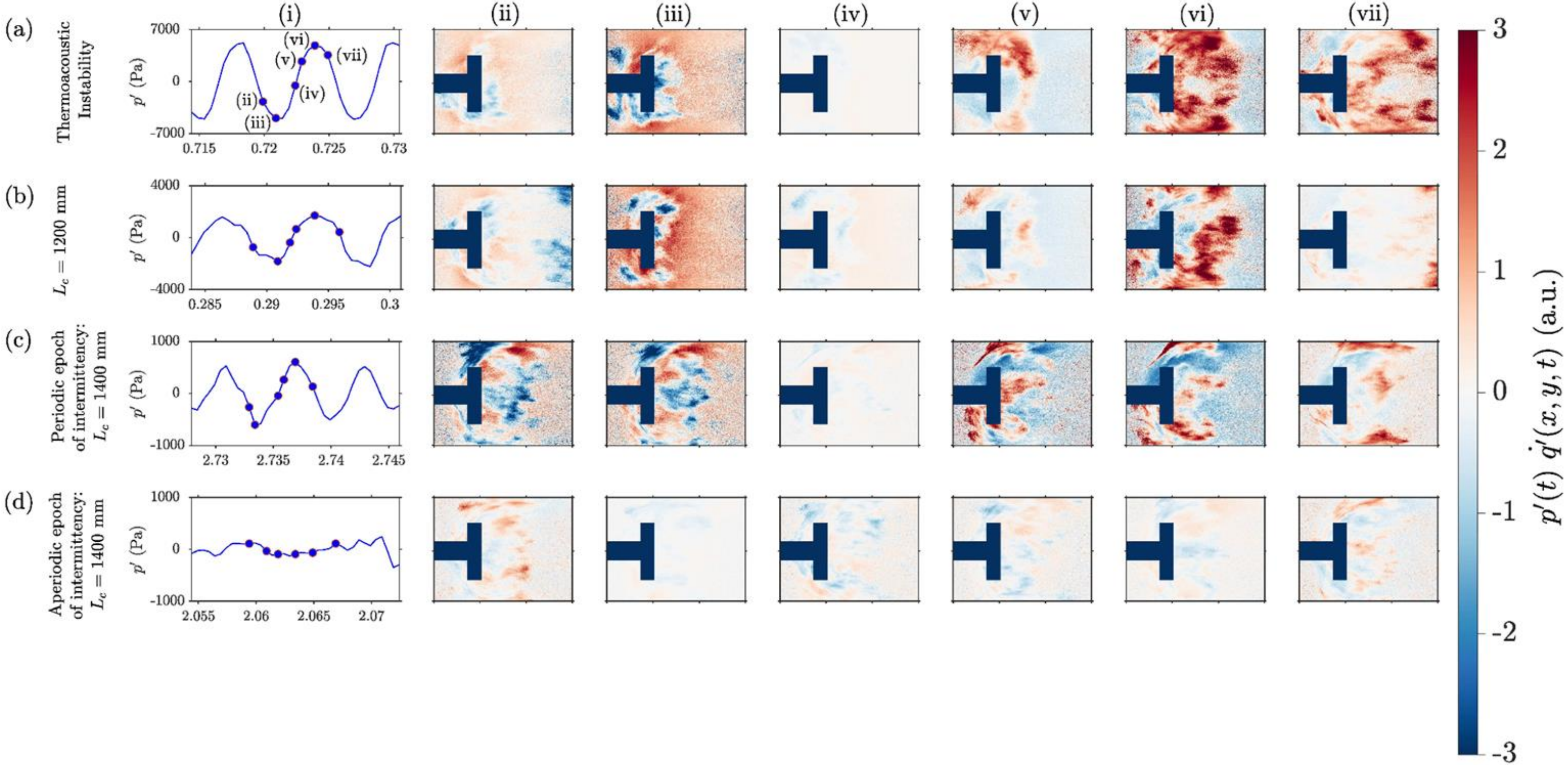
High spatial coherence of acoustic power sources during low values of self-coupling tube length.

Loss of acoustic power structures



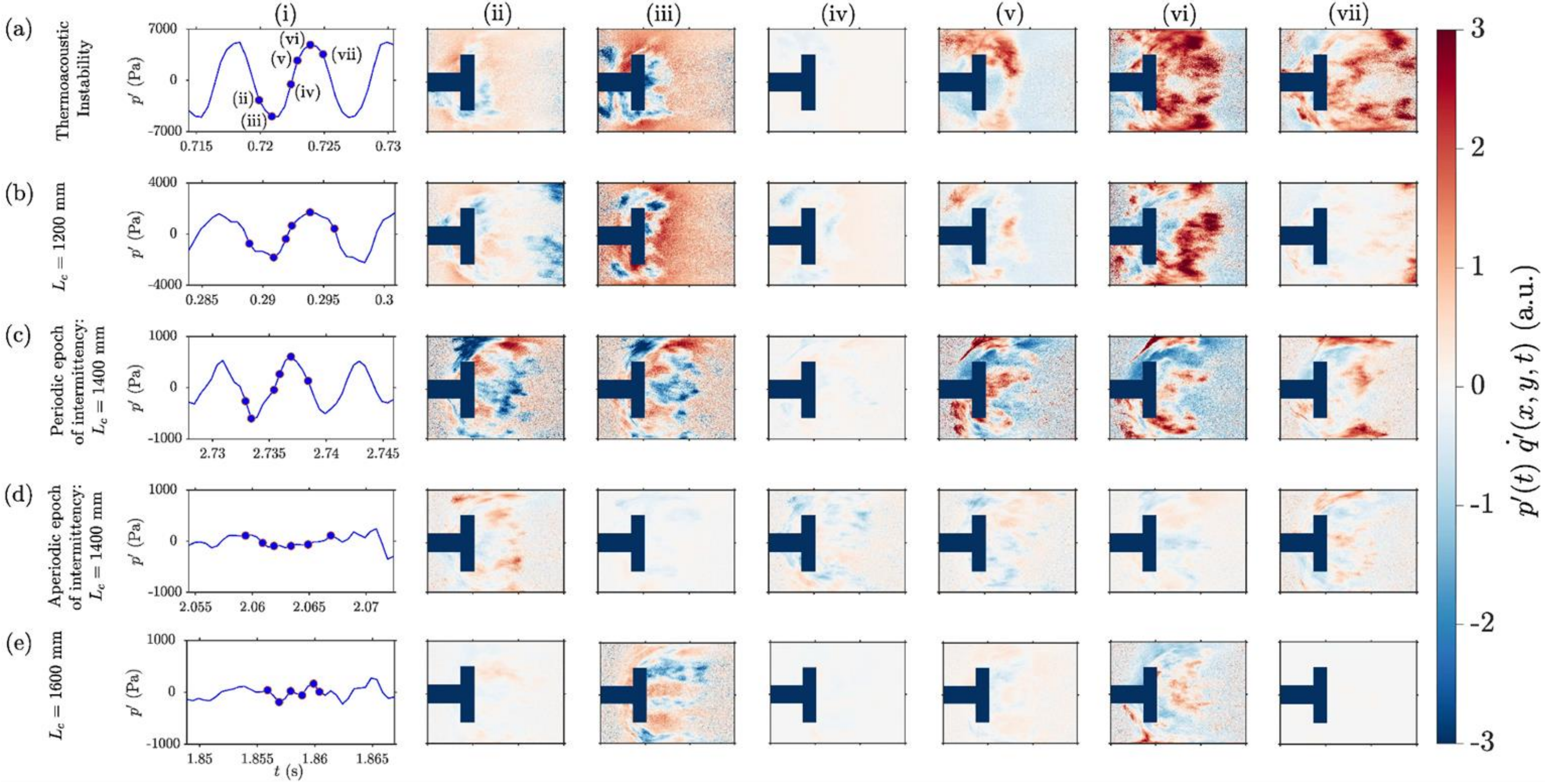
High spatial coherence of acoustic power sources exists during periodic epochs of intermittency.

Loss of acoustic power structures



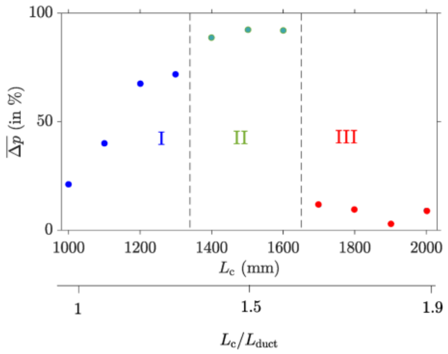
Small scale patches of acoustic power sources during the aperiodic epoch of intermittency.

Loss of acoustic power structures



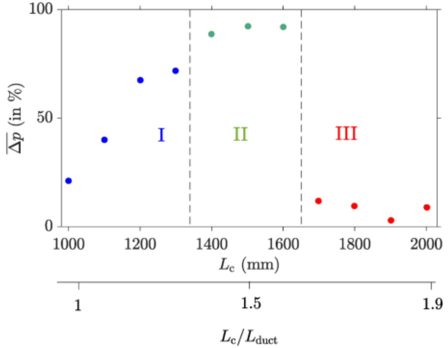
Spatial distribution of acoustic power sources is disordered and granular in nature during maximum suppression.

Summary

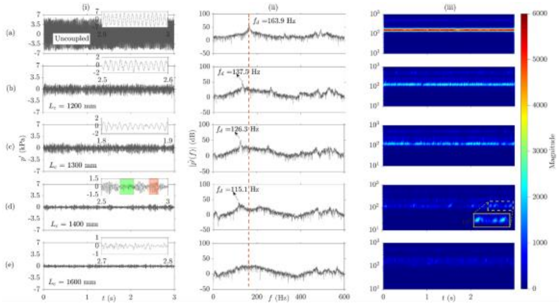


Suppression of thermoacoustic instability

Summary

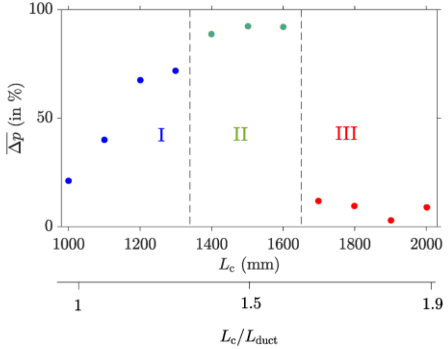


Suppression of thermoacoustic instability

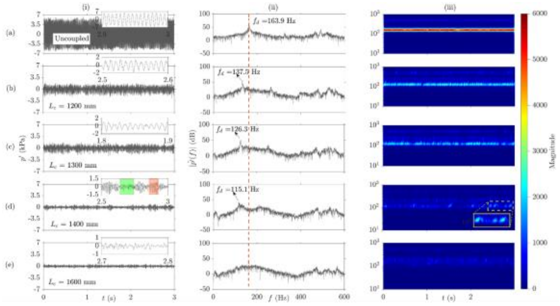


Transition through intermittency

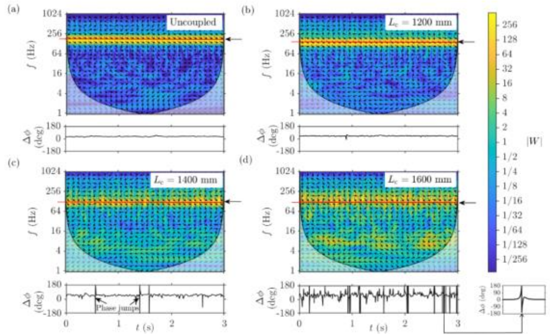
Summary



Suppression of thermoacoustic instability

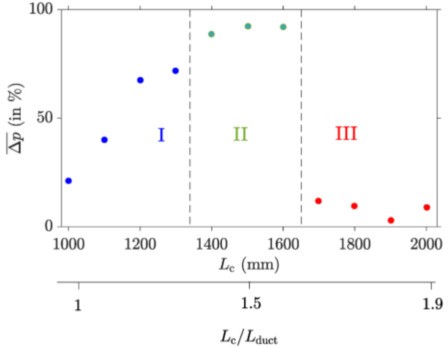


Transition through intermittency

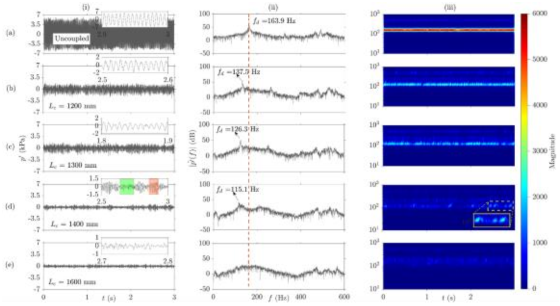


Coupled behaviour of p' and $\dot{q}'$ oscillations

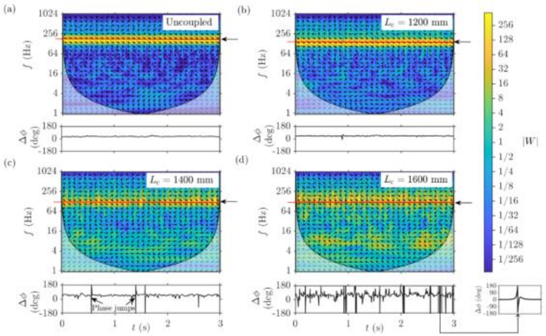
Summary



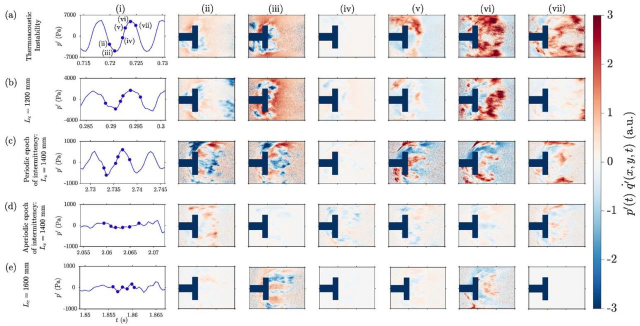
Suppression of thermoacoustic instability



Transition through intermittency

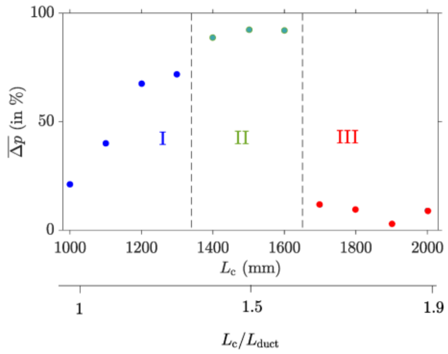


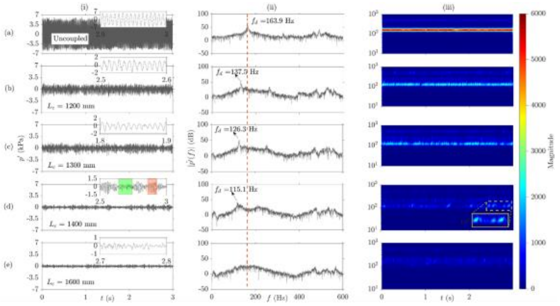
Coupled behaviour of p' and $\dot{q}'$ oscillations



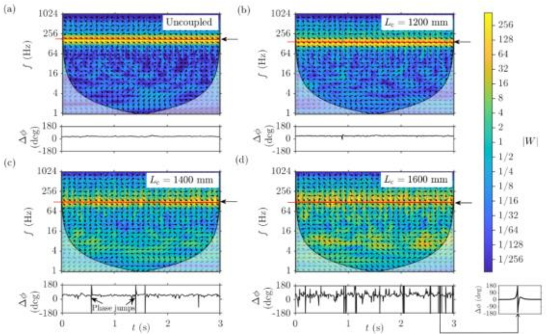
Spatial distribution of acoustic power sources and sinks

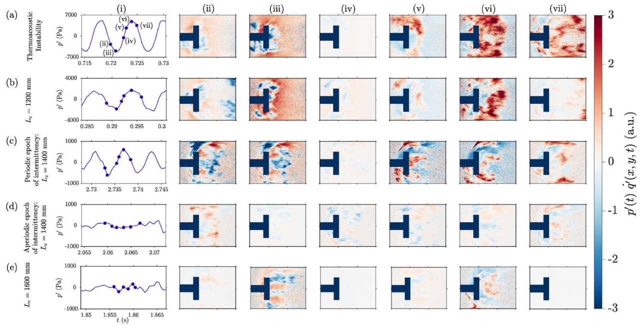
Summary





The results are published in Sahay, A., Kushwaha, A., Pawar, S. A., Midhun P. R., Dhadphale, J. M., Sujith, R. I.; Mitigation of limit cycle oscillations in a turbulent thermoacoustic system via delayed acoustic self-feedback. *Chaos* 1 April 2023; 33 (4): 043118.





Thank you!