Sustainable combustion technologies need acoustics research

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Overview

1. Introduction and background

2. Modelling combustion instabilities with the Green's function

3. Model predictions from my group – past and present

4. Conclusions

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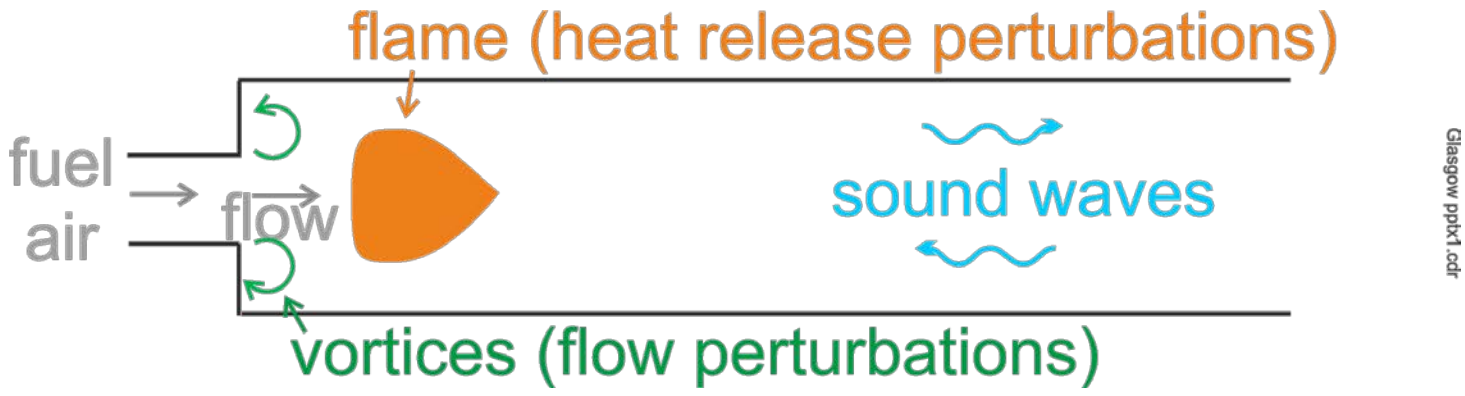
Sound plays a crucial role in combustion instabilities

Generic combustion system



Flames interact with sound → thermoacoustic instability

demo: Rijke tube

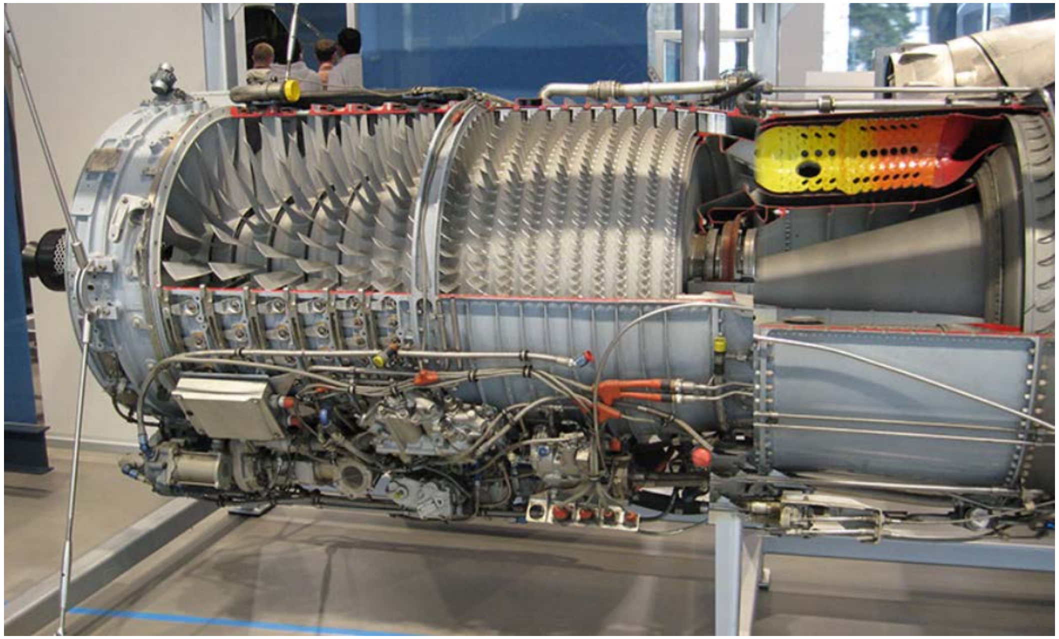
Flow perturbations interact with sound → aeroacoustic instability

demo: orifice tube

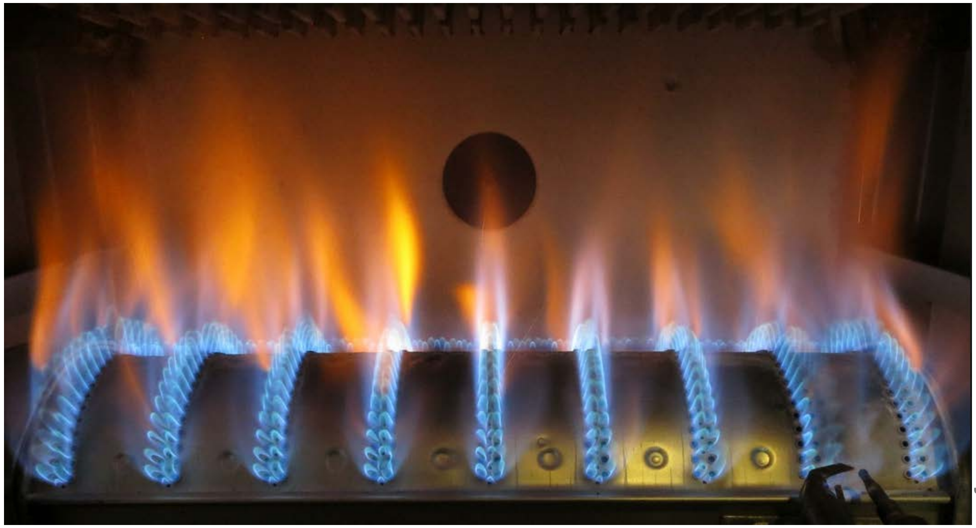
Multiple interactions with sound → combustion instability

Where do combustion instabilities occur?

gas turbine
engines



boilers



from:
https://greenflame.london/gas-certificate-london/gas-flame/

Where do combustion instabilities occur?

from: www.thermaltechengg.com/company-profile.html

from: www.bgr.in/news/nasa-sends-three-smartphones-into-space-to-use-them-as-low-cost-satellites

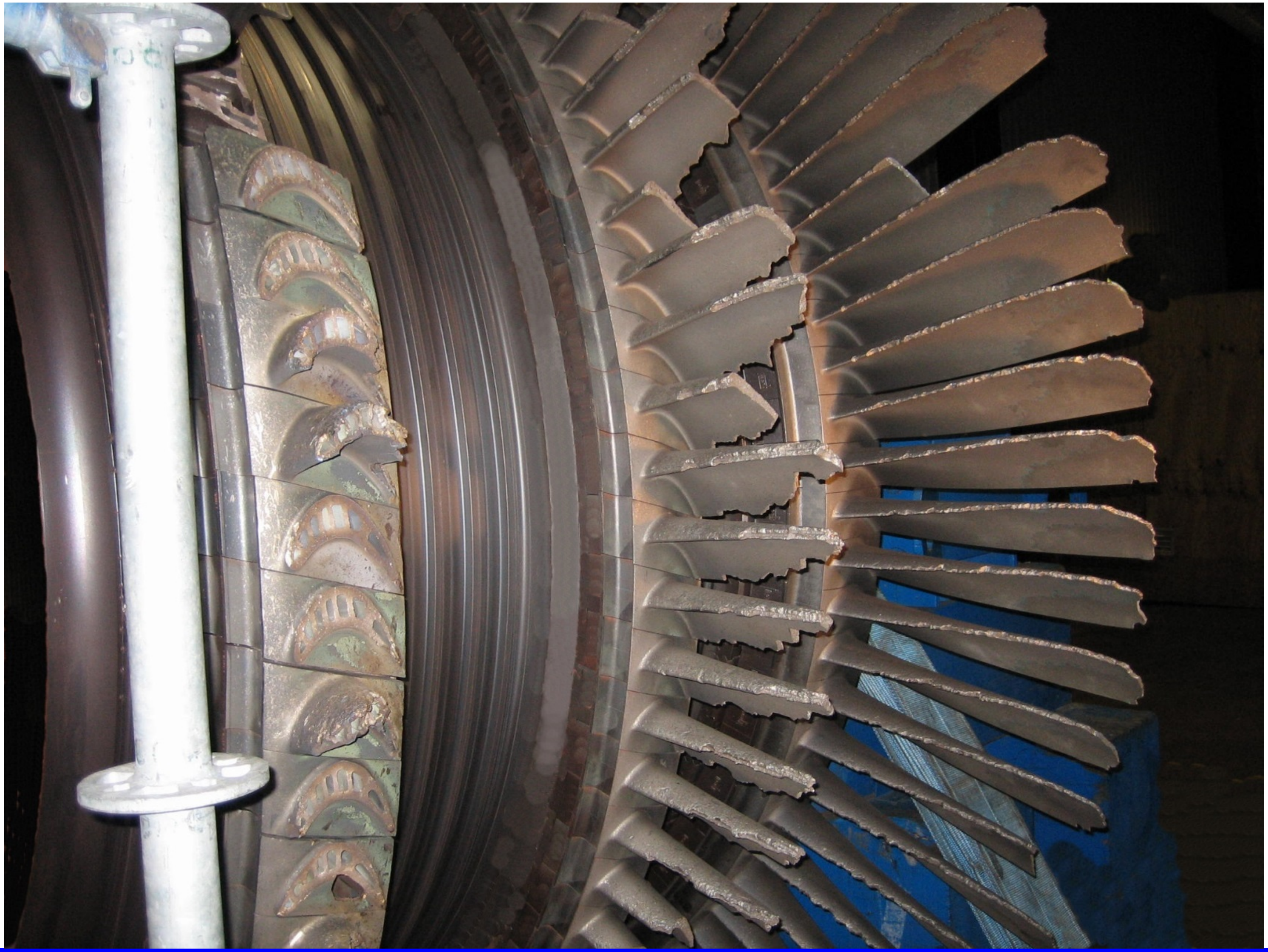
furnaces

rockets

Combustion instabilities can occur whenever there is a continuously burning flame in a cavity.

Combustion instabilities can be destructive

Gas turbine damaged by a combustion instability



Instabilities tend to occur without warning

Possible triggers of a combustion instability:

- wear and tear over a long time
- noise
- change in ambient temperature
- other unknown factors …

Generally:
some change in condition – even a tiny change!

Low-pollution combustion systems are susceptible to combustion instabilities

Reduced-pollution combustion technologies

- use lean premixed flames
- burn at low temperatures
- use hydrogen-blend fuels

Zero-carbon combustion technologies

- use carbon-free fuels (hydrogen, ammonia)
- use biofuels

Benefits
- minimise CO_2 production
- minimise NO_x production

Problems
- risk of combustion instabilities
- flame flashback (for hydrogen)

Combustion systems and instability control strategies need to be re-designed for carbon-free fuels

What is a premixed flame?

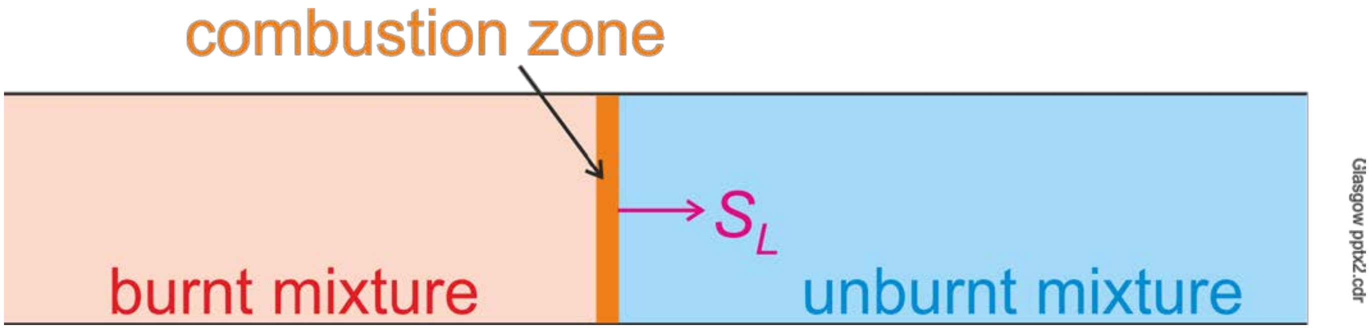
Flame: visible part of an exothermic chemical reaction

fuel + oxidizer → combustion products + light

Premixed flame

- fuel and oxidizer are mixed prior to combustion
- combustion takes place in a thin interface

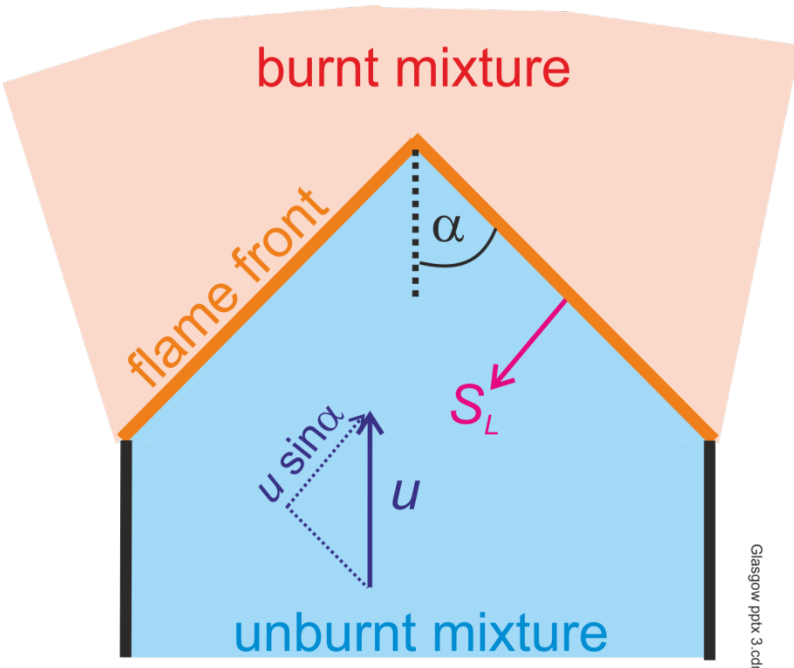
Flame sheet in a stationary premix



S_L: laminar flame speed, depends on:

- fuel type
- fuel/oxidizer ratio

Bunsen-burner flame in a uniform velocity field



S_L: laminar flame speed

u : velocity of premix

α : half-angle of flame

kinematic balance:

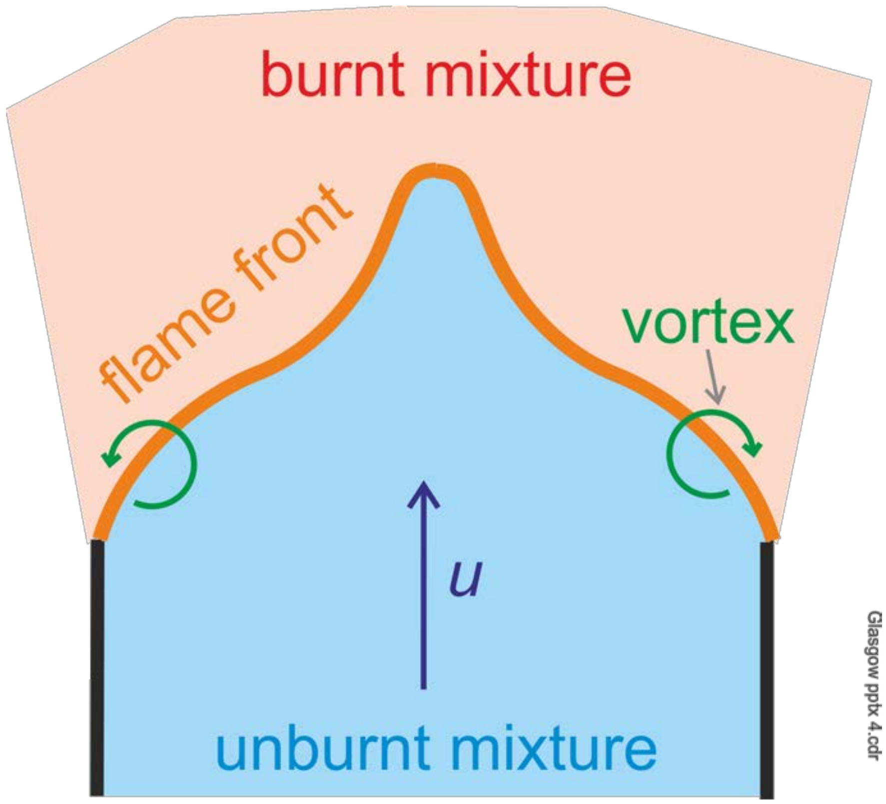
$$u \sin\alpha = S_L$$

A stationary flame adjusts its angle to the velocity ratio $\dfrac{S_L}{u}$.

increase in S_L $\rightarrow$ increase in α $\rightarrow$ flame becomes flatter

increase in u $\rightarrow$ decrease in α $\rightarrow$ flame becomes longer

Bunsen-burner flame in a vorticity field



flame surface area ~ heat release rate

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Outline of mathematical modelling approach

Separate combustion system into two elements:

combustion system = acoustic resonator + unsteady flame

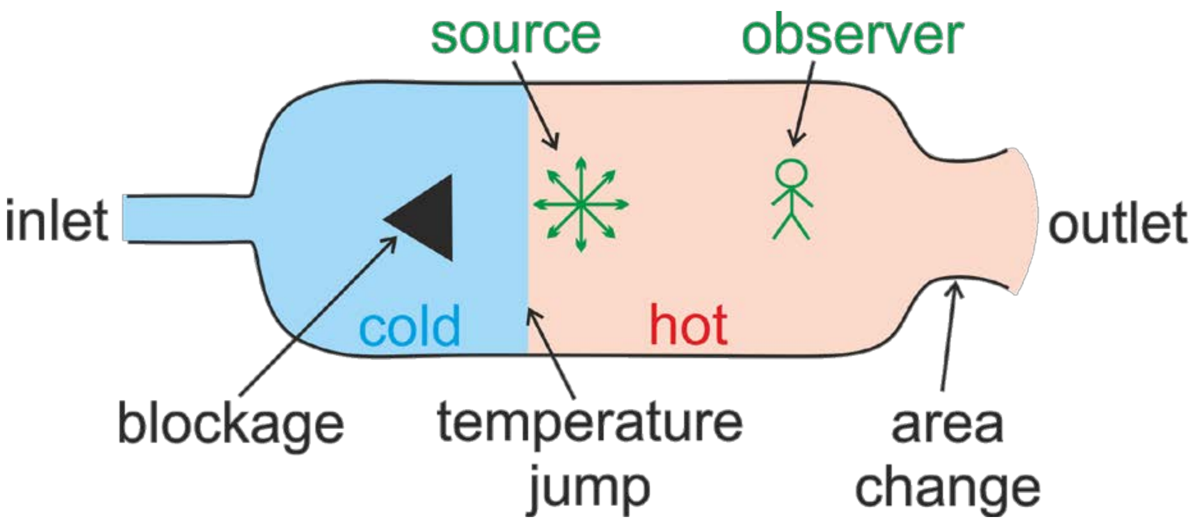
Acoustic resonator:
modelled by tailored Green's function

Unsteady flame:
modelled by amplitude-dependent transfer function

The two elements are then combined by a Green's function approach

The tailored Green’s function describes the acoustic resonator

Acoustic resonator and its tailored Green’s function



 pressure impulse, fired at point *x** and time *t**

 observer, measuring response at point *x* and time *t*

Physical name: impulse response of the resonator

Mathematical name: tailored Green's function

The tailored Green's function is a superposition of modes

General form of the tailored Green's function:

$$G(x,x^*,t-t^*) = \begin{cases} 0 & \text{before the impulse} \\ \sum_{n=1}^{\infty} g_n(x,x^*)\, e^{-i\omega_n (t-t^*)} & \text{after the impulse} \end{cases}$$

Green's function amplitudes

eigenfrequencies of acoustic resonator

Superposition of modes *n*

$g_n(x,x^*)$ and ω_n can be

- calculated analytically for quasi-1D geometries
- measured for any geometry

Flame response in the frequency domain

input: $\bar{u} + \hat{u}(\omega)e^{-i\omega t}$ $\longrightarrow$ flame $\mathcal{T}(\omega)$ $\longrightarrow$ output: $\bar{Q} + \hat{Q}(\omega)e^{-i\omega t}$

Flame transfer function: $\mathcal{T}(\omega) = \dfrac{\hat{Q}(\omega)/\bar{Q}}{\hat{u}(\omega)/\bar{u}}$

velocity amplitude

Flame describing function: $\mathcal{T}(\omega, A) = \dfrac{\hat{Q}(\omega, A)/\bar{Q}}{\hat{u}(\omega)/\bar{u}}$

$\mathcal{T}(\omega, A)$ can be

- calculated analytically for linear laminar flames
- calculated numerically (low effort) from level-set approach
- calculated numerically (high effort) from combustion CFD
- measured for many flames

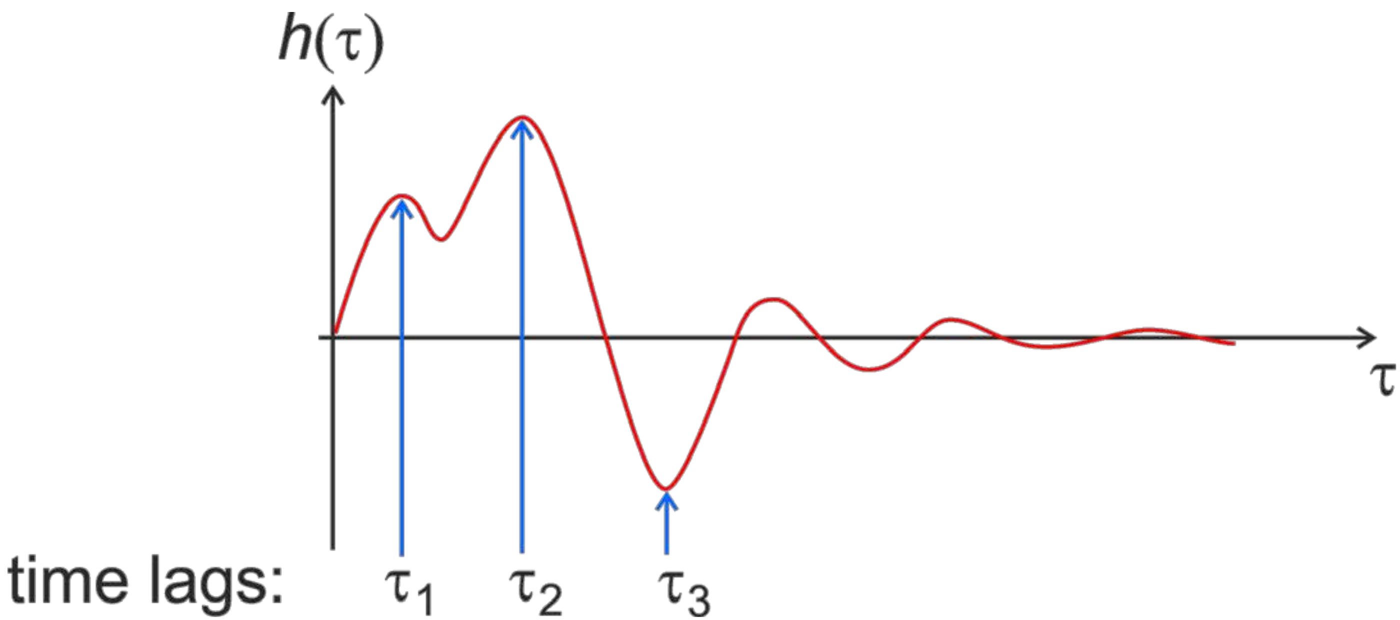
Flame response in the time domain

frequency domain $\xrightarrow[\text{Fourier transform}]{\text{inverse}}$ time domain

$$\frac{\hat{Q}(\omega)}{\bar{Q}} = \mathcal{T}(\omega)\frac{\hat{u}(\omega)}{\bar{u}} \longrightarrow \frac{Q'(t)}{\bar{Q}} = \int_0^t h(\tau)\frac{u'(t-\tau)}{\bar{u}}\,\mathrm{d}\tau$$

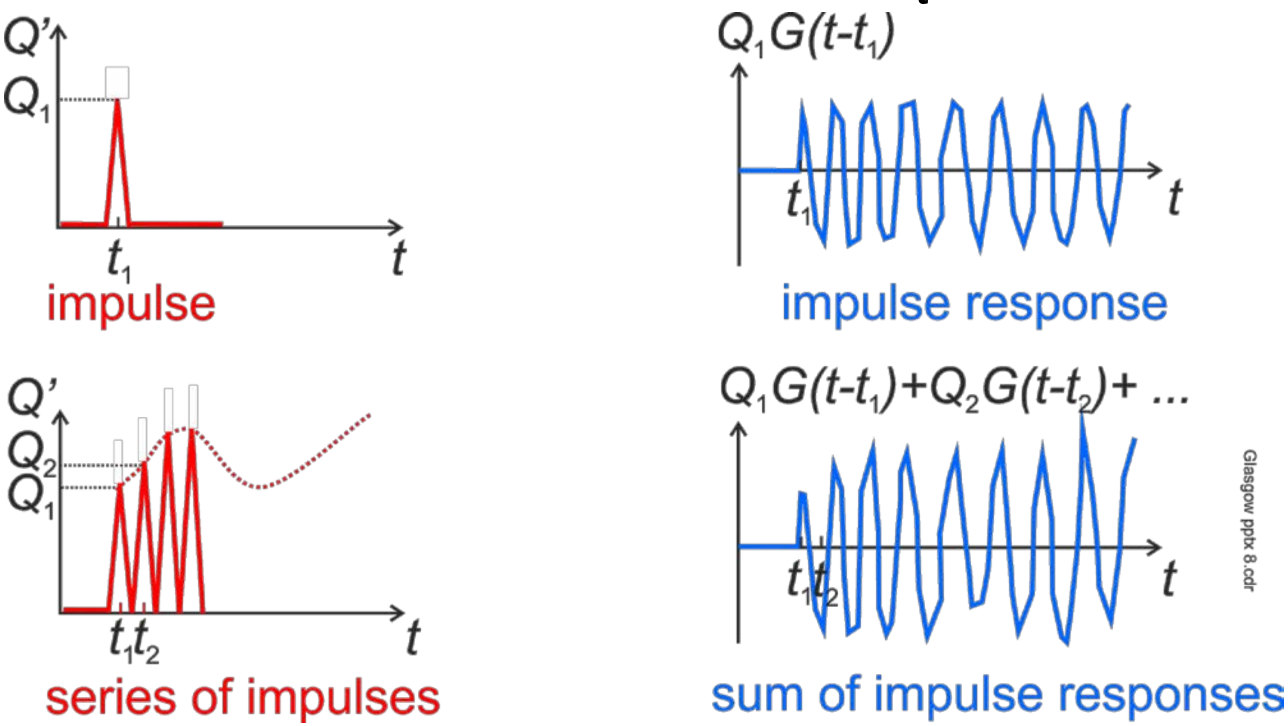
impulse response

typical result for a flame's impulse response:



Green's function approach combines resonator and flame

Governing integral equation: $u_q'(t) = \int_{t^*} Q'(t^*)G(t-t^*)\,\mathrm{d}t^*$



Iteration to find time history of $u_q'(t), Q'(t)$

$$u_q'(t+\Delta t) = \int_{t^*}^{t} Q'(t^*)G(t-t^*)\,\mathrm{d}t^* \longrightarrow Q'(t+\Delta t) = \mathcal{F}(u_q'(t+\Delta t))$$

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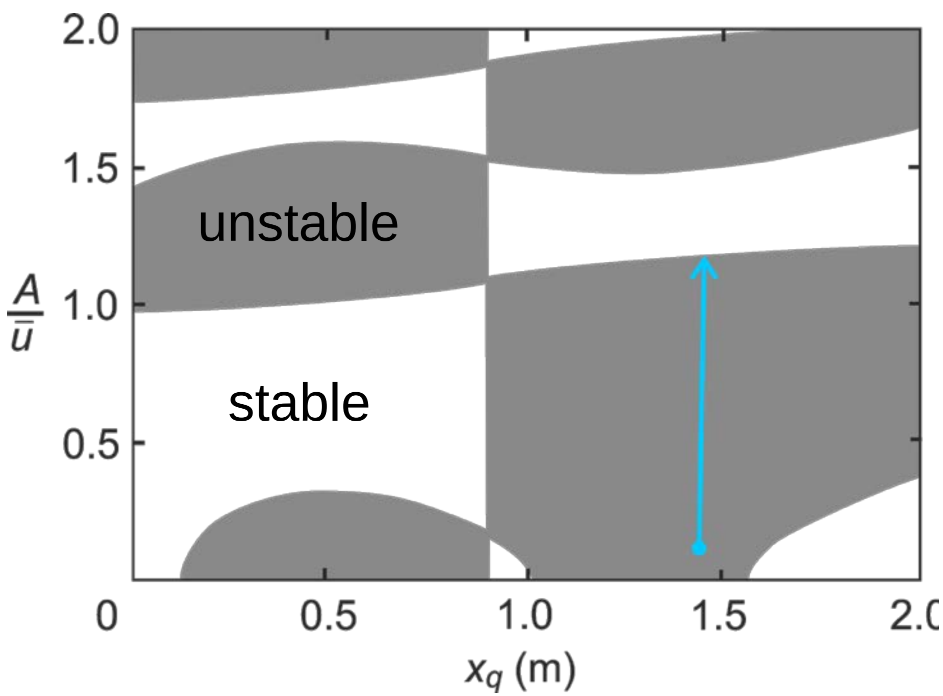
Prediction of limit cycle amplitude and hysteresis with Alessandra Bigongiari

Acoustic resonator: tube with open ends

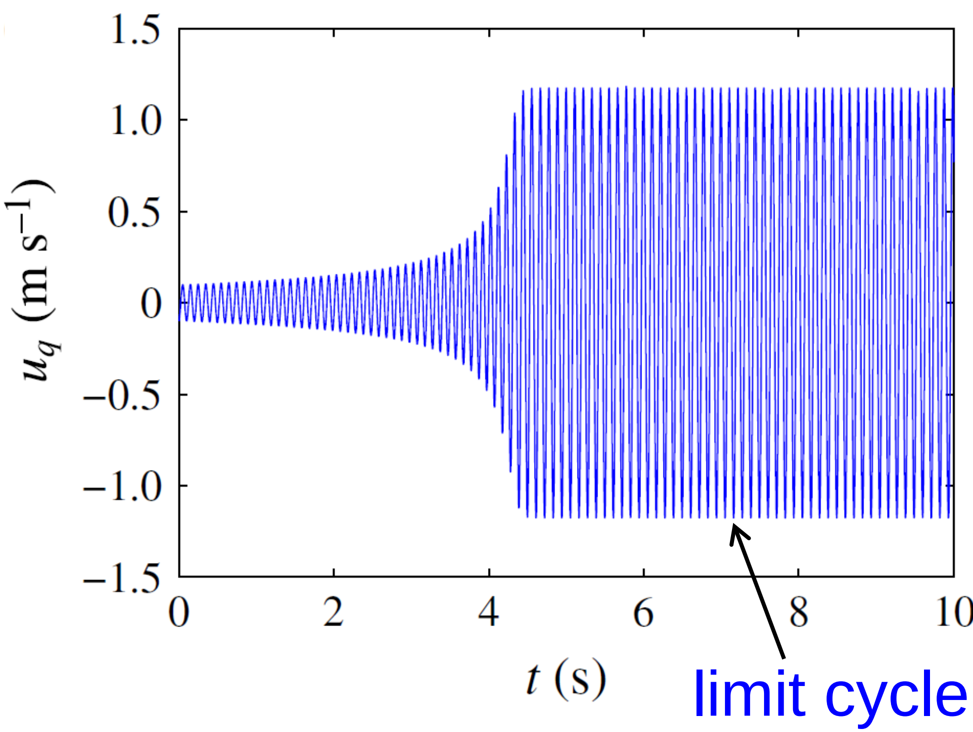
amplitude-dependent

Flame: described by nonlinear time-lag law $\dfrac{Q'(t)}{\overline{Q}} = n_1 \dfrac{u_q'(t-\tau)}{\overline{u}} - n_0 \dfrac{u_q'(t)}{\overline{u}}$

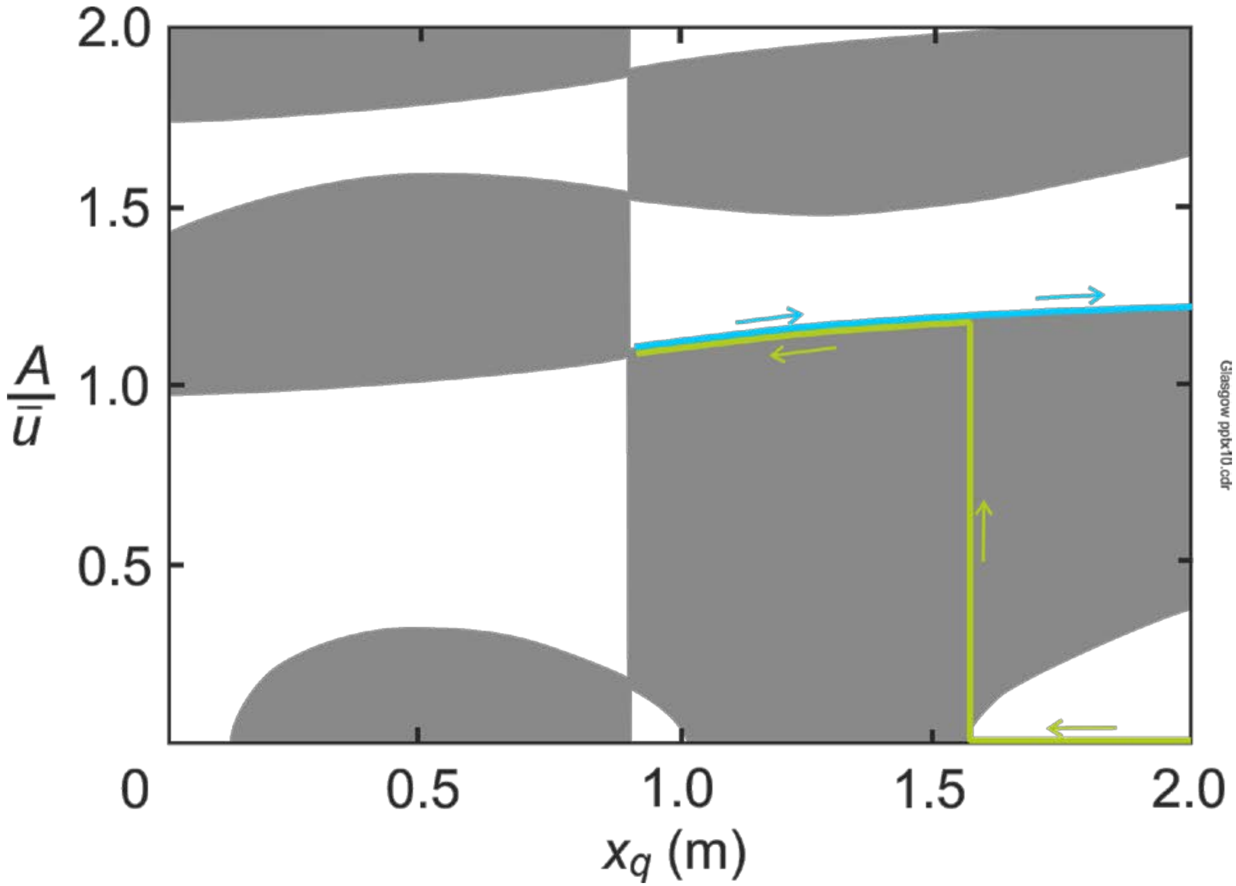
stability map



time history at $x_q = 1.47\,\text{m}$



Prediction of limit cycle amplitude and hysteresis with Alessandra Bigongiari



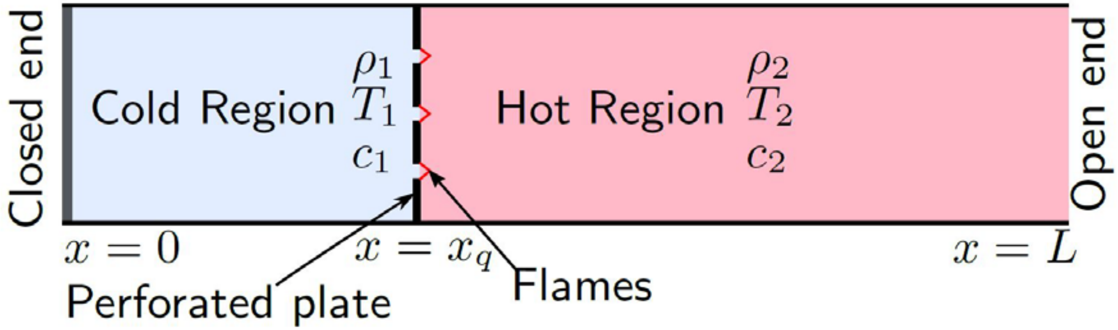
backward path

forward path

different → hysteresis

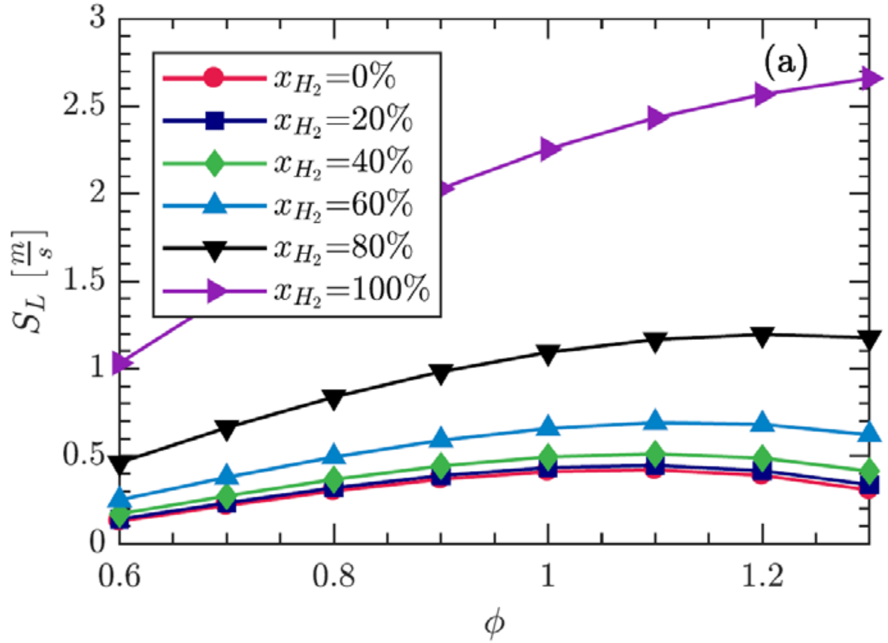
further details in: Bigongiari, A. & Heckl, M.A. (2016) A Green's function approach to the rapid prediction of thermoacoustic instabilities in combustors. *Journal of Fluid Mechanics* 798, 970-996.

Acoustic resonator:



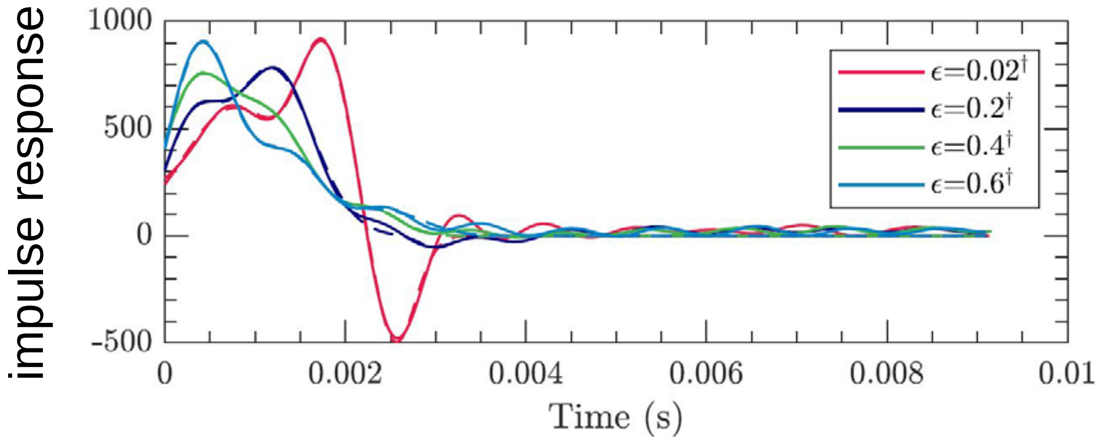
Flame:

H_2 - enriched methane flame with laminar flame speed S_L depending on equivalence ratio ϕ and H_2-concentration x_{H2}

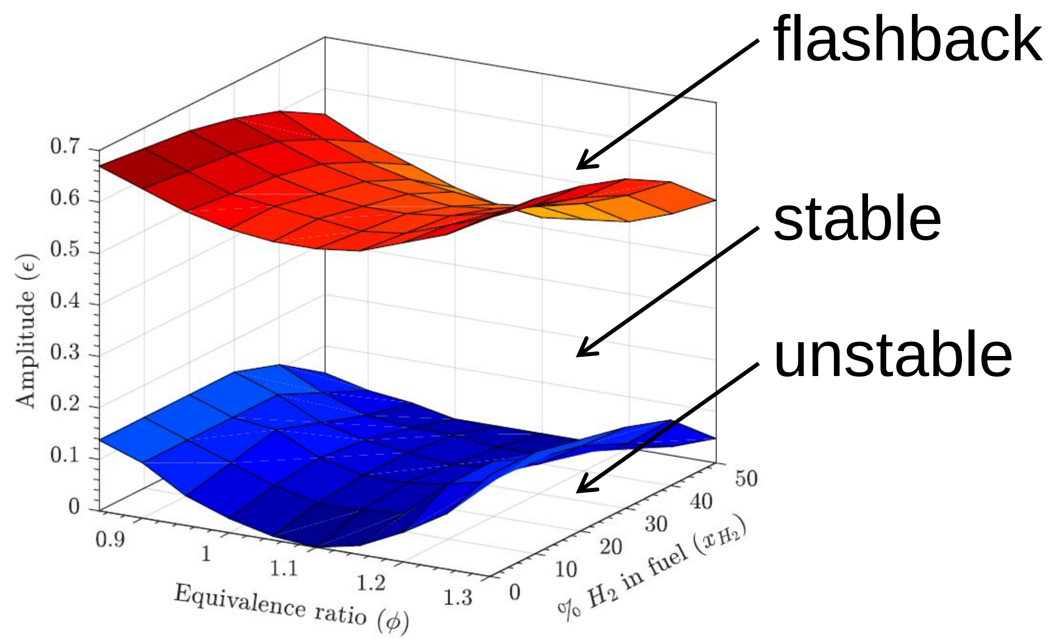


S_L increases dramatically at high H_2 concentrations

Impulse response of flame



3-D map for stability and flashback

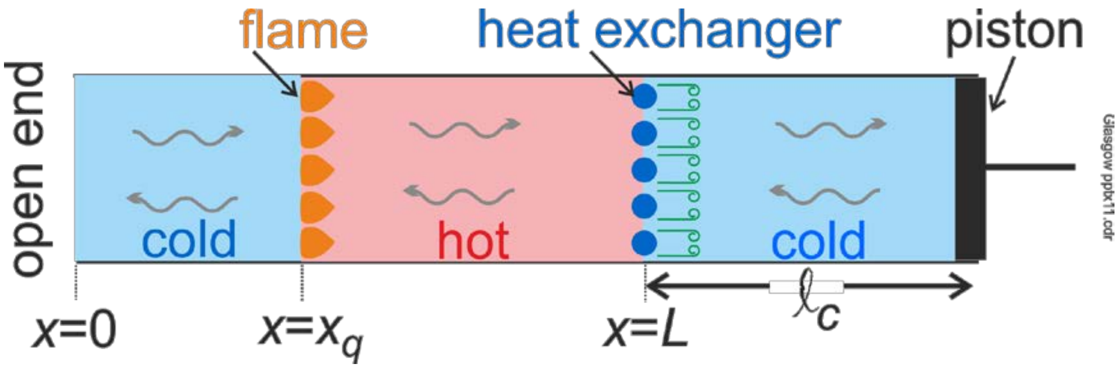


further details in:

Gopinathan, S.M., Surendran, A. & Heckl, M.A. (2021) Effect of equivalence ratio on stability and flashback of combustion systems using hydrogen-blended fuels. *Proceedings of the Symposium on Thermoacoustics in Combustion: Industry meets Academia (SoTiC 2021), Munich, Germany, 6-10 September 2021*

Passive instability control in a boiler with Aswathy Surendran

Acoustic resonator:



Flame:

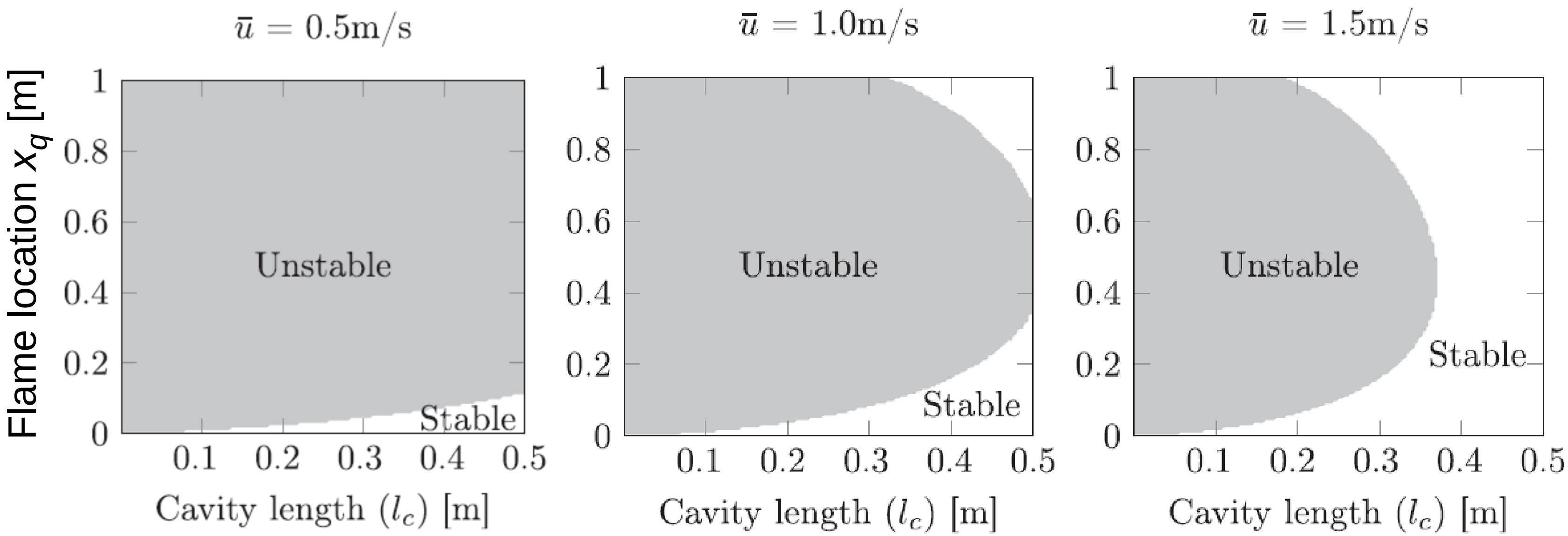
modelled by flame transfer function $$\frac{\hat{Q}(\omega)}{\bar{Q}} = n e^{i\omega\tau} \frac{\hat{u}_q(\omega)}{\bar{u}}$$

Heat exchanger: heat sink + sound scatterer

Heat sink
modelled in terms of heat transfer function, calculated by CFD

Sound scatterer
modelled in terms of scattering matrix, calculated analytically with quasi-steady approach

Variable parameters: cavity length ℓ_c
flame location x_q
mean flow velocity $\bar{u}$
temperature difference
tube spacing …



further details in: Surendran, A., Heckl, Maria, Hosseini, N. and Teerling, O.J. (2018) Passive control of instabilities in combustion systems with heat exchanger. International Journal of Spray and Combustion Dynamics, Vol. 10(4), pp. 362-379.

Effects of noise on instabilities with Sadaf Arabi

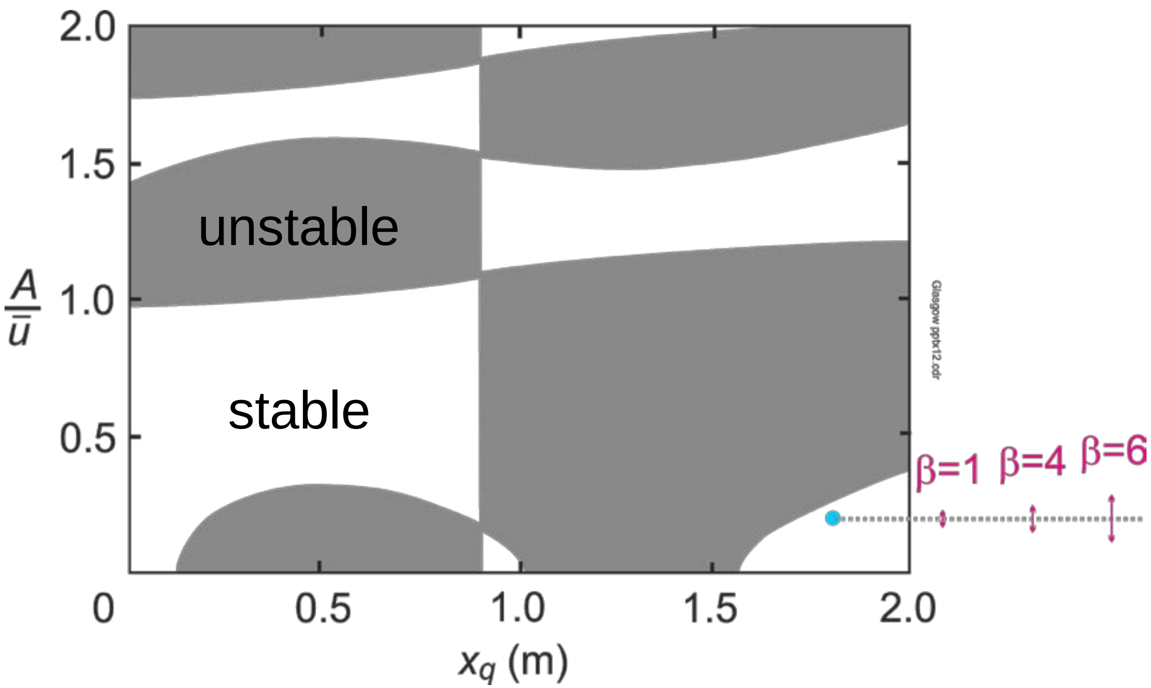
Acoustic resonator: tube with open ends

amplitude-dependent

Flame: described by nonlinear time-lag law $\frac{Q'(t)}{\overline{Q}} = n_1 \frac{u_q'(t-\tau)}{\overline{u}} - n_0 \frac{u_q'(t)}{\overline{u}}$

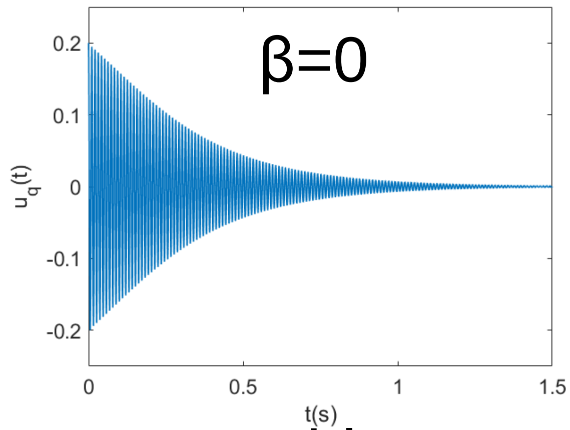
Noise: pink noise, level measured by β

Stability map:

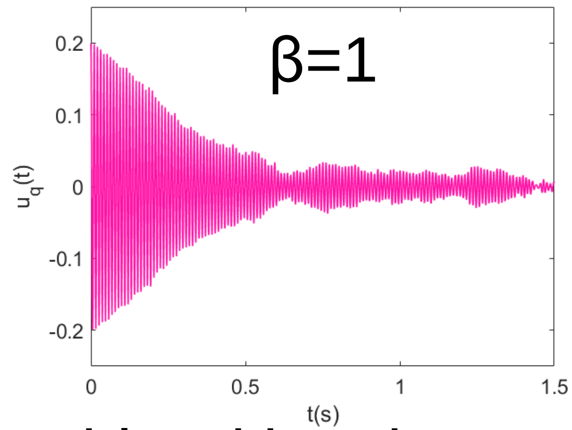


further details in: Arabi, S. and Heckl, Maria (2022) The effects of different types of noise on thermoacoustic systems using a Green's function approach. *Proceedings of the InterNoise 2022*, to be held 21-24 August 2022, Glasgow, UK.

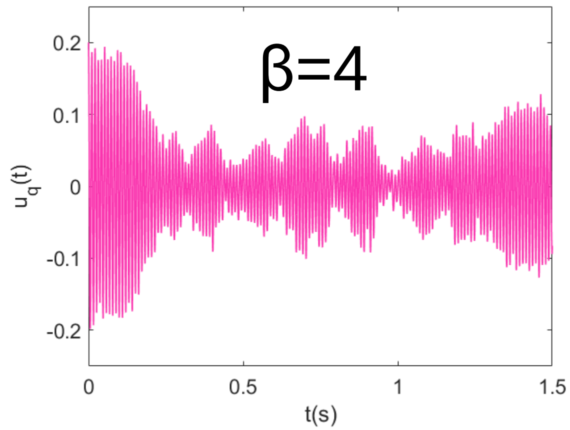
Time histories with different levels of noise



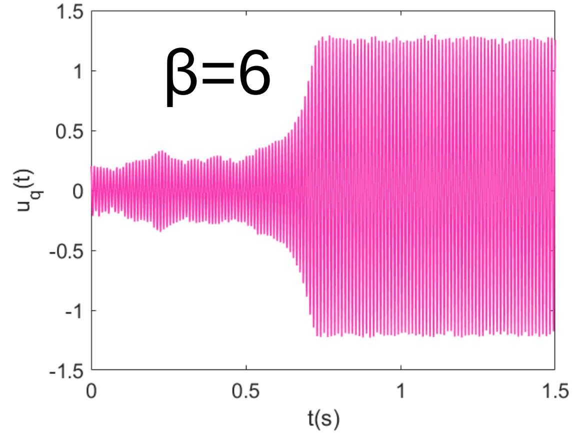
stable



stable with noisy residue



intermittent, not sustained



instability is triggered

The POLKA project

POLKA: POLlution Knowhow and Abatement

funded by: Horizon 2020 (Marie-Curie ITN)

total budget: €4.02 million

duration: 2019 – 2023 (4.5 years)

POLKA website https://polka-eu.org/

16 network partners (across Europe and India)

15 PhD positions

POLKA logo:

POLKA aims: gain insight into H_2 combustion instabilities

POLKA session at InterNoise: Tuesday, 23/08, 08:00 – 10:20

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Conclusions

The Green's function gives physical insight into:

- nonlinear dynamics (limit cycles, hysteresis, …)
- instability and flashback of hydrogen flames
- potential strategies to control combustion instabilities
- noise effects on combustion instabilities

Very useful modelling tool!

Sound plays a key role in combustion instabilities

Sustainable combustion technologies need acoustics research!

Thank you!

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