Extremum-Seeking Control of Combustion Instabilities

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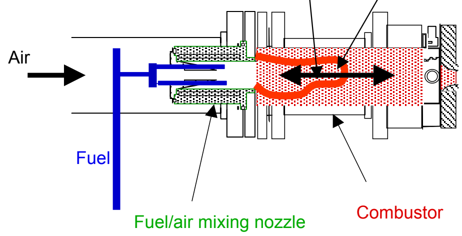
Adaptive Algorithm for Active Combustion Control

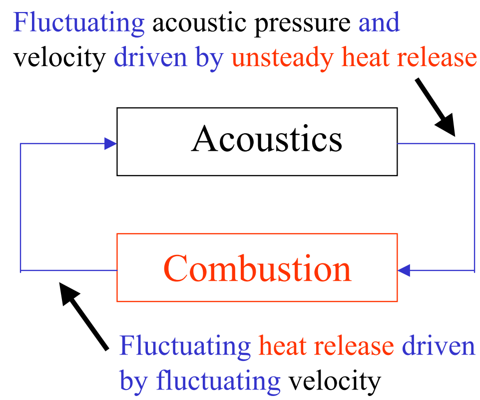
Outline:

- Reasons for considering adaptive algorithms
- Description of the selected algorithm
- Motivation for the choice of the algorithm
- Experiments with minimum-seeking algorithm on single nozzle rig
- Model for average pressure magnitude
- Simulation of engine transients
- Technical challenges/Needs

Thermo-acoustic instability

Coupling of ***acoustics*** *with* ***heat release*** *results in pressure oscillations*





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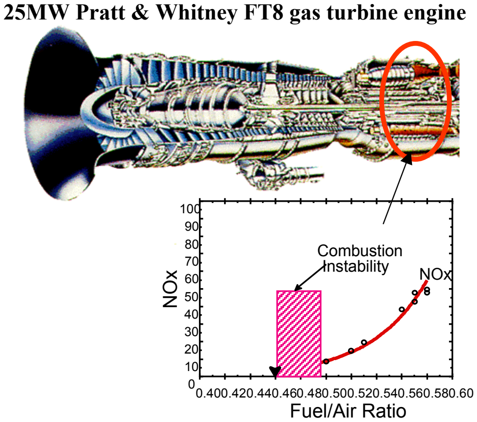
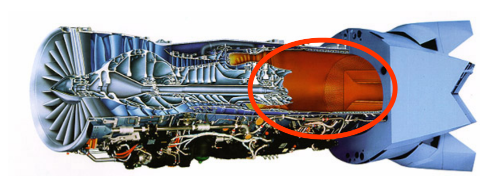
Thermo-acoustic instabilities affect cost and performance of gas turbines and rocket engines

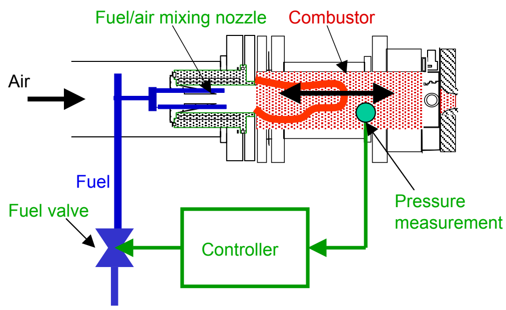
25MW Pratt & Whitney FT8 gas turbine engine

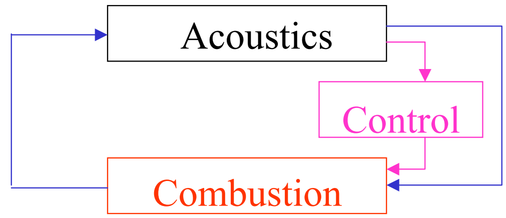


- Power generation: pressure oscillations prevent low emission operation
- Military aeroengines: afterburner screech and rumble limit performance, passive fixes increase weight, maintenance costs
- Rockets: passive fixes increase weight, limit payload

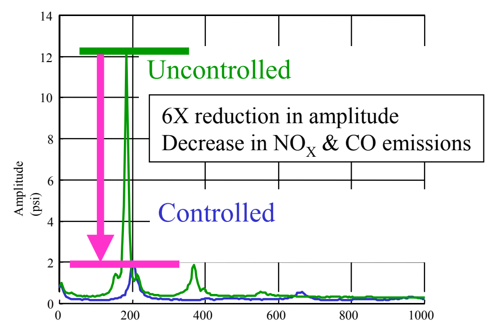


Active fuel control can suppress oscillations





Experiment in UTRC 4MW Single Nozzle Rig



- Numerous demonstrations at universities and industrial rigs
- Rolls-Royce demonstrated control in afterburner
- Siemens implemented control in 260MW gas turbine engine
- Phase-shifting control effective, but no models to guide selection of parameters

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Requirements of Active Combustion Instability Control

Active combustion instability control on a gas turbine engine must keep pressure oscillations at an acceptable level:

- over a large range of operating conditions
- during transients
- without perfect model of the process dynamics

Reasons for using extremum-seeking control

- imperfect model
- unknown and varying model parameters, difficult to ID
- large range of operating conditions, including fast engine acceleration and deceleration

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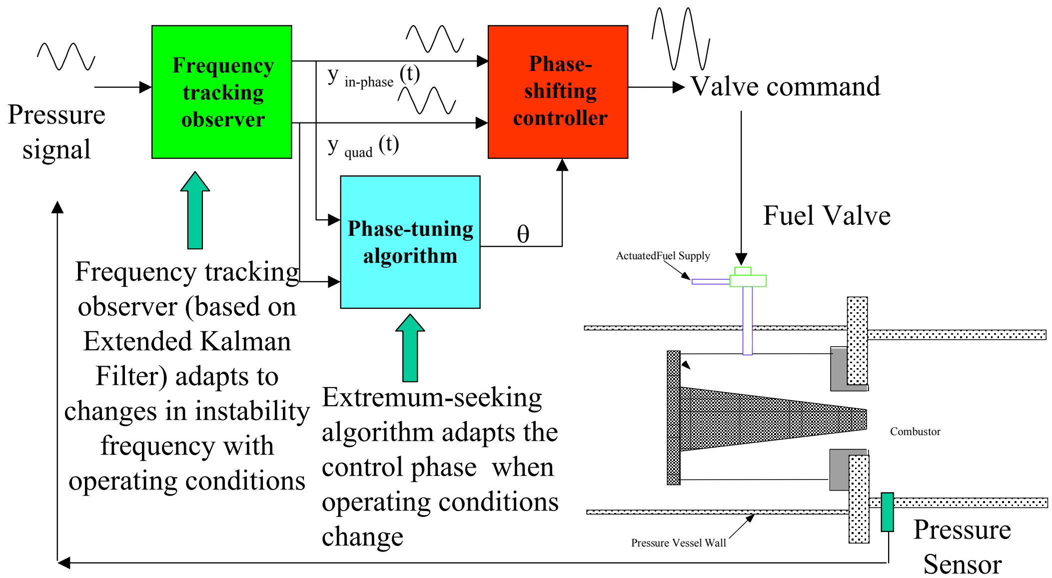
Control algorithm must satisfy performance specification during engine acceleration and deceleration transients

Adaptive controller has been developed



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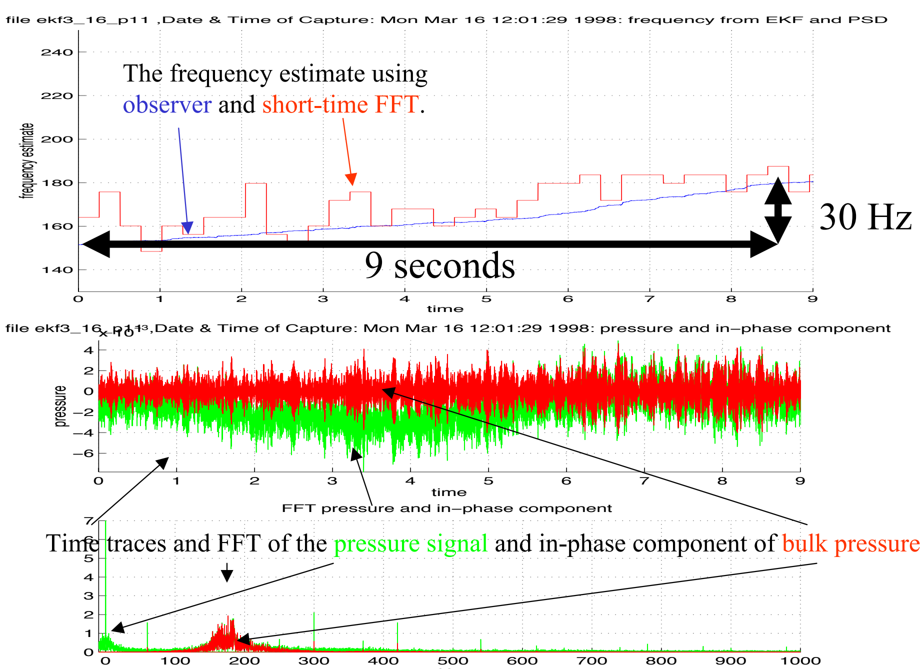
Frequency tracking algorithm based on Extended Kalman Filter allows to isolate the pressure mode of interest when operating conditions change

Frequency estimation with the frequency tracking observer during a rig warm up.

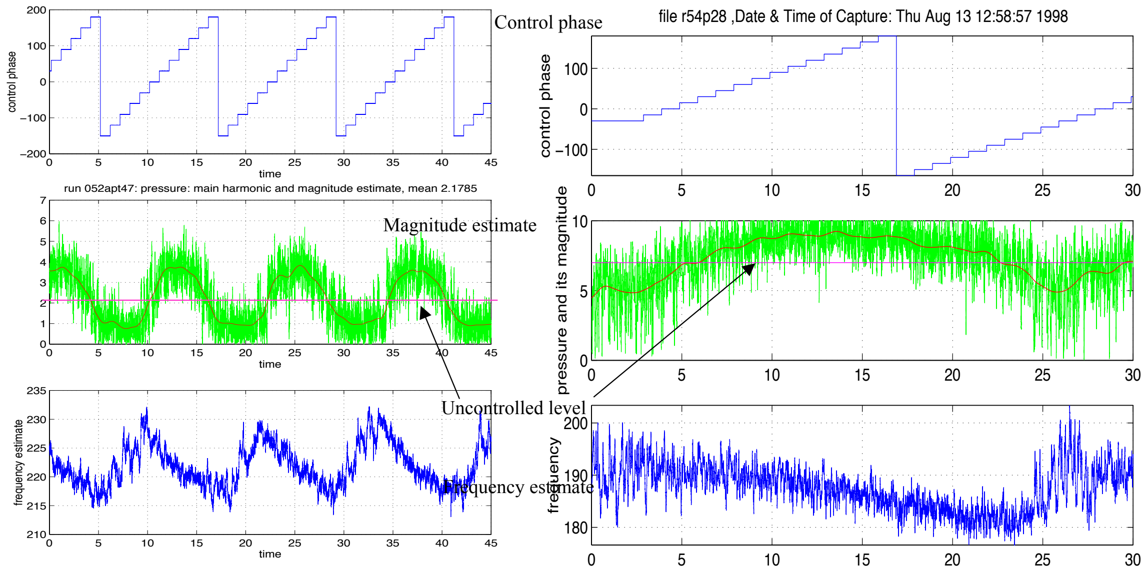


Time traces and FFT of the pressure signal and in-phase component of bulk pressure mode

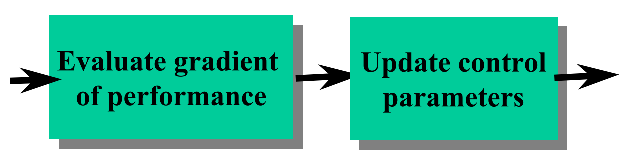
Technical challenges for adaptive algorithms

- **Phase-magnitude map changes** as a function of operating conditions
- Mean pressure magnitude measurement is affected by **noise**

high power low power

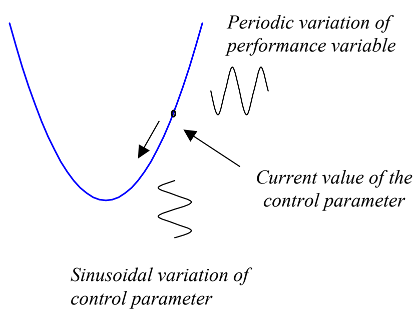


Extremum-Seeking Control: Options



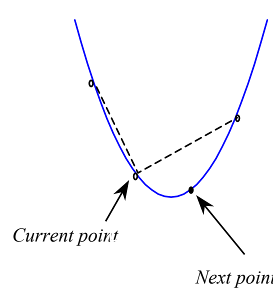
Classical algorithm

Correlation of variations determines direction of change of mean control variable



Triangular search (Y. Zhang)

New control parameter determined by subdivision of an interval determined by previous control parameters



Ref. A. Banaszuk, K.B. Ariyur, M. Krstic, and C.A. Jacobson, An Adaptive Algorithm for Control of Combustion Instability, *Automatica*, 40, 2004, 1965-1972.

Ref: Y. Zhang, "Stability and Performance Tradeoff with Discrete Time Triangular Search Minimum Seeking", Proc. of American Control Conference, Chicago 2000

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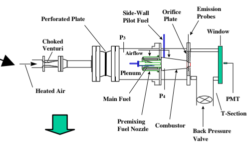
Model for average pressure magnitude was developed

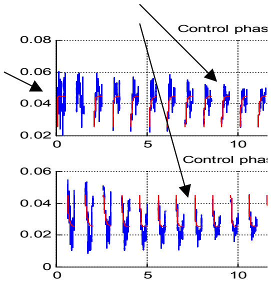
Experimental combustion rig



1. Averaging of experimental transient responses to forcing

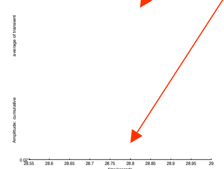
Control phase is a square wave with frequency 1Hz and magnitude of 90 degrees (peak-to-peak)

Experimental data



Model

2. Fi
mat



Model of dependence of pressure magnitude on the control phase

$$\dot{A}(t) = g(A(t), \theta(t)) + n(t)$$

A - average pressure magnitude

θ - control phase

n - driving stochastic disturbance

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Model extracted form experimental data has been used to develop and test adaptive algorithms for control of combustion instability

Model allows to study extremum-seeking adaptive algorithms off-line

UTRC team:

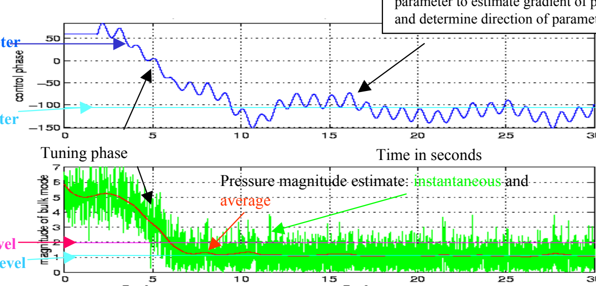
Dr. Andrzej Banaszuk

Dr. Youping Zhang

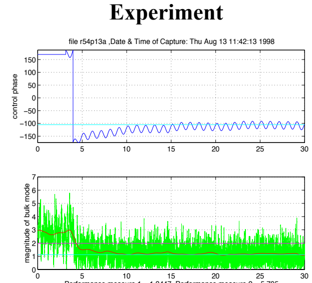
Stability, robustness, and performance of extremum-seeking algorithms has been analyzed by

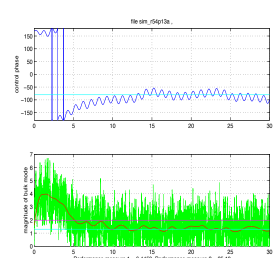
Dr. Miroslav Krstic (UCSD)

Small periodic variation is introduced in control parameter to estimate gradient of pressure magnitude and determine direction of parameter update



Experiment — **Model simulation**

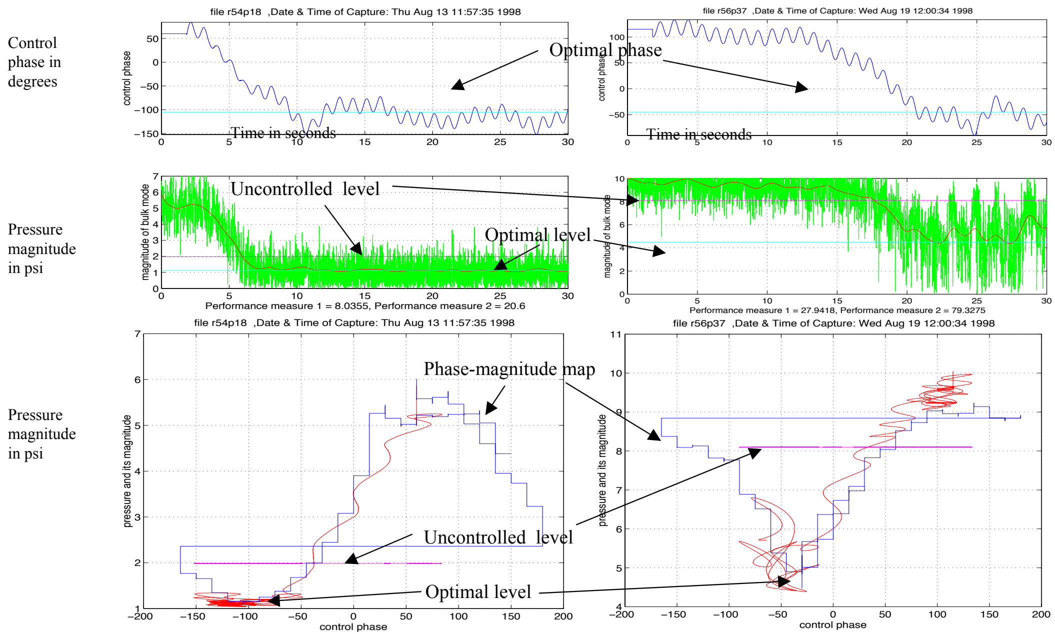




- **Model allowed to develop and test extremum-seeking adaptive algorithms off-line**
- **Number of expensive experiments was reduced**
- **Performance of adaptive algorithms during simulated engine transients was studied**

Summary of results: two extremum seeking schemes were successfully demonstrated on UTRC 4MW single nozzle rig in August 1998.

Excellent performance at high power | Improved performance at low power



Control phase in degrees | Control phase in degrees

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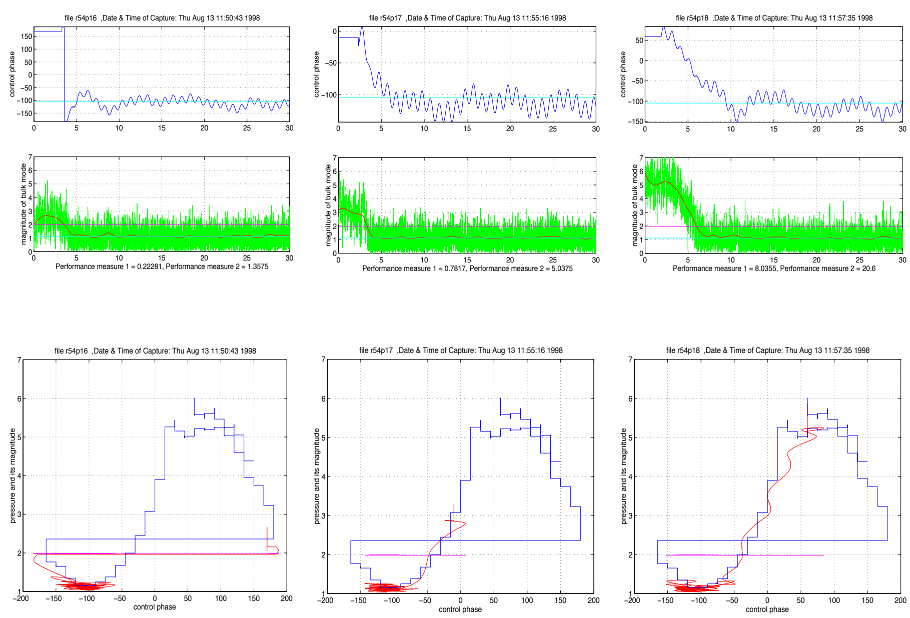
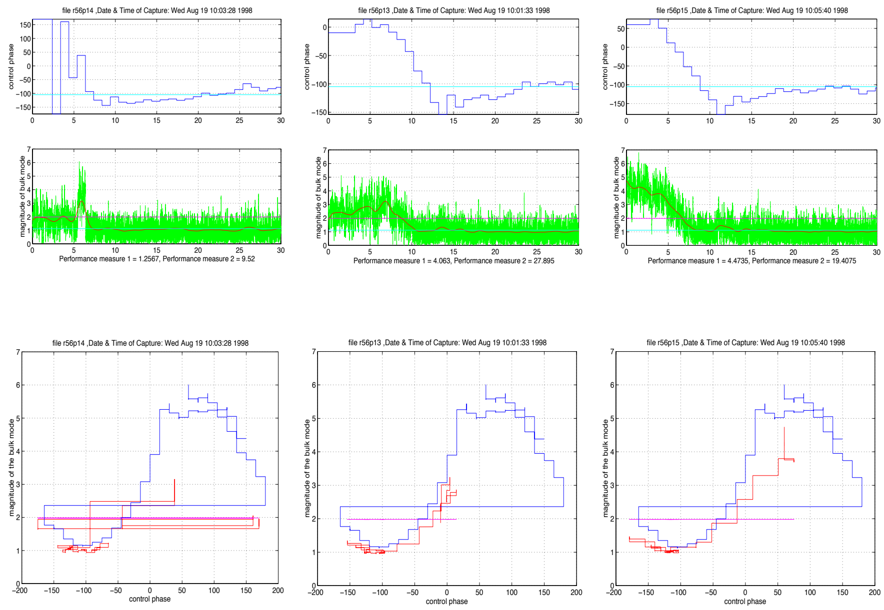
Classical algorithm: initialization transients at high power.

Initial phase 170 degrees | Initial phase -10 degrees | Initial phase 60 degrees



Triangular search algorithm: initialization transients at high power

Initial phase 170 degrees | Initial phase -10 degrees | Initial phase 60 degrees



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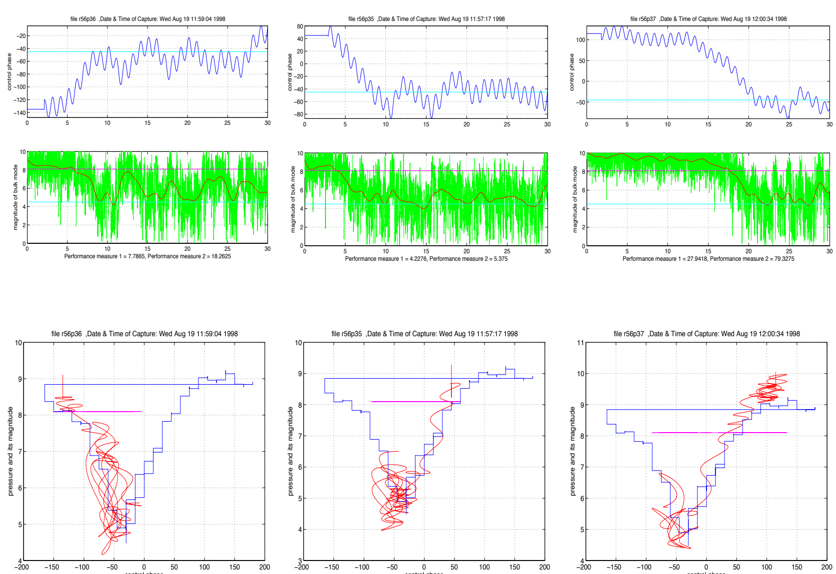
Classical algorithm: initialization transients at low power

Initial phase -135 degrees | Initial phase 45 degrees | Initial phase 115 degrees



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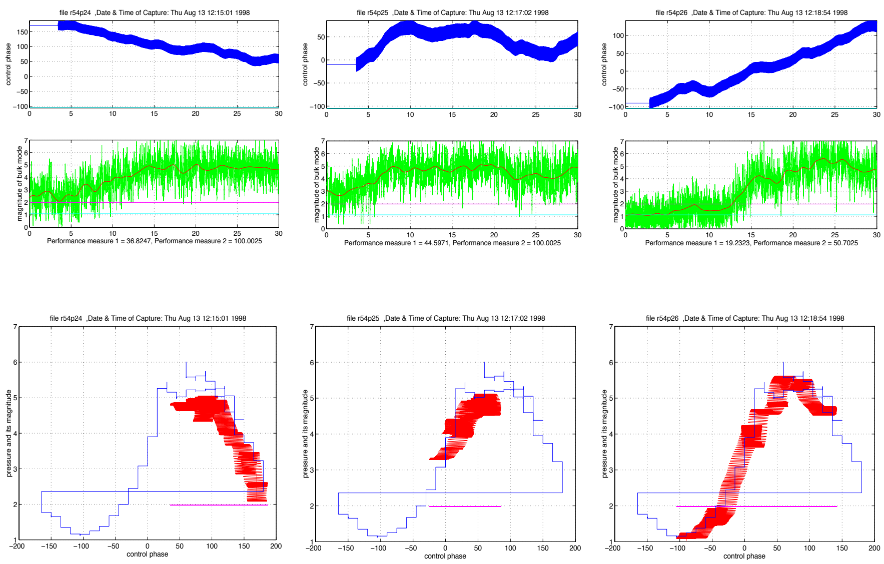
Too high sinusoidal variation frequency cause phase inversion => classical algorithm finds maximum instead of minimum

Initial phase 170 degrees   Initial phase -10 degrees   Initial phase 90 degrees



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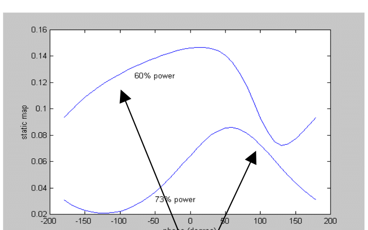
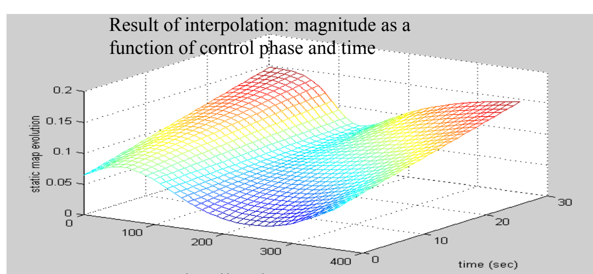
Model extracted form experimental data used to simulate performance of adaptive algorithm during engine acceleration and deceleration transients

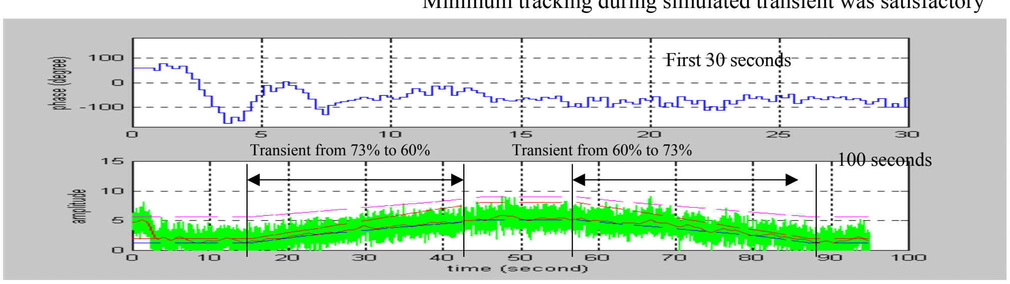
Extremum-seeking adaptive algorithm meets performance specification requirements



Phase-magnitude maps at two power levels were interpolated



Minimum tracking during simulated transient was satisfactory



Technical challenges:

- dealing with high noise level and engine transients
- non-conservative stability and performance guarantees
- finding fundamental limits of minimum-seeking schemes

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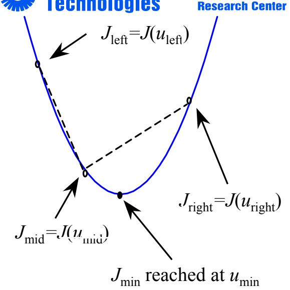
Summary:

- Adaptive controller for combustion instability has been developed and tested in 4MW combustion rig at UTRC in summer 1998
- Controller performed well in initialization transients
- Adaptive control met performance specifications in simulated engine acceleration transients

Backup

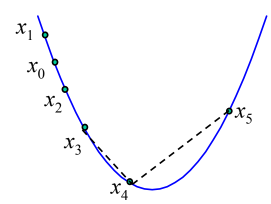
Concept



Feature
- •Infinite memory
- •Allow forgetting

$$\boxed{u_{\text{left}} < u_{\text{mid}} < u_{\text{right}} \text{ and } J_{\text{left}} > J_{\text{mid}}, J_{\text{right}} > J_{\text{mid}} \overset{\text{convexity}}{\Rightarrow} u_{\text{left}} < u_{\text{min}} < u_{\text{right}}}$$

Initialization



- Wrong direction: flip direction immediately

$$(x_2 - x_0)(x_1 - x_0) < 0$$

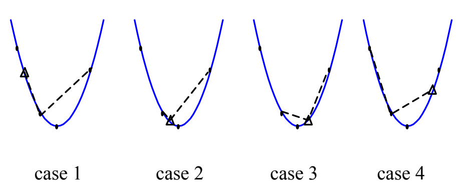
- Right direction: increment step size to accelerate triangle points location:
$(x_5 - x_4) = k(x_4 - x_3)$, $(x_3 - x_2) = k(x_2 - x_0)$, $k > 1$

Feature
- •At most one step wrong
- •Exponential acceleration
- •At most

$$n = \left[\log_k\left(\frac{x}{\Delta}(k-1)+1\right)\right]$$

steps to cover a length x interval with initial step size Δ and maximum step size $\Delta_{\max}=k^{n-1}\Delta$,
- •Allow adjustable $\Delta, \Delta_{\max}$

Searching



Next point Δ chosen to maximize the shrinking of interval

Feature
- •Exponential speed of interval shrinking

$$k = \frac{\sqrt{5}-1}{2}$$

Adaptation

Feature
- •Automatic adaptation of step size to distance to minimum and noise level
  - Minimum step size renders change in cost function such that $|\Delta_{\min} J(\Delta_{\min} u)| > |\text{noise}| * (1\text{-attenuation}) + |\text{ripple}|$
  - Step size is adjustable on-line
  - Track changes in $J_{\min}$ via re-initialization
- •Avoid escape from minimum
- •Accelerate search when far from minimum
- •Decelerate search when close to minimum
- •Keep on minimum shaking of the system to track variation
- •No external excitation necessary

Ref: Y. Zhang, "Stability and Performance Tradeoff with Discrete Time Triangular Search Minimum Seeking", Proc. of American Control Conference, Chicago 2000