ETH zürich

Exploring Thermoacoustics while learning control: System Identification, Nonlinear Dynamics and Closed-Loop Experiments

Andrea Iannelli

iannelli@control.ee.ethz.ch

IfA Open House 2019

AUTOMATIC CONTROL LABORATORY

Thermoacoustics in a nutshell

use pressure waves to *move* heat
or convert thermal in acoustic energy

Dynamically coupled

ACOUSTICS

- Mechanical vibrations
- Speakers
- Piezoeletric devices

TA ENGINE
(T difference creates sound, hence mechanical power)

TA REFRIGERATOR
(sound can produce heat exchange, hence T difference)

HEAT TRANSFER

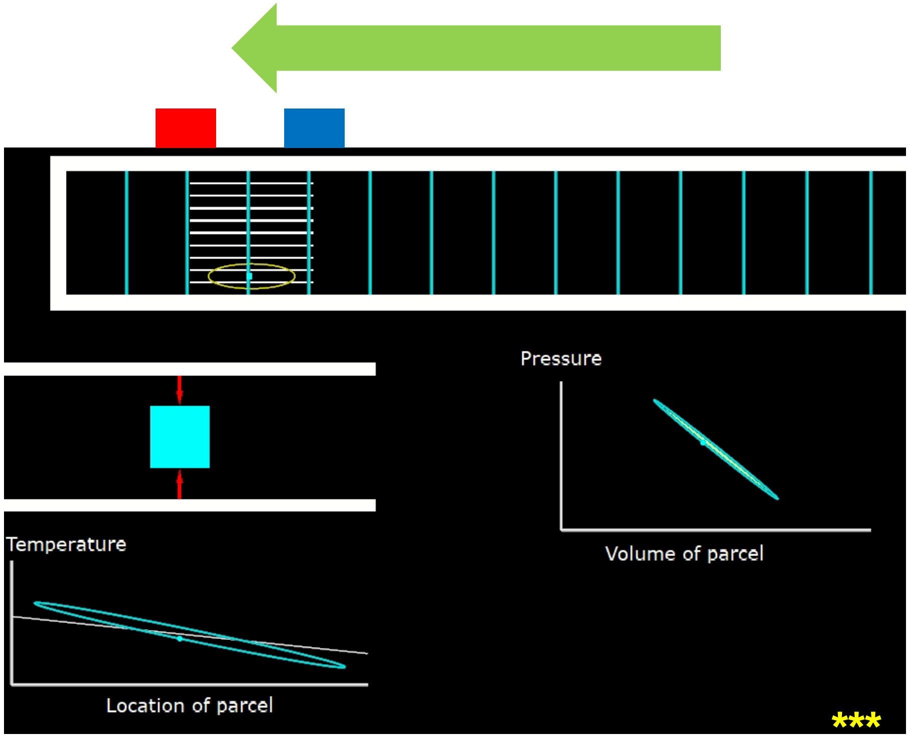
- Waste heat
- Combustion
- Solar thermal energy

*** from "Thermoacoustics" by G. Swift

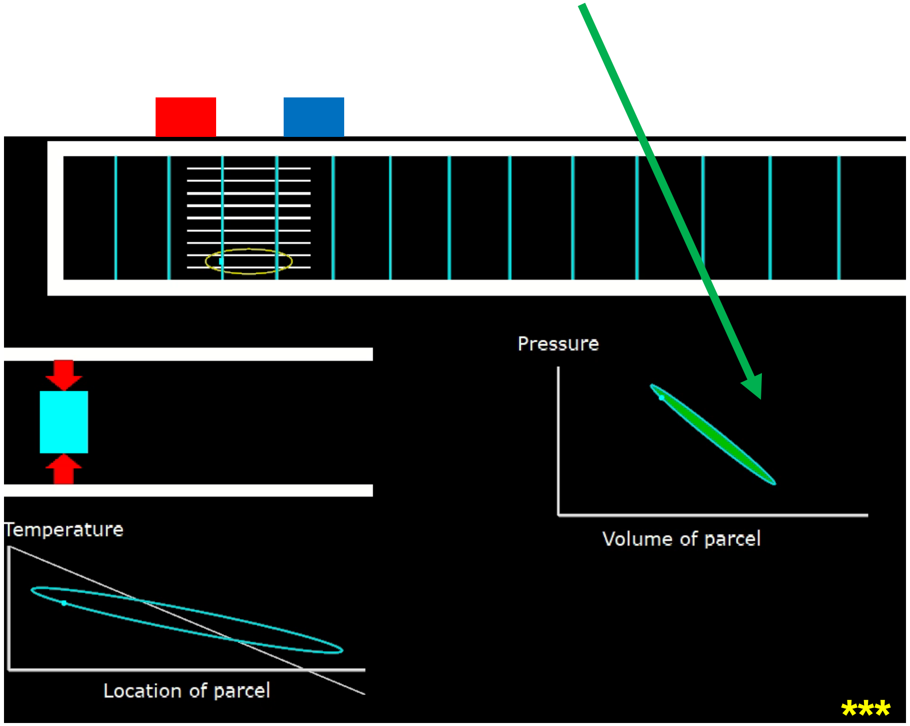
Example (standing wave)

Gas pumps heat in the solid from right to left (even when left is hotter than right!)

Solid pumps heat into the parcel of gas, which does net work per cycle



REFRIGERATOR



ENGINE

Strong temperature gradients & pressure waves

Advantages of TA

- No moving parts→Mechanical simplicity (reliability, higher efficiency, low costs, low maintenance,…)
- Noble gases used as working fluids (unlike refrigerants)
- Easily coupled (engine+refrigerator: heat-powered cooler)
- Great potential for exploiting solar energy and waste heat

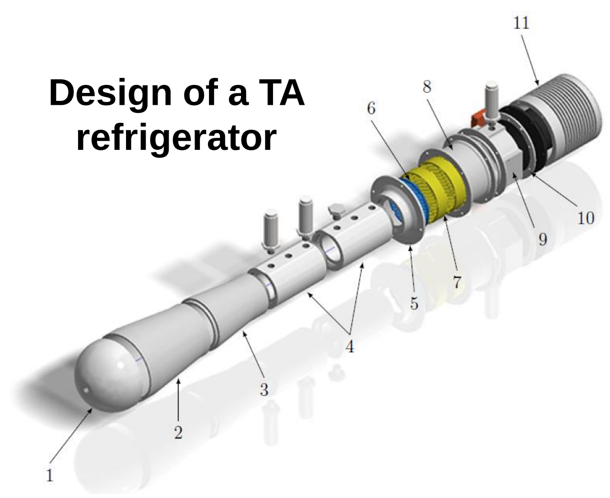
Does it work?

- Several successful applications
- TA refrigerator for Space Shuttle Discovery (certified by NASA)
- Research centers (Los Alamos NL) and companies

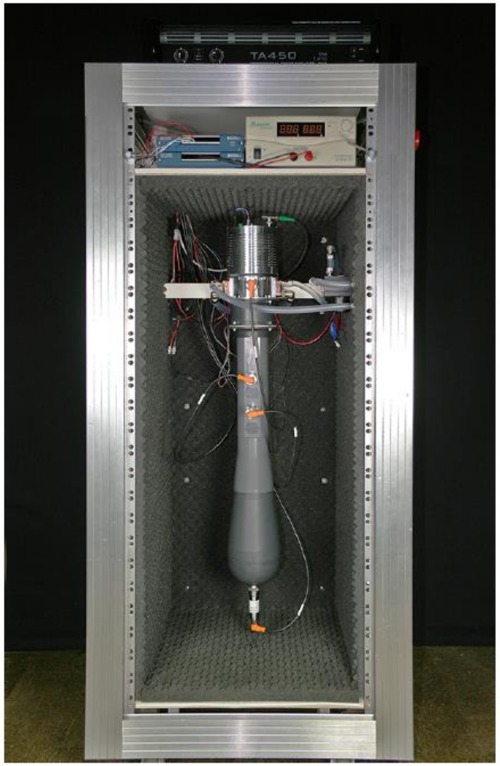
Previous works at IfA

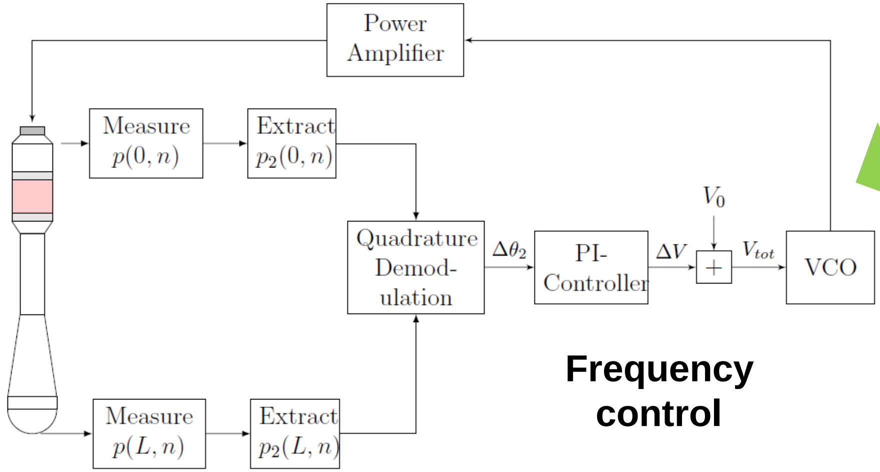
"Design Construction and Resonance Tracking of a Laboratory-Scale Loudspeaker-Driven Thermoacoustic Cooler"

Design of a TA refrigerator



Manufacturing and testing



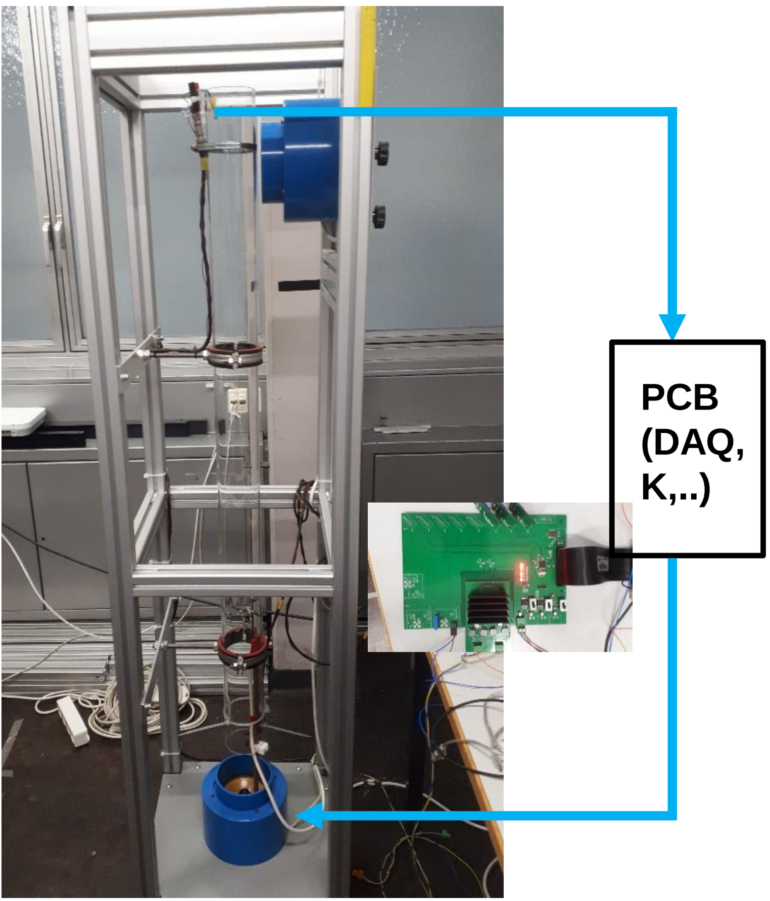


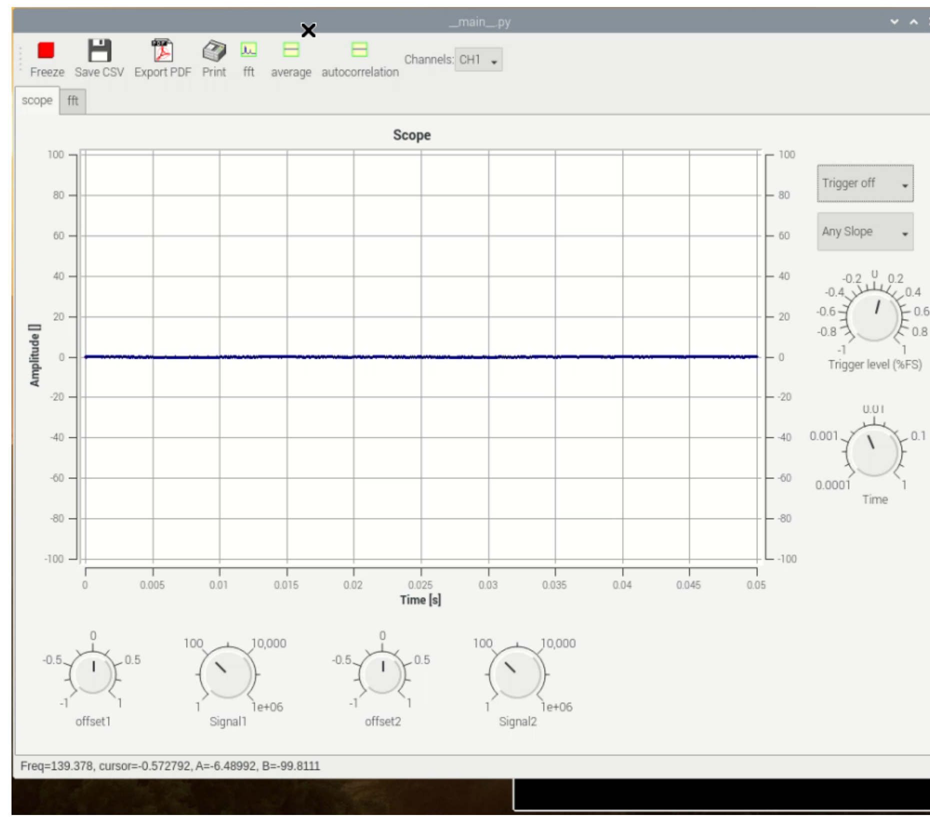
Frequency control

Current works at IfA

“Design and deployment of a control board for thermoacoustic experiments”

RIJKE TUBE (prototype of thermoacoustic instabilities)





Strands of research in Automatic Control

Modelling for control

- From **Navier-Stokes** to **state-space representation**
- **First-principles** driven modelling
- Trade-off **complexity-accuracy**

Thermoacoustics system identification

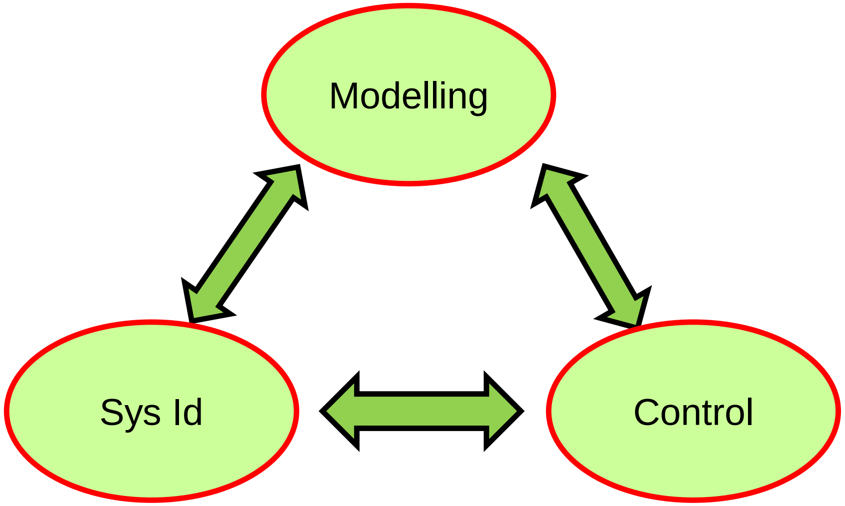
✓ Identification of the **nonlinear responses** (equilibrium, Limit Cycles)
✓ Linear (**periodic**) and **nonlinear** system identification **algorithms**
✓ **Identifiability** issues

Control of thermoacoustics phenomena

○ Definition of the **objectives** (harvested power, efficiency)
○ **Development** of new control design **approaches**
○ **Experimental** testing

Challenges (and why this is cool)

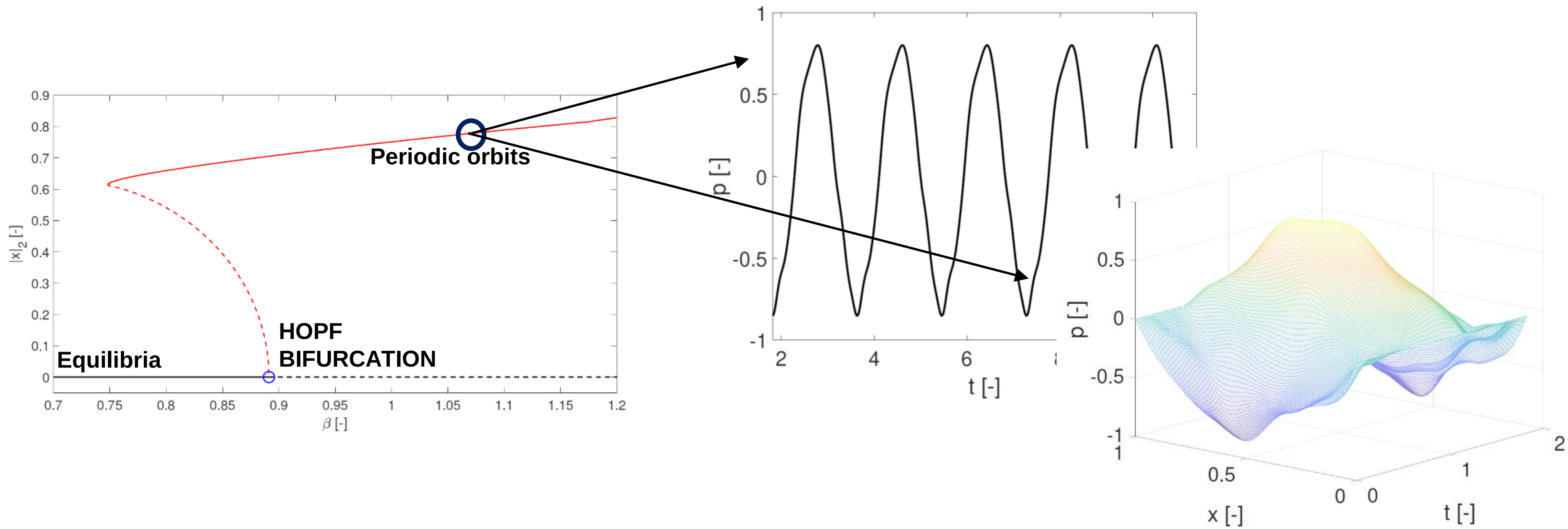
- These tasks are coupled



- Topics are diverse (great opportunity for learning)
- Thermoacoustics are rich dynamical systems
- Only few results out there, (almost) any study will provide a contribution to the field!

Project 1 (MA)

"Modeling and identification of Limit Cycle Oscillations in thermoacoustic instabilities"



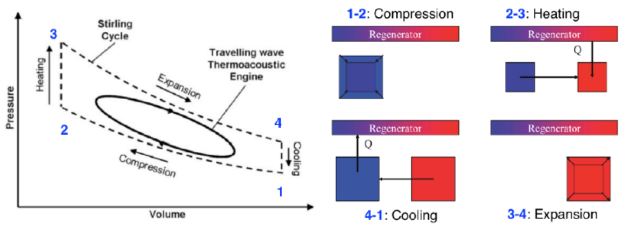
Directions

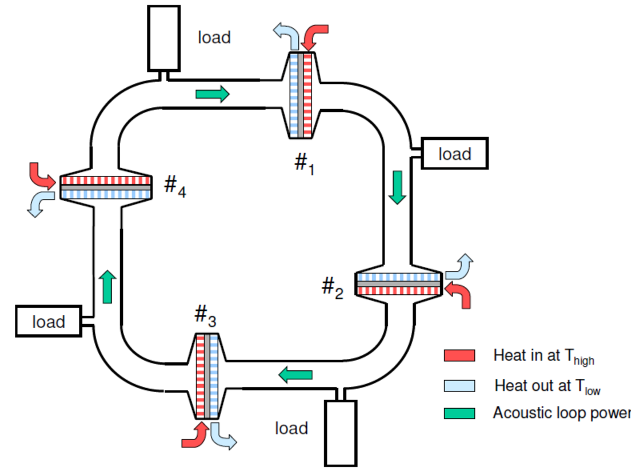
- Investigate complexity-accuracy trade offs in **control oriented modelling** (derivation of first principles models + validation)
- System identification of **oscillating systems** (<u>**NEW**</u>: introduce LCO as qualitative constraint of the identification process)

Project 2 (MA)

"Design, control, and testing of a travelling wave thermoacoustic machine for energy harvesting"

STIRLING CYCLE





AVAILABLE DEMONSTRATOR

Directions

- Comparison **standing vs. travelling wave** machines **performance**
- **Experiments** with available demonstrator at IfA
- Design of harvesting solutions, possibly involving **feedback control to limit known limitations** (efficiency, minimum T gradient to trigger self-sustained waves)

ETH zürich

Thank you!

Other topics:

- **Robust control**
- **System Identification**
- **Bifurcation, continuation-based constrained optimization**

Be in touch!!

iannelli@control.ee.ethz.ch

http://people.ee.ethz.ch/~andreaia/