Extremum Seeking Control of Thermoacoustic Coolers

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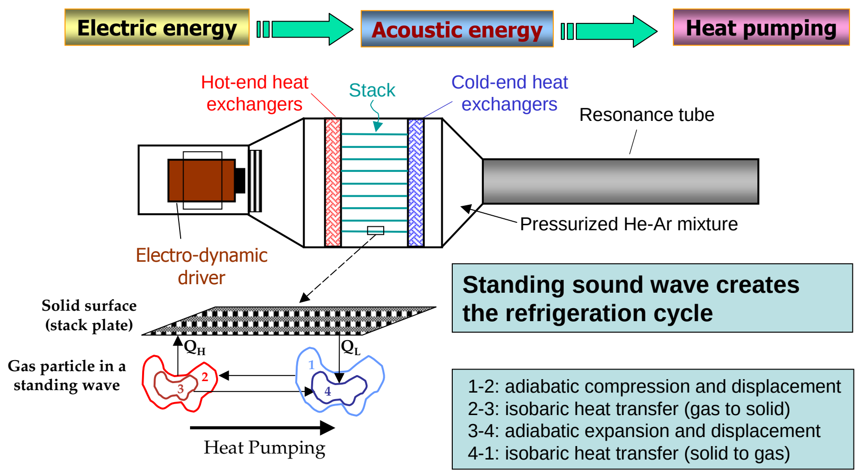
REF. Extremum Seeking Control of Tunable Thermo-acoustic Coolers, Y. Li, M. Rotea, G. Chiu, L. Mongeau, I. Paek, IEEE Transactions on Control Systems Technology, Vol. 13, No. 4, July 2005

Outline

- Thermoacoustic cooling
  - Working principles
  - Benefits and limitations
- Tunable thermoacoustic cooler
- Extremum seeking control of tunable cooler
- Experimental results
- Conclusions

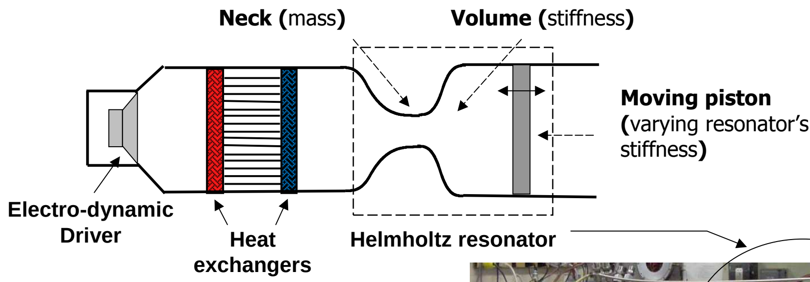
Thermoacoustic Cooling

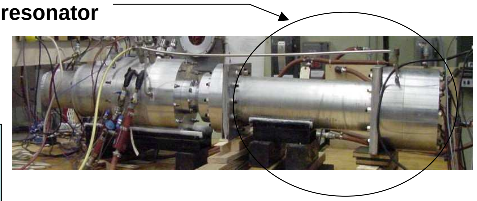


Thermoacoustic Cooling

- Benefits
  - Environmentally benign (inert gases)
  - Simple, easy to maintain configuration
- Limitations
  - Very hard to model → hard to tune key parameters (driver, stack location, duct geometry) for best performance
- Existing prototypes
  - Acoustic Stirling Heat Engine (Los Alamos National Lab)
  - Triton 10 kW refrigerator (Penn State)
  - Space Thermo-acoustic Refrigerator (NASA)
  - Purdue 300 W standing wave unit
  - Miniature thermo-acoustic cooler (Rockwell Science Center)

Tunable Thermoacoustic Cooler





Tuning Variables

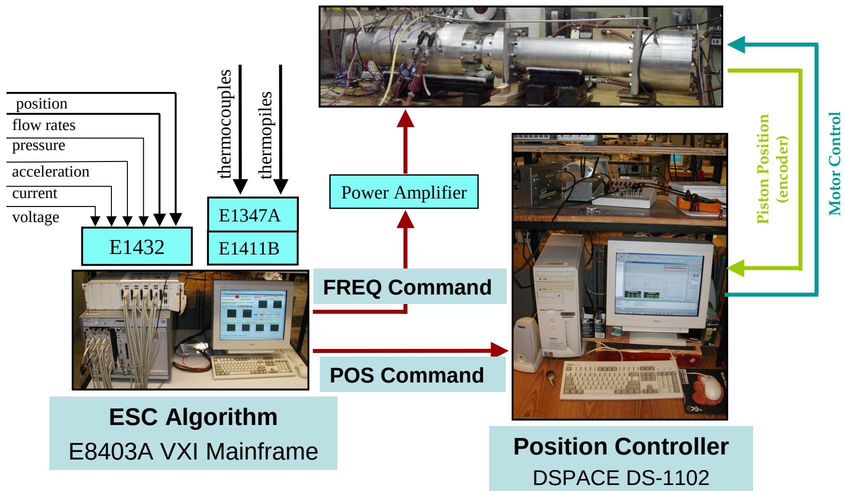
Performance and efficiency sensitive to variations in

- Piston position
- Driver frequency

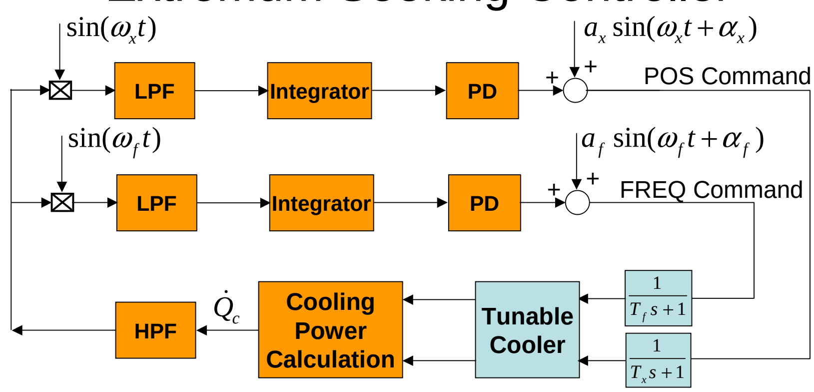
Control Problem

- Develop an algorithm that tunes the *driver frequency* and *piston position* to maximize the cooling power autonomously
- Main features
  - Mathematical model not available
  - Easy to estimate cooling power from mass flow rate and temperature gradient across cold-side heat exchanger
  - Stable dynamics
- An ideal application for Extremum Seeking Control (ESC)

Automatic Control of Tunable Thermoacoustic Cooler



Extremum Seeking Controller



(Tuning mechanism)

ESC Parameters

- High pass filter (HPF)
- Low pass filters (LPF)
- Dither frequencies, amplitudes and phases (ω_x, a_x, α_x; ω_x, a_x, α_x)
- PD gains (4 gains)

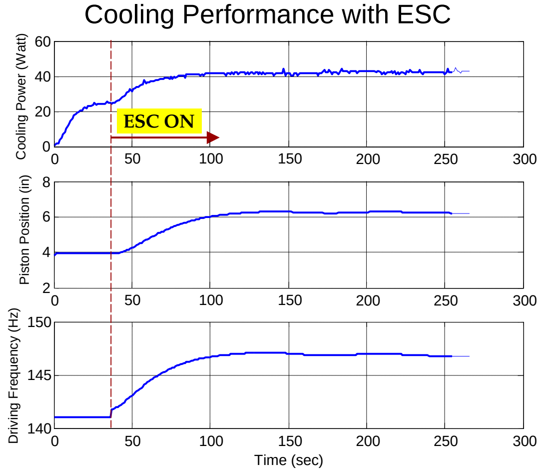
Design Guidelines

- Dither signal parameters
  - Distinct frequencies ($\omega_x \neq \omega_f$)
  - Frequencies should be high but below the first corner frequency of the tuning mechanism dynamics ($\omega_x = 0.1/T_x$, $\omega_f = 0.1/T_f$)
  - Phase angle of dither signal should be close to zero at the output of tuning mechanism dynamics (< $\pi/2$ in magnitude)
  - Small amplitudes but above noise floor
- Filters
  - Dither frequencies in the pass-band of the HPF (2nd order)
  - Dither frequencies in the stop-band of the LPF (2nd order)
- PD gains
  - Initial guess from linear stability analysis
  - Need an estimate for the Hessian of the cost function at the optimum
- Further details in Rotea, 2000 ACC

Experiment – Fixed Operating Condition

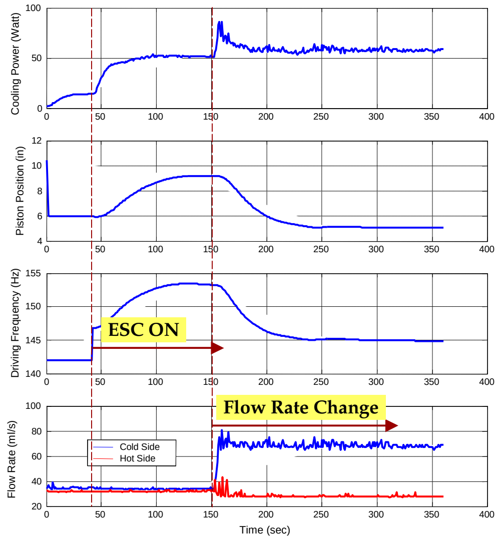
POS in.	FREQ Hz	POWER W
4	141	22.65
	142	29.92
	143	35.67
	144	28.63
	145	21.25
5	142	15.89
	144	34.12
	145	39.68
	146	35.12
	148	19.34
6	140	4.95
	142	9.00
	144	18.55
	145	23.86
	146	35.99
	147	41.28
	148	38.00
	149	30.36
	150	19.36
7	146	16.34
	148	33.34
	149	41.21
	150	40.70
	151	34.69
	153	19.63
8	151	32.16
	152	35.60
	153	31.74

Cooling Performance with ESC



ESC quickly finds optimum operating point (41.3W, 147Hz, 6.2in)

Experiment – Varying Operating Condition



ESC tracks optimum after cold-side flow rate is increased

Experiment – Sensitivity to PD Gains

K_{px}	K_{dx}	K_{pf}	K_{df}	$\dot{Q}_{c\ ss}$ (Watt)	Settling time (5%, sec)	x_{ss} (inch)	f_{ss} (Hz)
4	0	6	0	54.47	109	8.4	152.3
4	2	6	3	60.63	58	10.1	156
4	4	6	6	58.2	56	10.6	157.2
4	20	6	20	UNSTABLE			

- Adding derivative action improves transient performance
- Large derivative action leads to instability
- The spring plate experienced its fatigue failure process throughout the test → the optimal system performance varied from test to test

Conclusion

- Manual tuning of thermoacoustic cooling devices is impractical
  - Tedious and expensive
  - Fixed device cannot deliver optimal performance when conditions change
- Clever tunable device + ESC = a practical alternative for autonomous performance optimization of thermoacoustic coolers
- ESC facilitates thermoacoustic refrigeration research
  - Efficient autonomous exploration of the device performance map