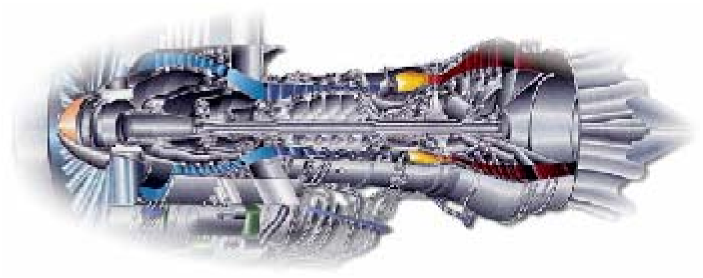
AEROSPACE APPLICATIONS OF CONTROL

CDS 101 Seminar
October 18, 2002



United Technologies

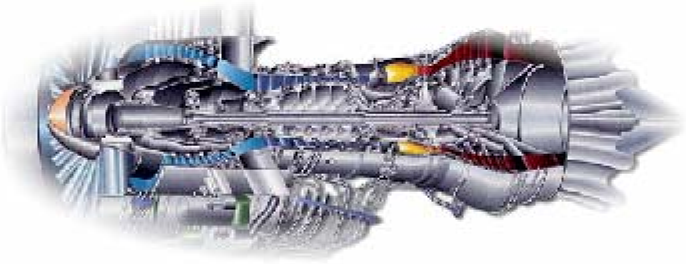
Scott A. Bortoff

Group Leader, Controls Technology

United Technologies Research Center

International Fuel Cell

Carrier



Pratt & Whitney

United Technologies

Otis

Sikorsky

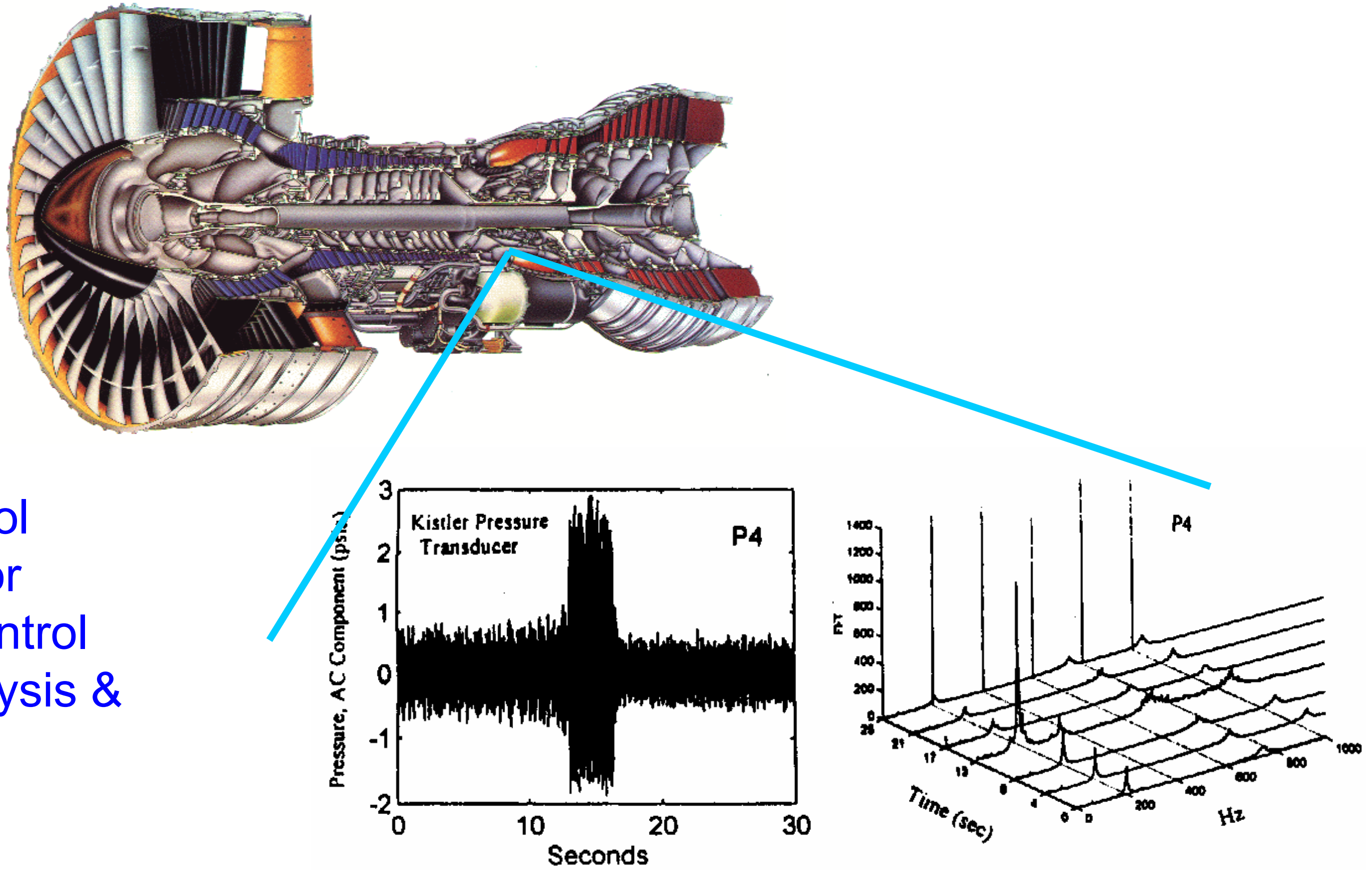
Hamilton-Sundstrand

- **$26.6 billion (2000)**
- **153,800 employees**
- **3 business groups...**
  - Aerospace
  - Building Systems
  - Power Solutions

Seminar Objectives

Emphasize the importance of modeling, feedback, uncertainty

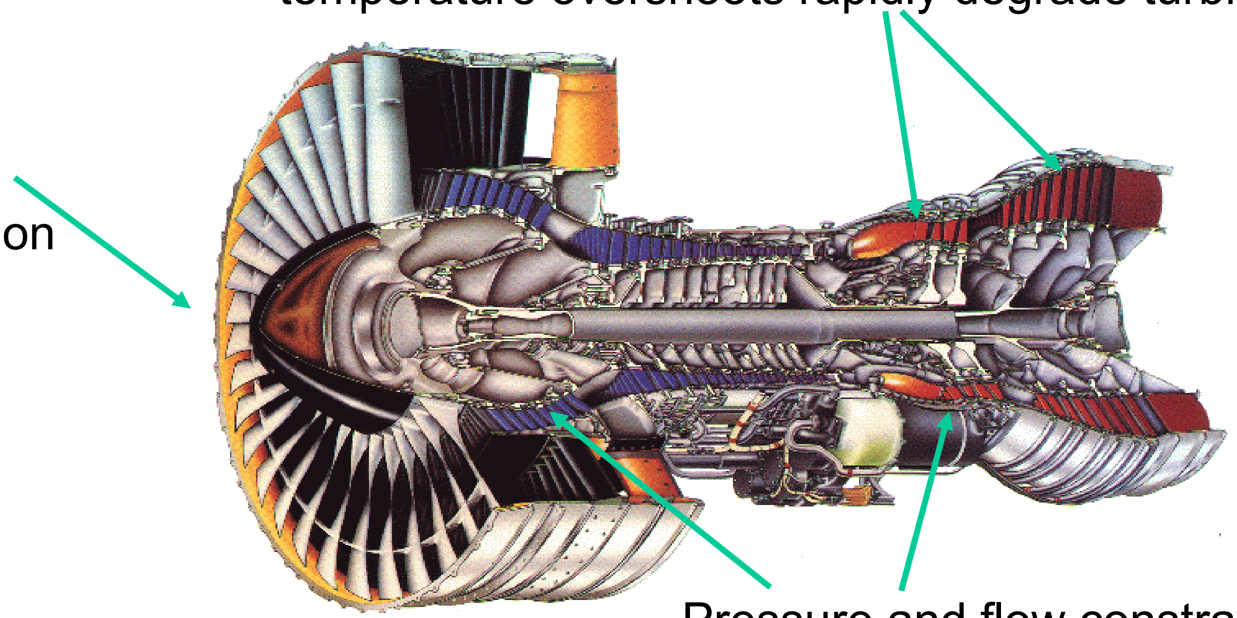
- Provide three examples of modeling
- Illustrate the relationship among modeling, uncertainty and feedback
- Provide an example of dynamic analysis.



1. Jet Engine Control
2. Electric Generator Transmission Control
3. Combustion analysis & control

Jet Engine Control Objectives

Track commanded thrust while maintaining constraints



Thermal efficiency increases with burner temperature
- nominal temperatures near melting point of parts
- temperature overshoots rapidly degrade turbine life

Speed constraints on fan & spool (to avoid structural failure). Structural constraints on fan & spool speeds

Pressure and flow constraints on compressor stages, to avoid stall, surge, flutter.

But…

- Fan and compressor efficiency best near stall, surge, and flutter boundaries.
- Thermal efficiencies highest with increased burner temperatures.
- Structure designed to minimize weight.

F-135 Engine Control

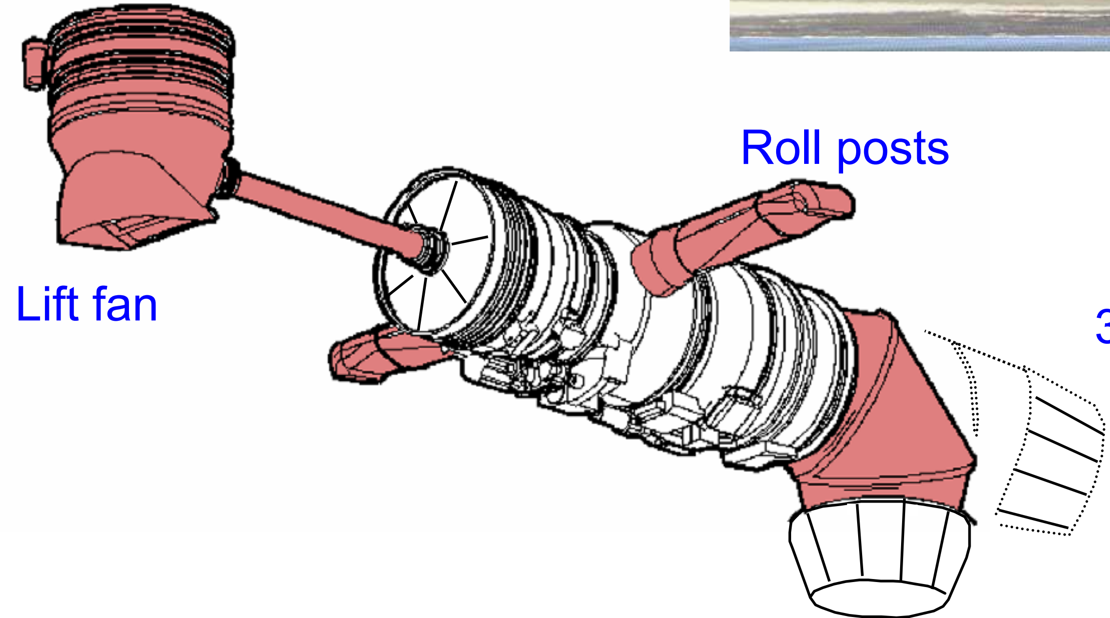
VTOL requirement means demanding control problem

JSF capable of vertical T/L

- 3DOF nozzle
- Roll posts
- Lift fan

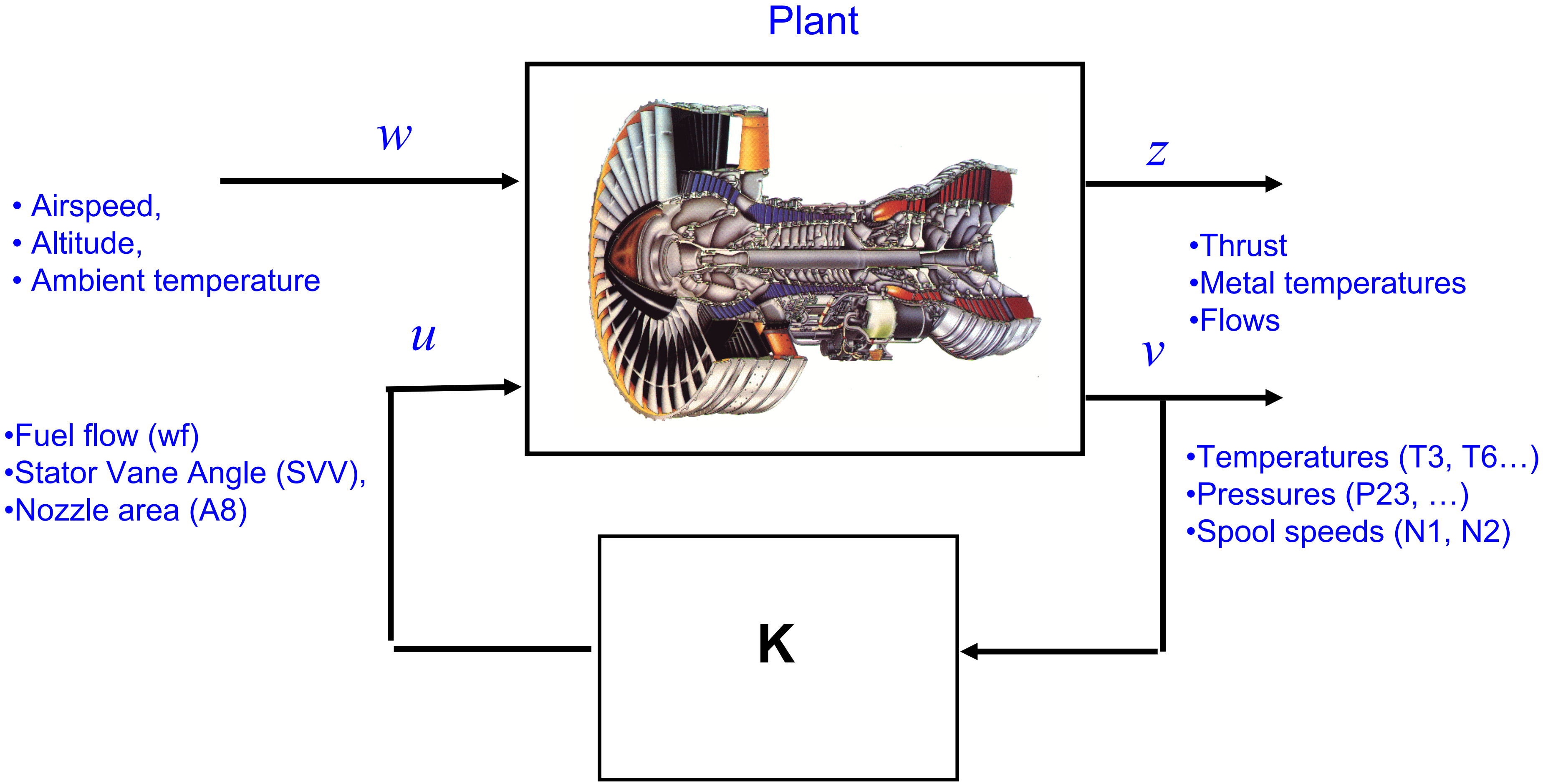
Challenges:

- Split Thrust has 10x bandwidth
- Precise modeling requirements
- Multivariable, nonlinear



Block Diagram – Jet Engine Control

Input & Output Signals



Plant

w

- Airspeed,
- Altitude,
- Ambient temperature

u

- Fuel flow (wf)
- Stator Vane Angle (SVV),
- Nozzle area (A8)

z

- Thrust
- Metal temperatures
- Flows

v

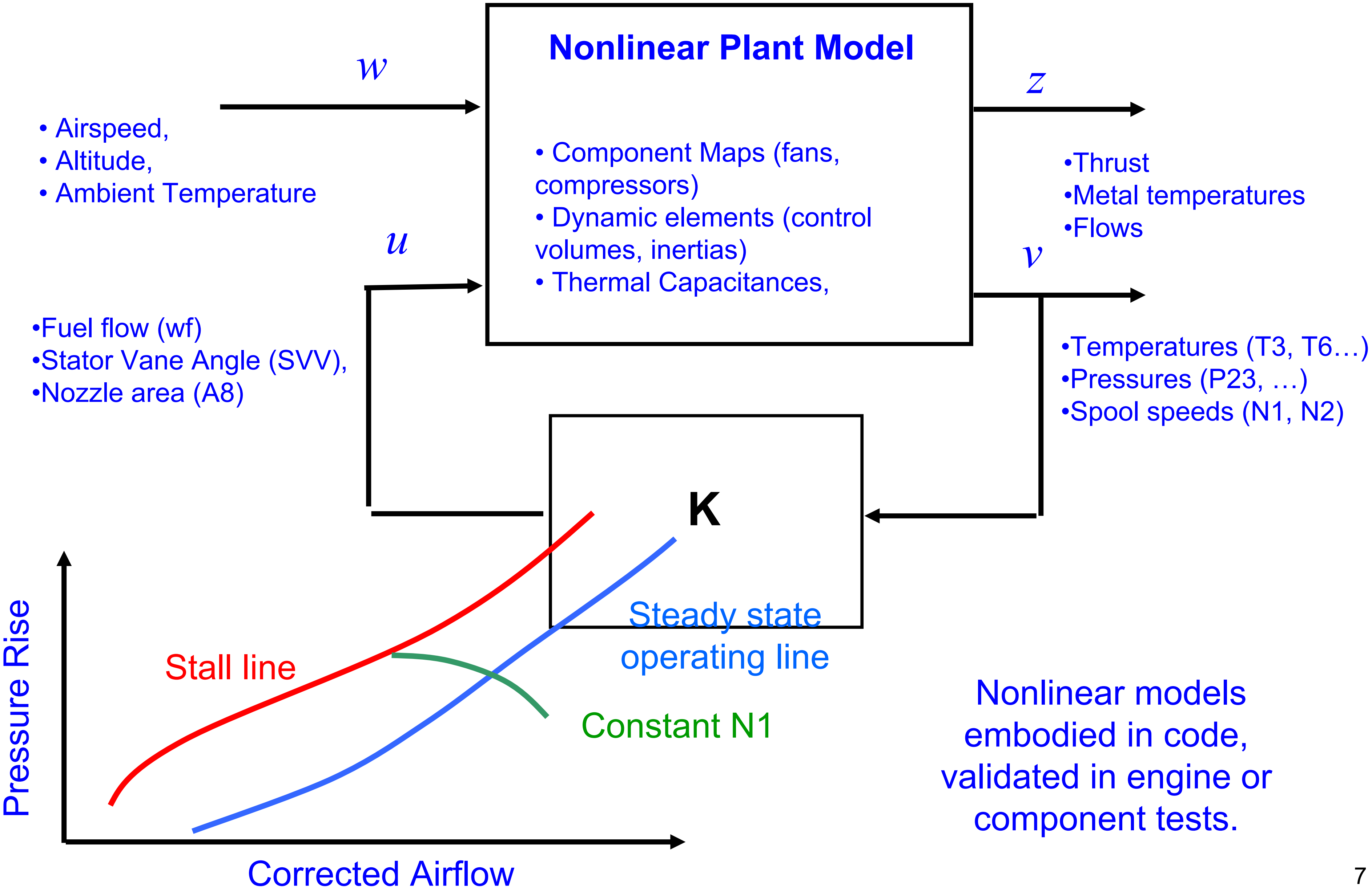
- Temperatures (T3, T6…)
- Pressures (P23, …)
- Spool speeds (N1, N2)

K

Track commanded thrust while respecting constraints

Jet Engine Dynamic Modeling

Nonlinear modeling



- Airspeed,
- Altitude,
- Ambient Temperature

- Fuel flow (wf)
- Stator Vane Angle (SVV),
- Nozzle area (A8)

Nonlinear Plant Model

- Component Maps (fans, compressors)
- Dynamic elements (control volumes, inertias)
- Thermal Capacitances,

- Thrust
- Metal temperatures
- Flows

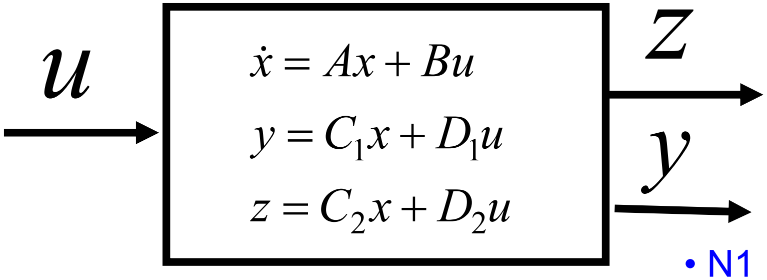
- Temperatures (T3, T6…)
- Pressures (P23, …)
- Spool speeds (N1, N2)

Nonlinear models embodied in code, validated in engine or component tests.

Jet Engine Control-oriented model

F100 example

- Main burner fuel flow (wf)
- Nozzle Jet area (A8)
- Inlet guide vane angle (CVV)



$$\dot{x} = Ax + Bu$$

$$y = C_1 x + D_1 u$$

$$z = C_2 x + D_2 u$$

- Engine thrust
- Surge Margin
- Spool speeds

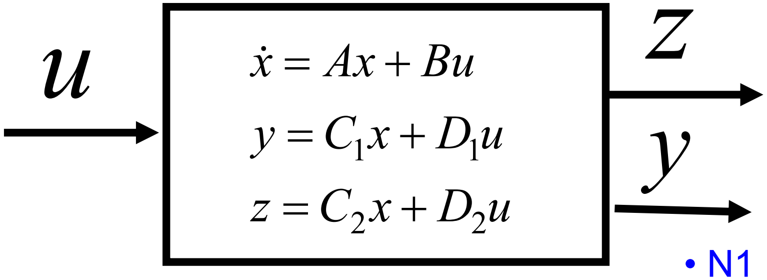
- N1 (low compressor speed)
- N2 (high compressor speed)
- P16 (high compressor outlet pressure)
- P18 (engine pressure ratio)
- P23 (low compressor pressure ratio)
- LPEMN (low compressor mach)

- Fan speed (N1)
- Compressor speed (N2)
- Compressor discharge pressure
- Interturbine volume pressure
- Augmentor pressure
- Fan discharge temperature
- Duct temperature
- Compressor discharge temperature
- Burner exit temperature 1 (fast)
- Burner exit temperature 2 (slow)
- Burner exit total temperature
- Fan inlet temperature 1 (fast)
- Fan inlet temperature 2 (slow)
- Fan turbine exit temperature
- Duct exit temperature 1
- Duct exit temperature 2

Jet Engine Control Design

Model reduction, multivariable analysis, design, constraints

- Main burner fuel flow (wf)
- Nozzle Jet area (A8)
- Inlet guide vane angle (CVV)



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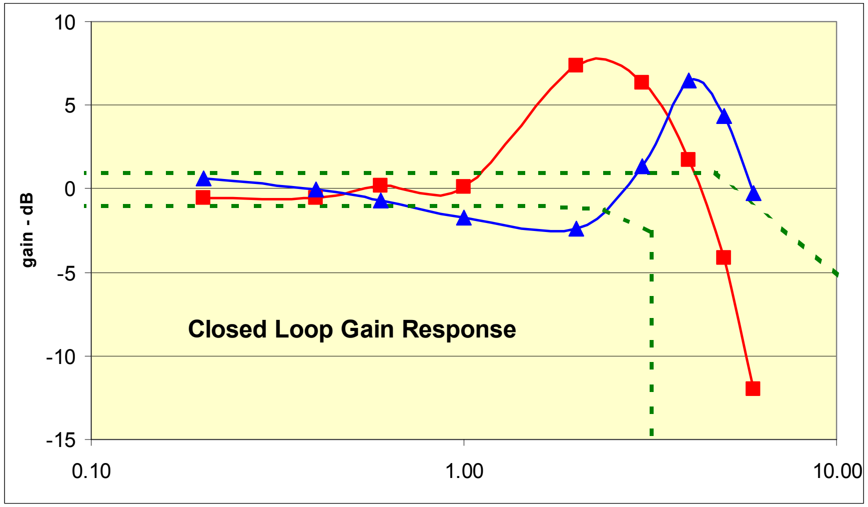
- Engine thrust
- Surge Margin
- Spool speeds

- N1 (low compressor speed)
- N2 (high compressor speed)
- P16 (high compressor outlet pressure)
- P18 (engine pressure ratio)
- P23 (low compressor pressure ratio)
- LPEMN (low compressor mach)

Steps…

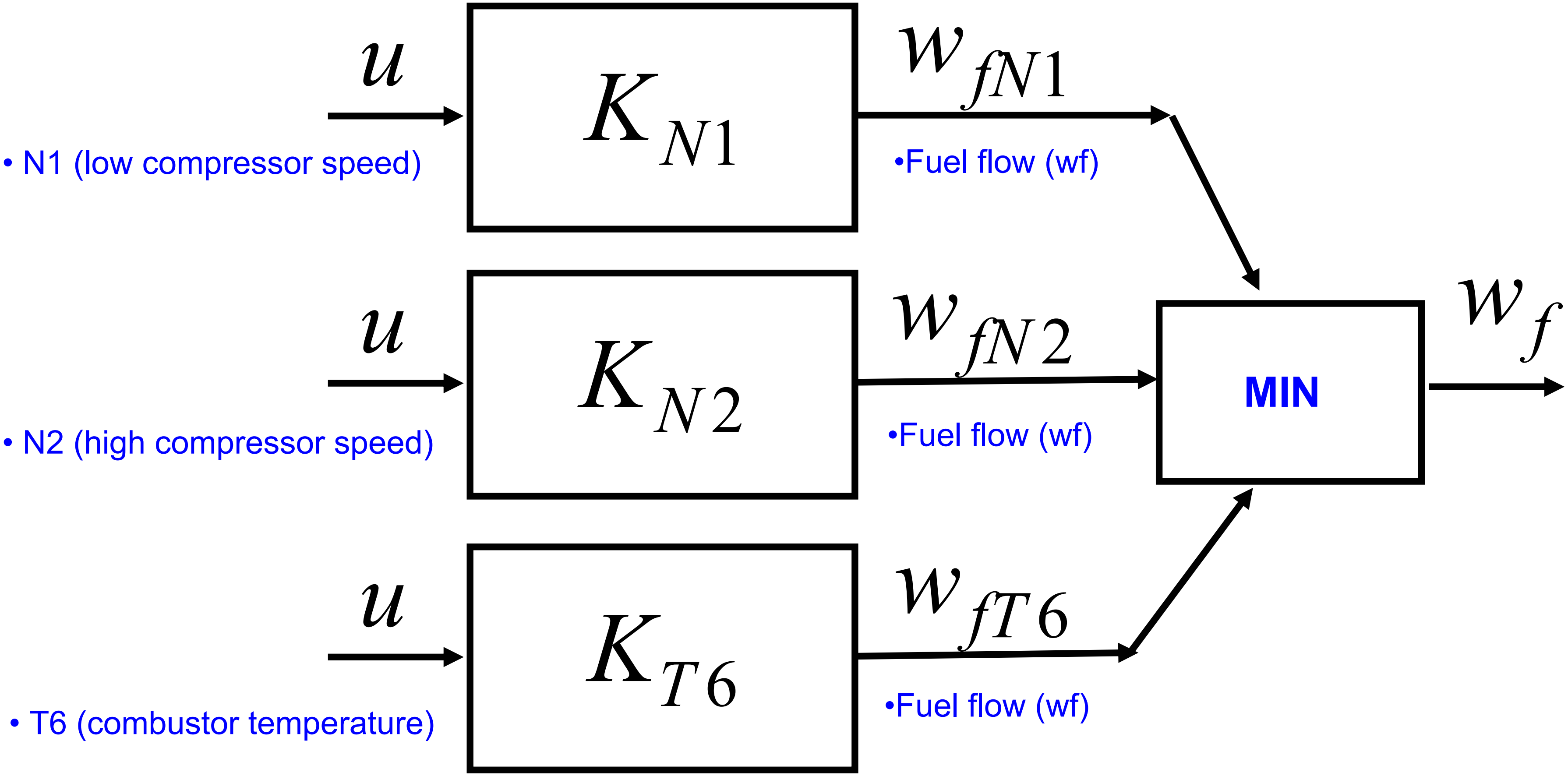
- **Model reduction**
- **Multivariable Analysis**
  - Input / output pairing
- **Design & Analysis**
  - Uncertainty
  - Customer specifications
- **Linear Simulation**
- **Constraint strategy (min/max)**
- **Nonlinear Simulation**
- **Engine test**



Control design concurrent to engine design

Jet Engine Control Design

Constraint Strategy



- N1 (low compressor speed)
- N2 (high compressor speed)
- T6 (combustor temperature)

•Fuel flow (wf)

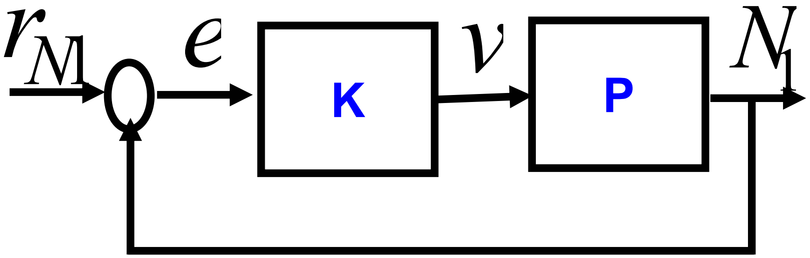
•Fuel flow (wf)

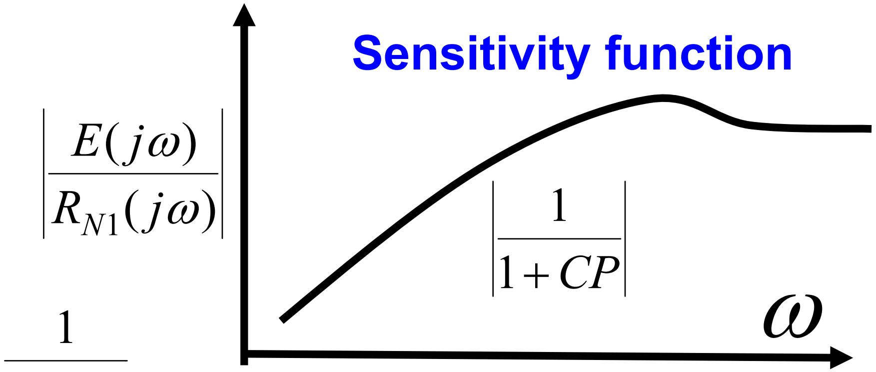
•Fuel flow (wf)

•Inputs paired with outputs.
•Several controllers run in parallel.
•Smallest value wins (hybrid system).

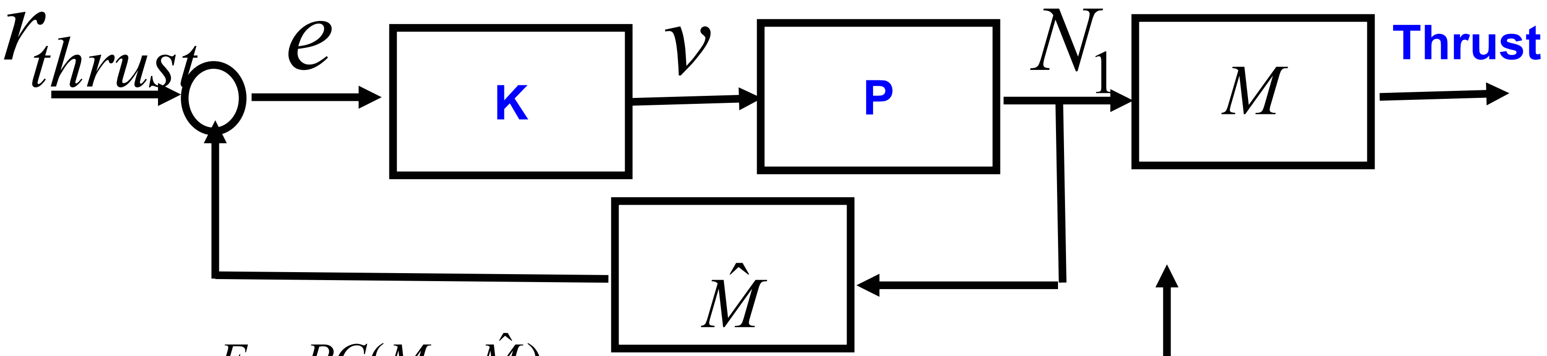
Can we close the loop on thrust ?

Simplified Robustness Analysis



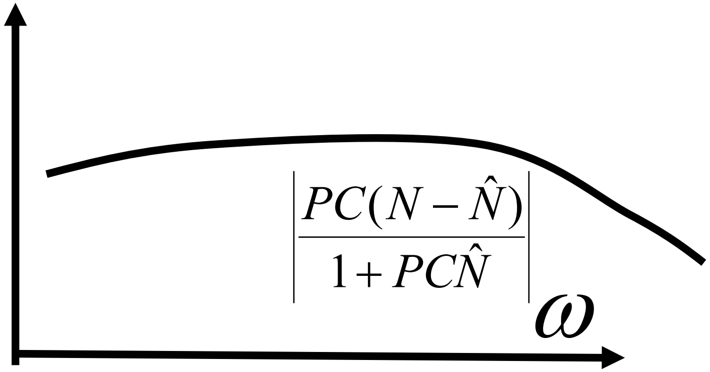


$$\frac{E}{R}=\frac{1}{1+CP}$$



$$\frac{E}{R}=\frac{PC(M-\hat{M})}{1+PC\hat{M}}$$

$$\left|\frac{E(j\omega)}{R_{N1}(j\omega)}\right|$$



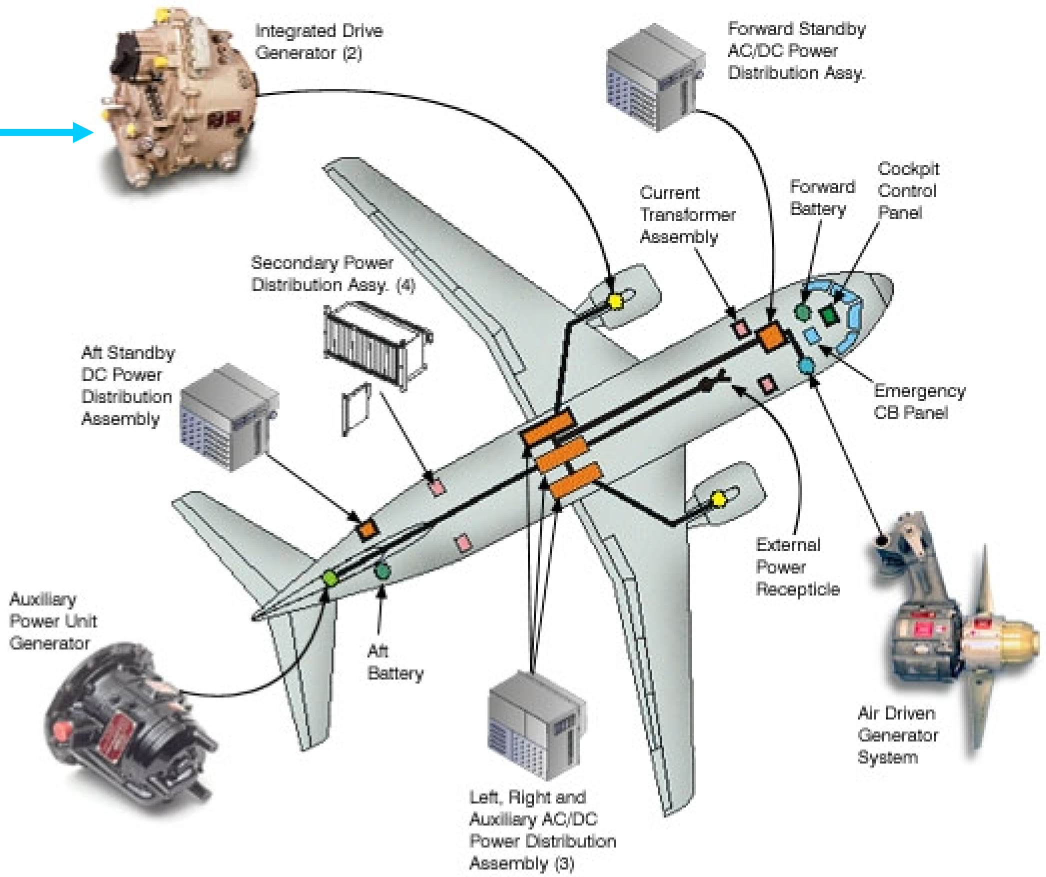
Example 2: Continuously Variable Transmissions

Introduction

CVTs Used to couple variable speed spool to constant frequency generator.

Current designs use planetary gear with hydraulic actuation to “add” or “subtract” speed.

HS owns 92% of the world’s market in airborne electrical generation.



PDA-Utitlity Function

TRU & Primary Distribution
High Power Secondary Loads
- Windshield Heat Probe
- Ventilation
- Exterior Lighting
- Fuel & Hydraulic Pump

SPDA-Utility Function

Engine Bleed Air
- Air System Control

Bleed Leak Detection
Wing/Tail Anti-Ice Control
Cabin Pressurization Control
Environmental Control System

Fuel Pump/Valve Control
Interior Lighting Control
Thrust Reverser Deployment
Oxygen Mask Deployment
Actuation Control
Windshield Heat Control

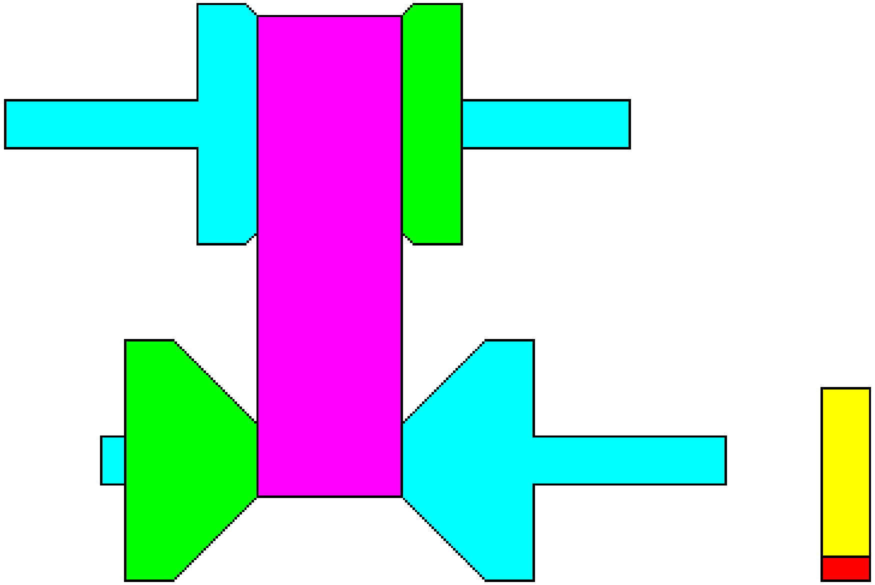
Belt – Type CVT

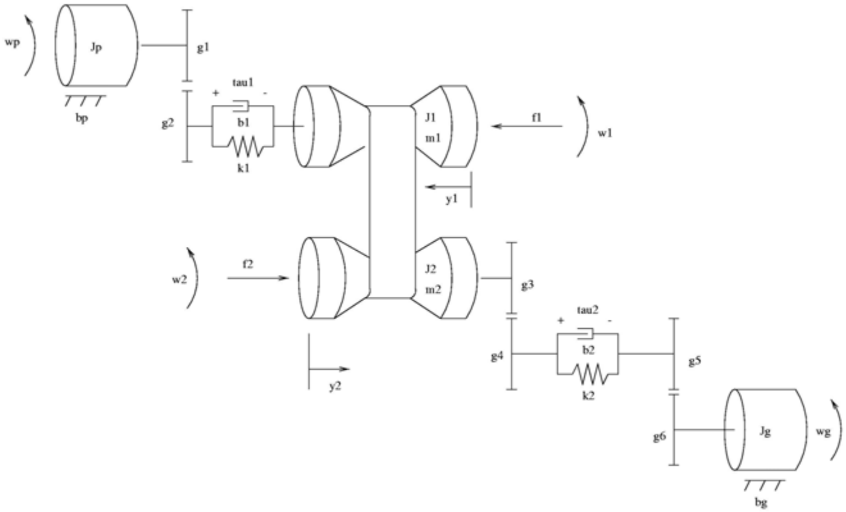
Controls objectives

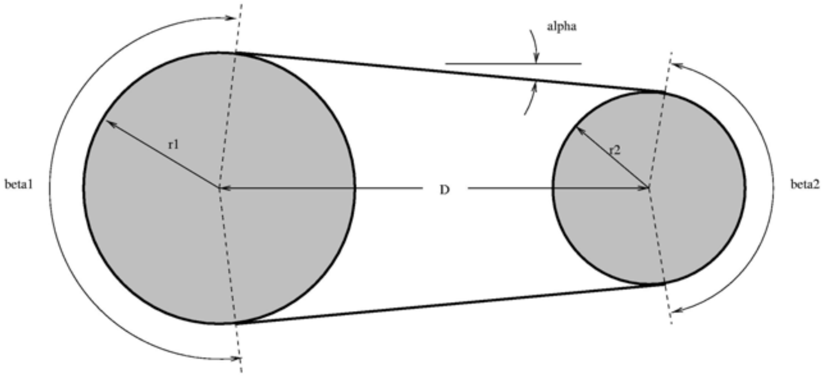
Used to couple variable speed spool to constant frequency generator

Control problem:

- Regulate generator speed
- minimize slip, maximize belt life
- Define control structure
  - Sensors,
  - actuators,
  - input/output variables
- Dynamic analysis of mechanism







Belt Type CVT Modeling

Non-holonomic rotational, nonlinear slip…

$$r_1\dot{q}_1 = r_2\dot{q}_2$$

Non-holonomic constraint

$$\gamma(r_1) = \frac{\dot{q}_2}{\dot{q}_1} = \frac{\omega_2}{\omega_1}$$

$$m_1(r_1)\ddot{r}_1 - \frac{1}{2}m'(r_1)\dot{r}_1^2 + b_5\dot{r}_1 = c_1(F_1 - \frac{\theta_1}{\theta_2}F_2)$$

radial dynamics

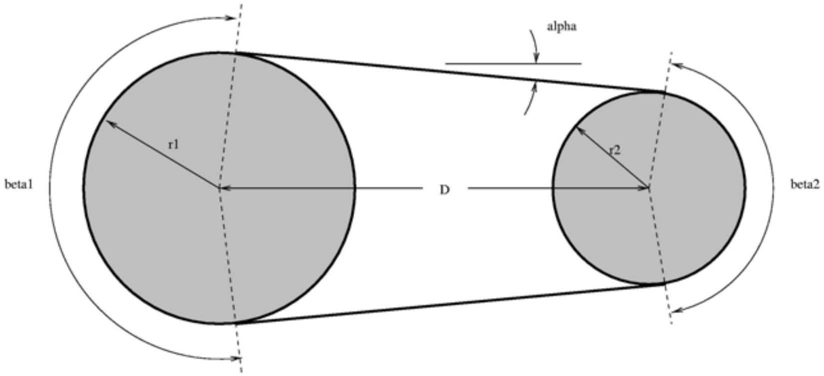
$$(J_1 + \gamma(r_1)^2 J_2)\dot{\omega}_1 + J_2\gamma'(r_1)\gamma(r_1)\omega_1 + b_3\omega_1 + b_4 = \tau_1 - \frac{g_3\gamma(r_1)}{g_4}\tau_2$$

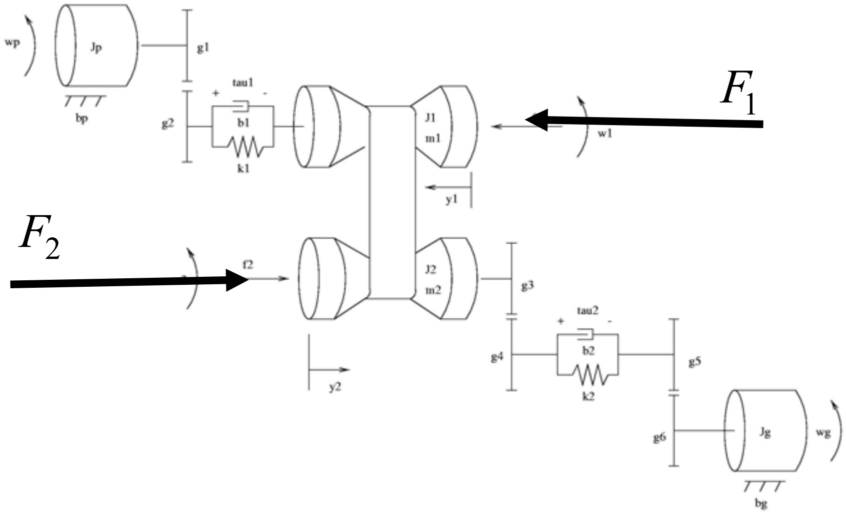
Rotational dynamics

$$\mu F_1 \geq \frac{\tau_1}{\tau_2}\cos\nu$$

$$\mu F_2 \geq \frac{\tau_2}{\tau_2}\cos\nu$$

No-slip conditions





CVT Anti-Slip Control

Models enable dynamic analysis, trade studies, parameter selection

$$\mu F_1 \geq \frac{\tau_1}{\tau_2} \cos \nu$$

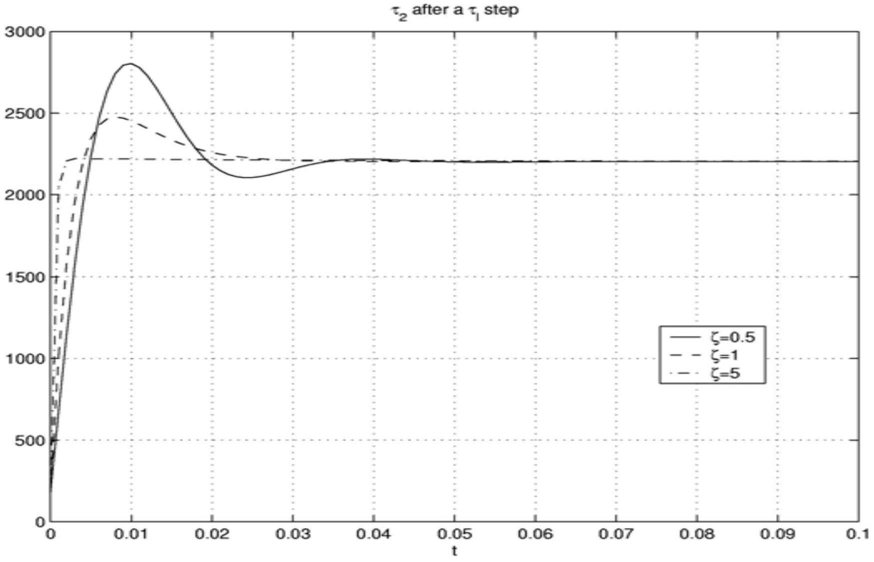
$$\mu F_2 \geq \frac{\tau_2}{\tau_2} \cos \nu$$

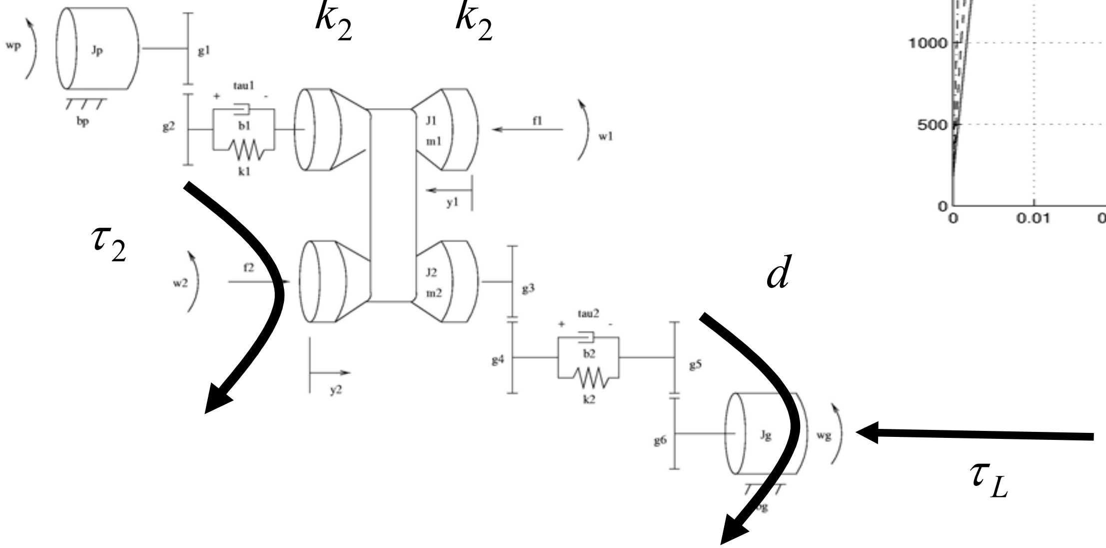
$$\frac{\tau_2}{\tau_L} = \frac{1 + s\frac{b_2}{k_2}}{1 + s\frac{b_2}{k_2} + s^2\frac{J}{k_2}}$$

$$\frac{d_2}{\tau_L} = \frac{1}{1 + s\frac{b_2}{k_2} + s^2\frac{J}{k_2}}$$

Main result: Bandwidth of hydraulic actuation system (F1, F2) must exceed bandwidth of tau2 / taul to prevent slip.

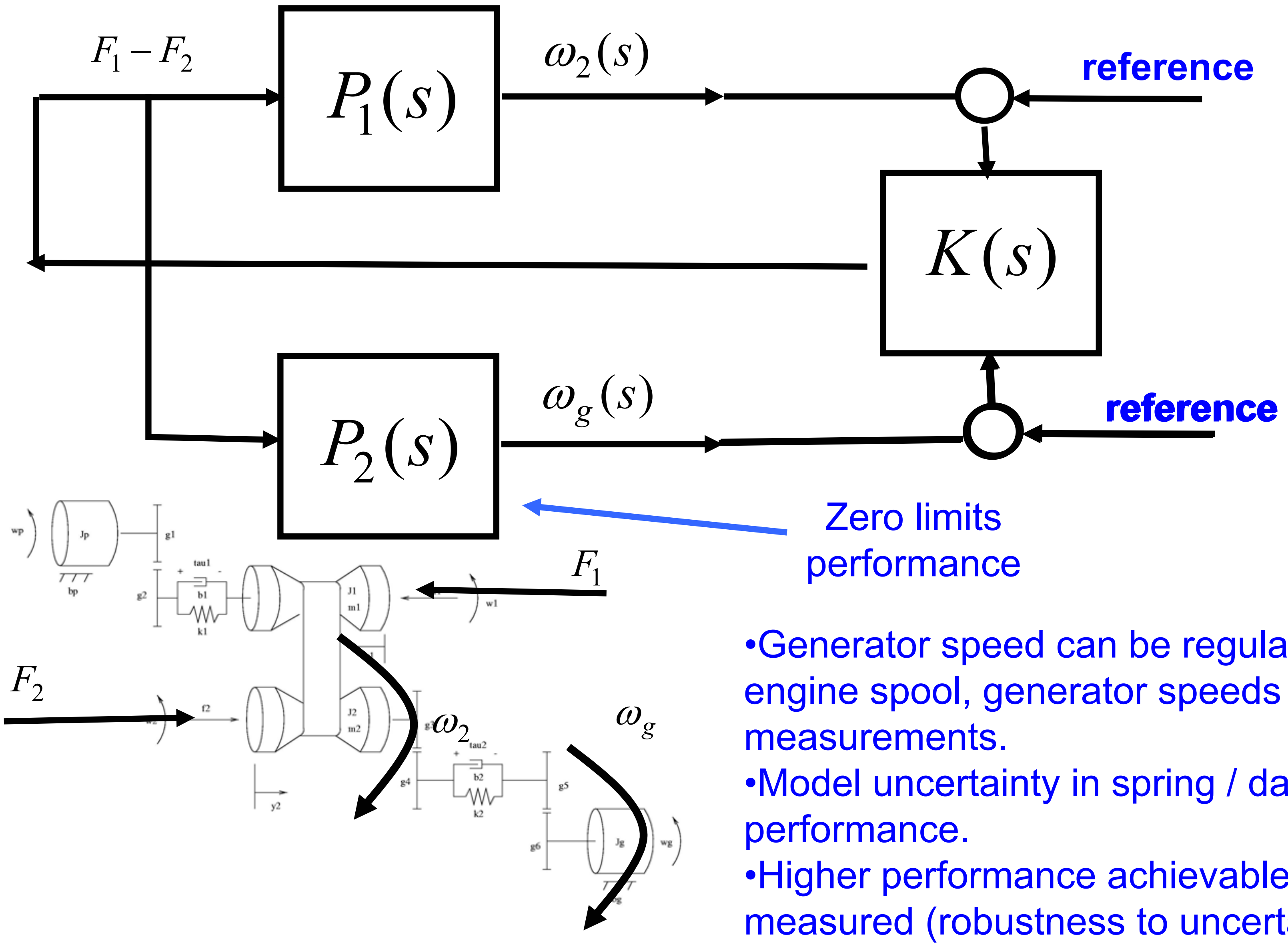
Zero means overshoot





CVT Speed Control

Models enable dynamic analysis, trade studies, parameter selection

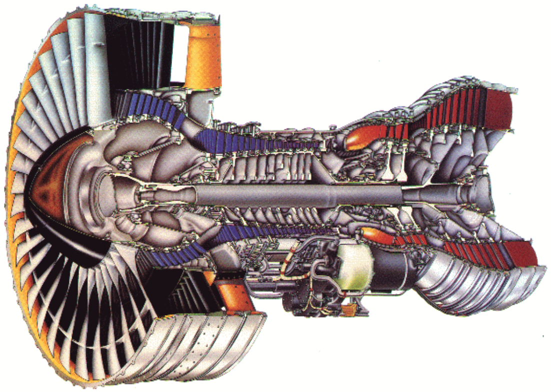


Zero limits performance

- Generator speed can be regulated using engine spool, generator speeds as measurements.
- Model uncertainty in spring / damper limits performance.
- Higher performance achievable if w2 measured (robustness to uncertainty).

Example 3: Combustion dynamics & control

Performance limitations in aero engines



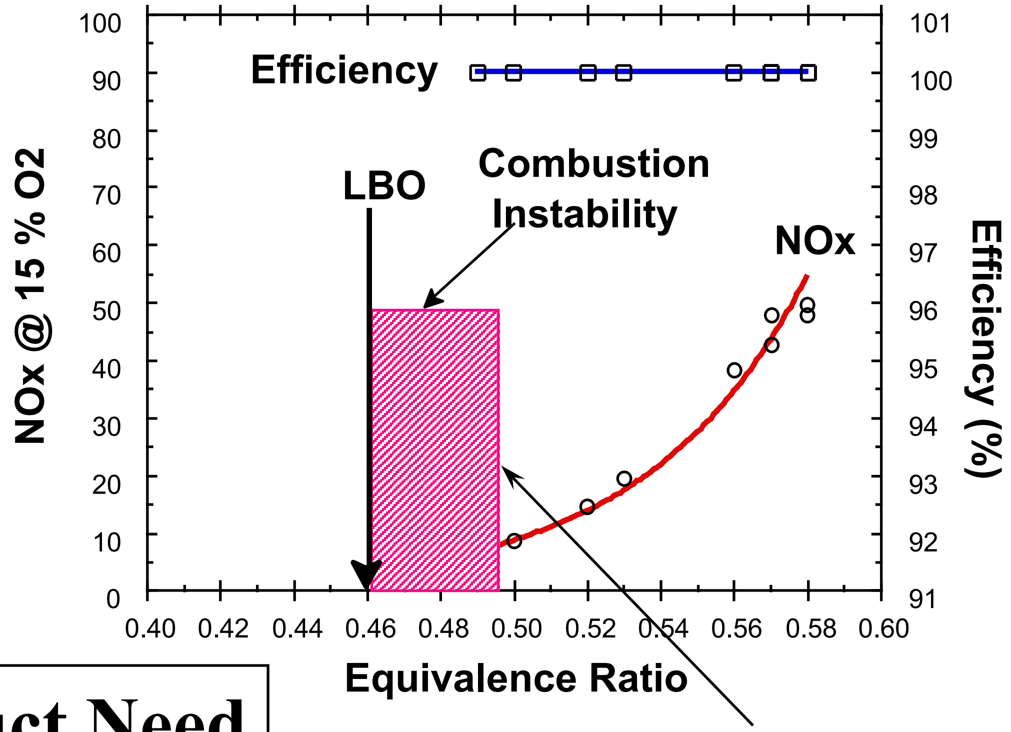
- Inlet separation
  - Separation of flow from surface
  - Possible use of flow control to modify
- Distortion
  - Major cause of compressor disturbances
- Rotating stall and surge
  - Control using BV, AI, IGVs demonstrated
  - Increase pressure ratio ⇒ reduce stages
- Flutter and high cycle fatigue
  - Aeromechanical instability
  - Active Control a possibility
- Combustion instabilities
  - Large oscillations cannot be tolerated
  - Active control demonstrated
- Jet noise and shear layer instabilities
  - Government regulations driving new ideas

Combustion Instabilities Will Occur

Combustion Instabilities Limit Minimum Achievable NOx Emissions

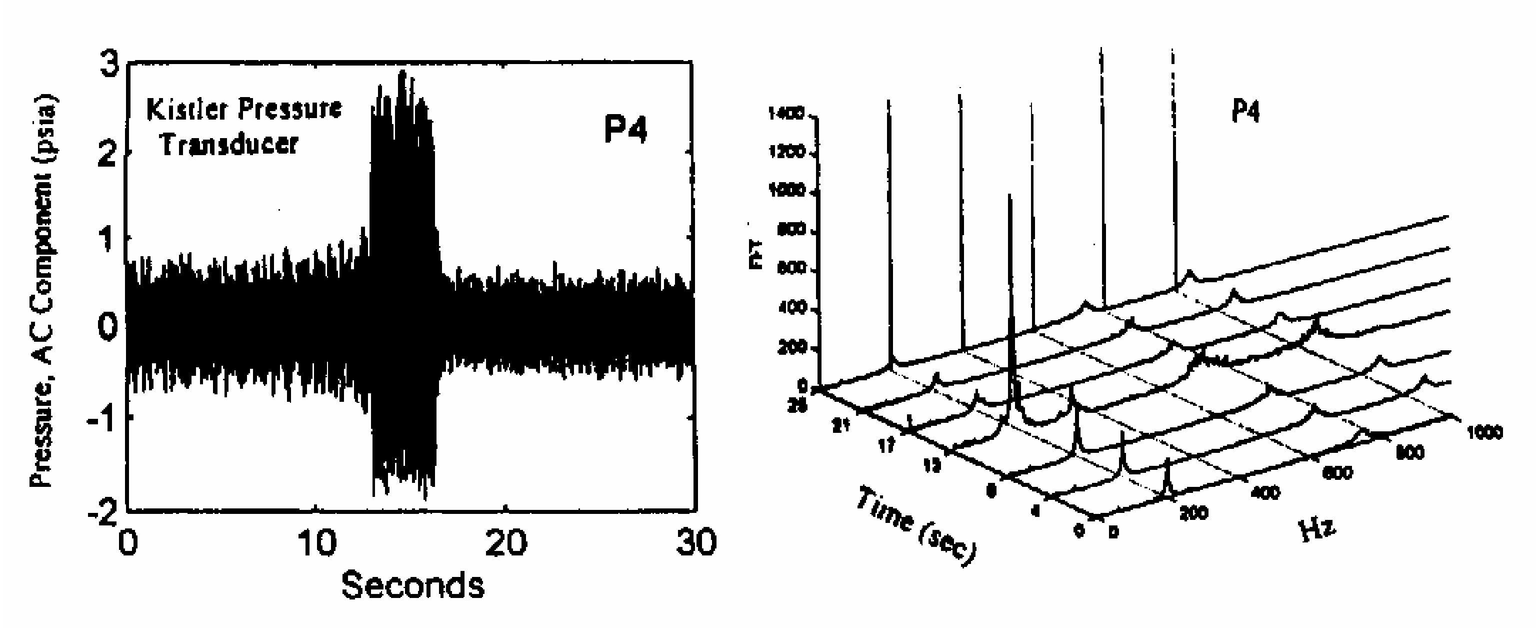
- **Goals:**
  - NOx/CO limits
  - RMS pressure limits
- **Wide range of operating conditions**
  - 50 - 100% power
  - -40 to 120 F ambient temp.
- **Instabilities inevitable**
  - combustion delay
  - convective delay
- **Passive design solution *may* be possible**
- **AIC can enable product**

Product Need



"Stability boundary" defined as maximum allowable pressure fluctuation level

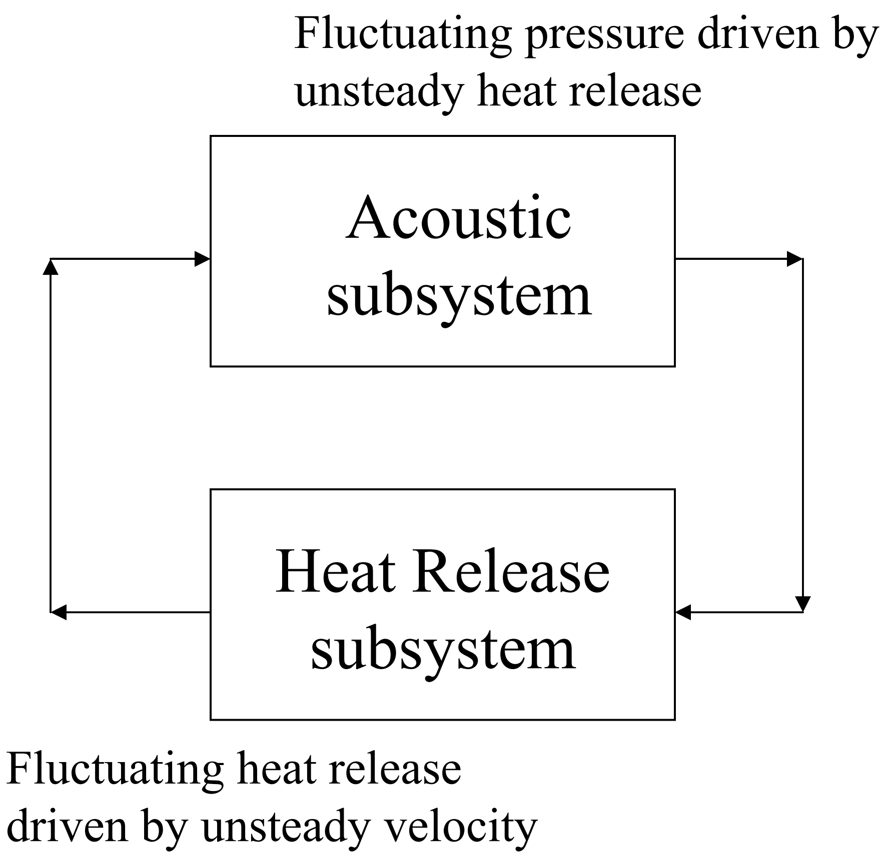
Combustors Experience Instabilities



Data obtained in single nozzle rig environment showing abrupt growth of oscillations as equivalence ratio is leaned out to obtain emissions benefit

Feedback Perspective on System Dynamics

- ***What is feedback?*** System coupling of a special type where inputs and outputs are dependent.
- ***Where does it occur?*** Most physically oscillatory (resonant) systems contain feedback - combustion dynamics is a prime example as shown. All control systems (sensor-actuator-controller or passive realization) contain explicit feedback loops.
- ***How is it used?*** To change dynamics and to cope with uncertainty.
- ***Why use it and when should it be applied?*** When dynamics are not favorable.


Fluctuating pressure driven by unsteady heat release

Acoustic subsystem

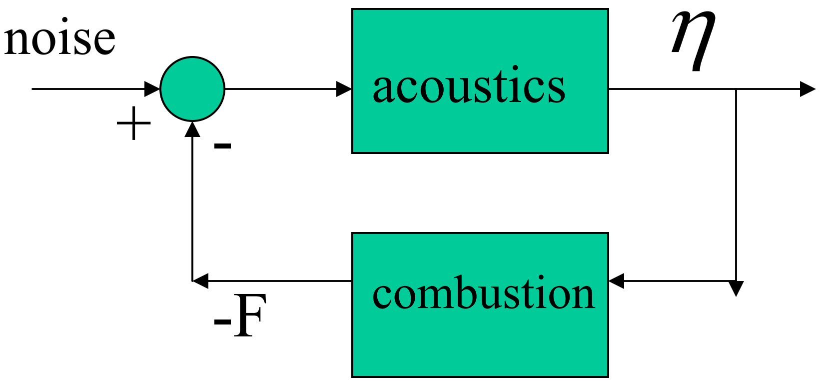
Heat Release subsystem

Fluctuating heat release driven by unsteady velocity

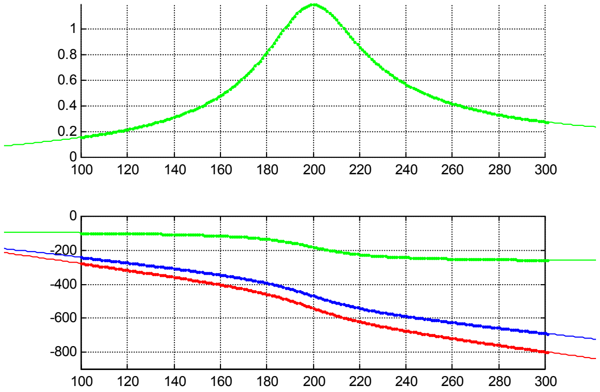
Stability analysis of combustion models using Nyquist criterion

$$\frac{d^2\eta}{d\,t^2}+\alpha\frac{d\,\eta}{d\,t}+\varpi^2\eta=F(t)$$ Acoustic mode driven by heat release

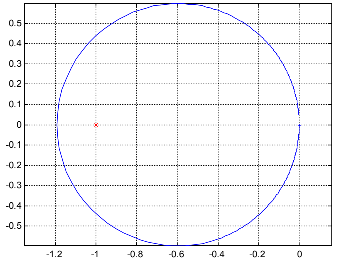
$$F(t)=K\frac{d}{d\,t}\eta(t-\tau)$$ Pressure-sensitive heat release



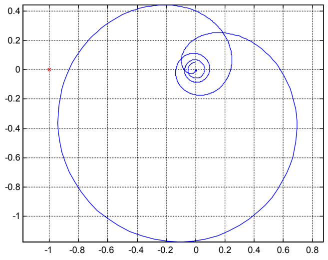
Bode plots for τ=0, 4ms, 5ms



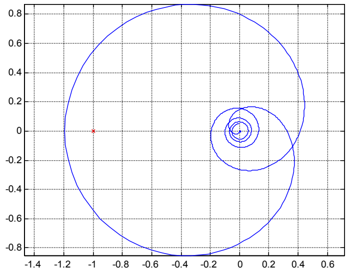
Nyquist for τ=0



Nyquist for τ=4ms



Nyquist for τ=5ms

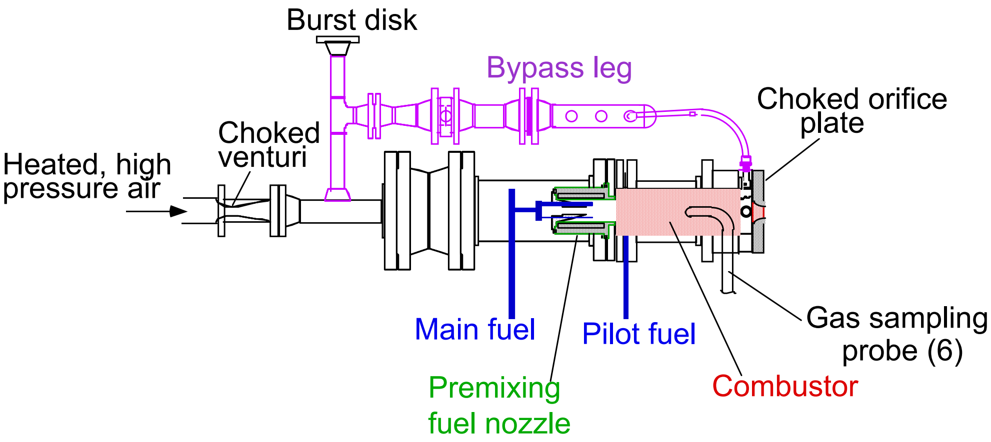


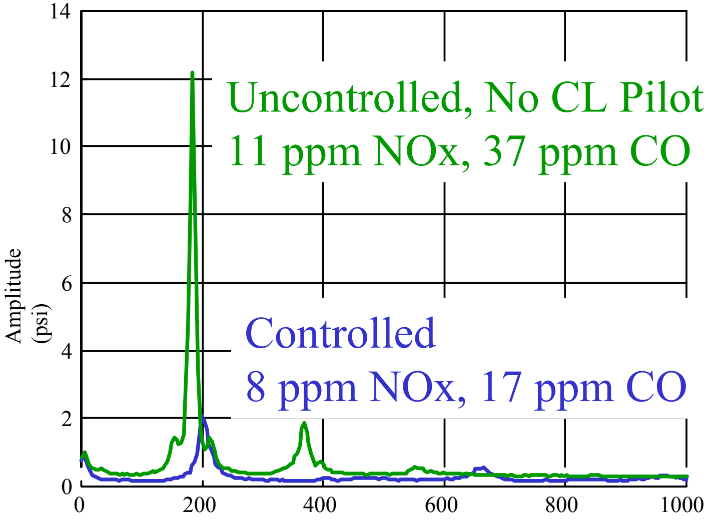
-1 inside => unstable

Example: Combustion Dynamics - Controlled and Uncontrolled

experiment in UTRC 4MW Single Nozzle Rig demonstrates 6X reduction in pressure amplitude, decrease in NO_X & CO emissions

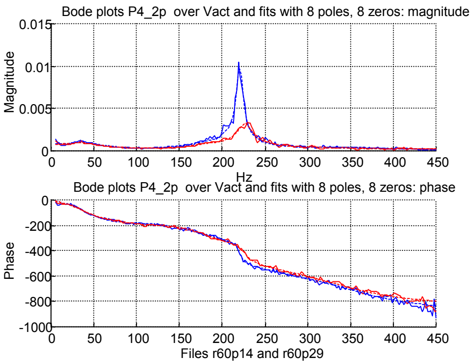
Control: a fraction of main fuel modulated by a valve driven by phase-shifted signal from a pressure transducer

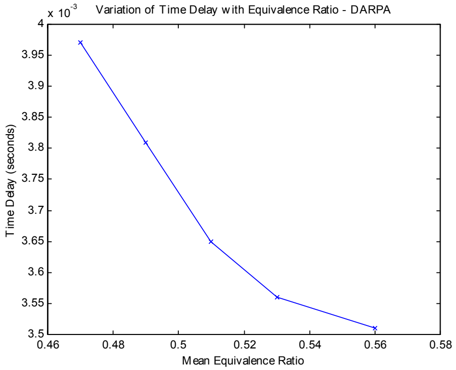




Control theory provides methods for enforcing desirable behavior

Combustion Dynamics & Control: Model Calibration and Use in Evaluation of System Modifications

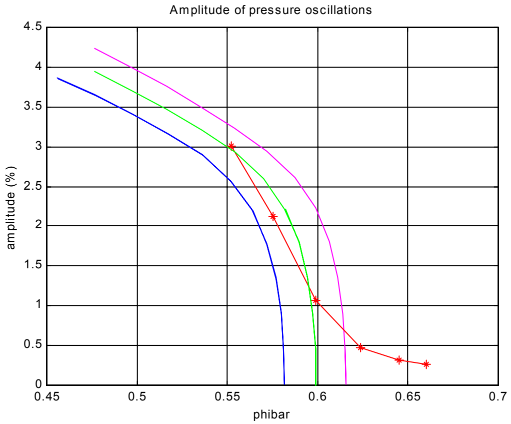




Data Analysis

Key parameters extracted from experiment (forced response tests) - trend in equivalence ratio (time delay) drives dynamical behavior

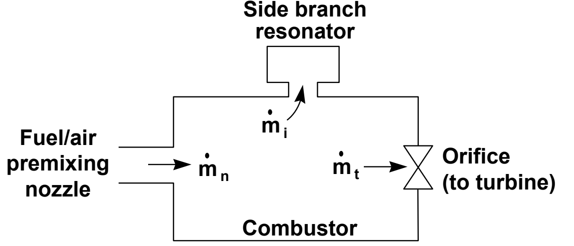
Analysis allows calibration of model from data to enable quantitative studies

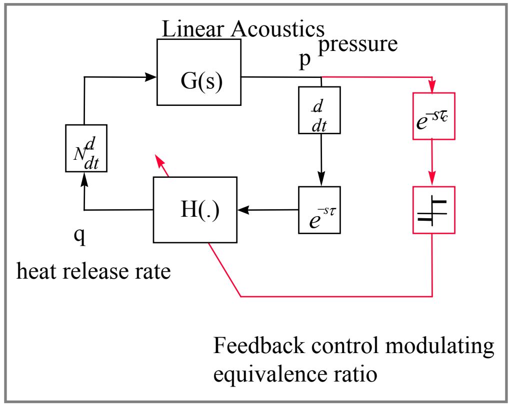


Calibration

- System level model captures experimental data quantitatively

Coupled Resonator - Combustor System





Evaluation of Mitigation Strategies

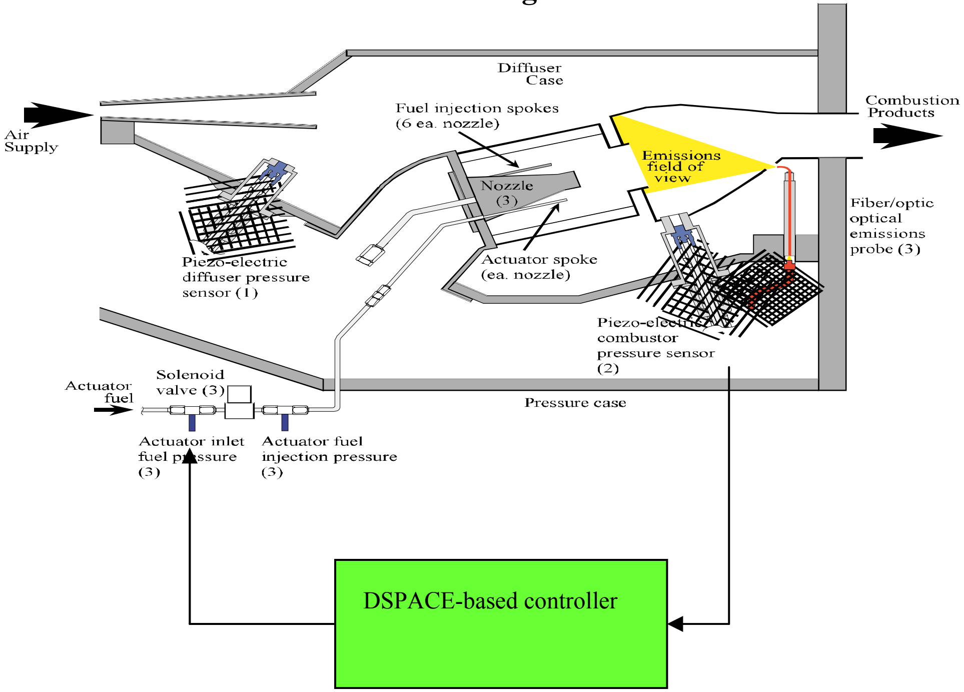
- Evaluate passive design changes (resonators) for size, placement, prediction of performance
- Evaluate active control for actuation requirements (bandwidth) and prediction of performance

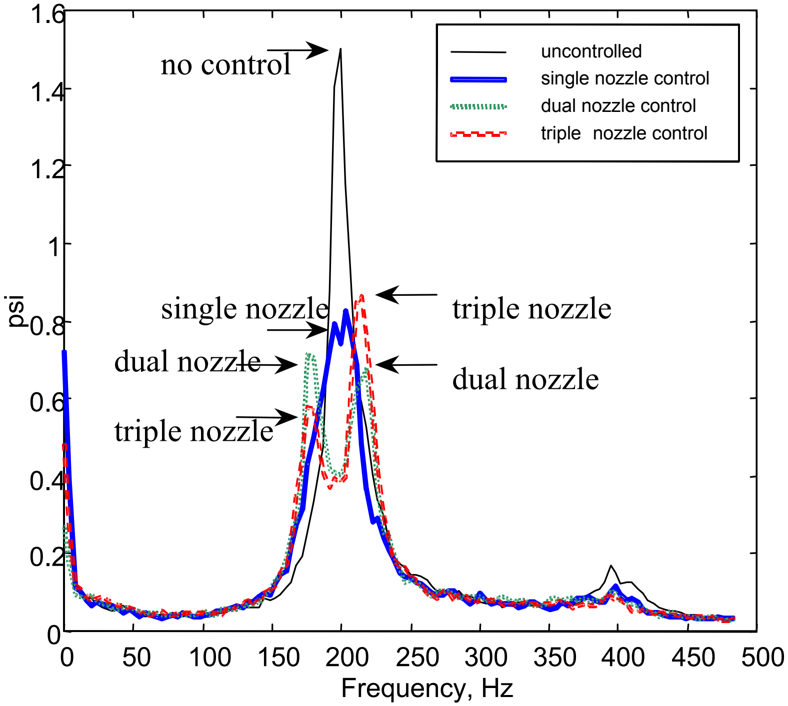
Case study: sector combustor controlled with on/off valves

Experimental setup

Results of closed-loop experiments

UTRC 8 MW three-nozzle sector rig controlled with on/off valves



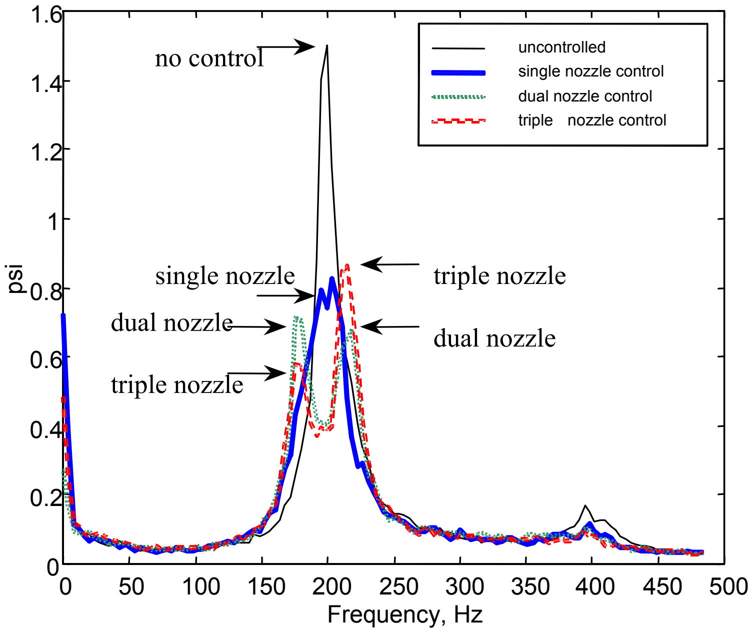


Can harmonic balance explain the observed behavior?

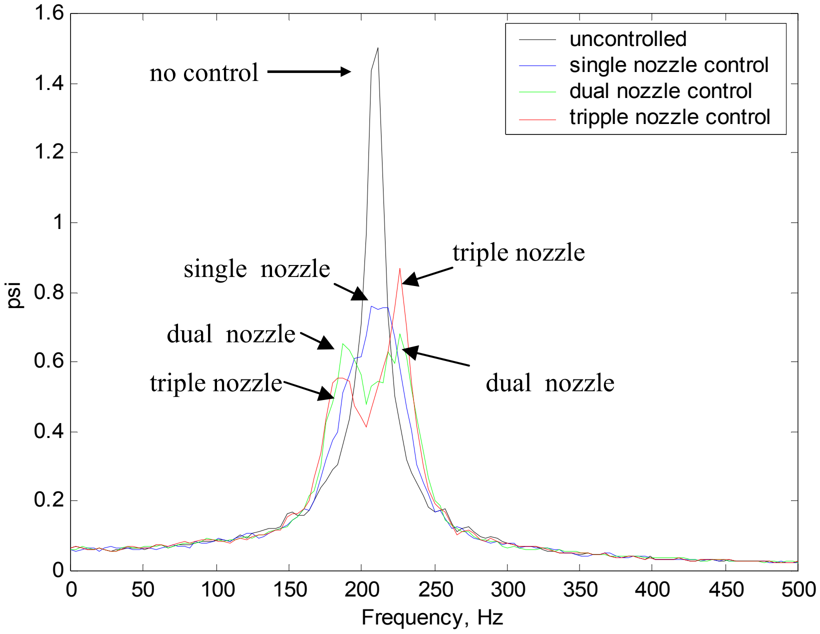
Model-based analysis explains peak-splitting

phase-shifting control excites the side bands

Experimental results in sector rig

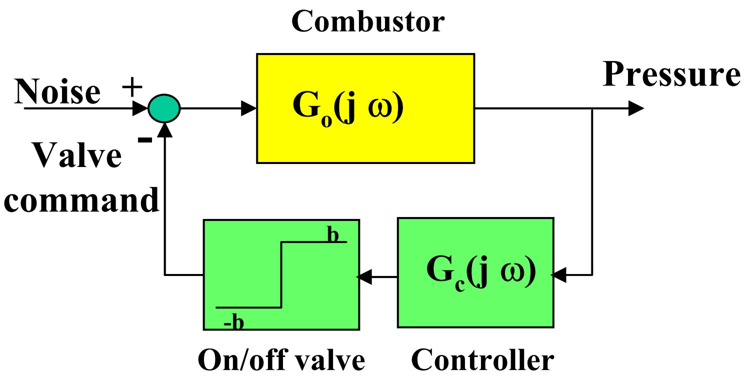


Simulation



- **Linear control theory indicates that peak-splitting will occur in the case of large delay in actuation path, high combustor damping, and limited actuation bandwidth**
- **Random-input describing function analysis allows to extend the results to nonlinear case**

Fundamental limits can be studied in nonlinear models with noise using Random Input Describing Functions



$$\frac{\text{Pressure }(j\ \omega)}{\text{Noise }(j\ \omega)} = \frac{G_o(j\ \omega)}{1 + N(A,\sigma)G_c(j\ \omega)\ G_o(j\ \omega)}$$

$= G_o(j\ \omega)\ S(j\ \omega)$, for

$S(j\ \omega) = 1/(1 + N(A,\sigma)\ G_c(j\ \omega)\ G_o(j\ \omega))$

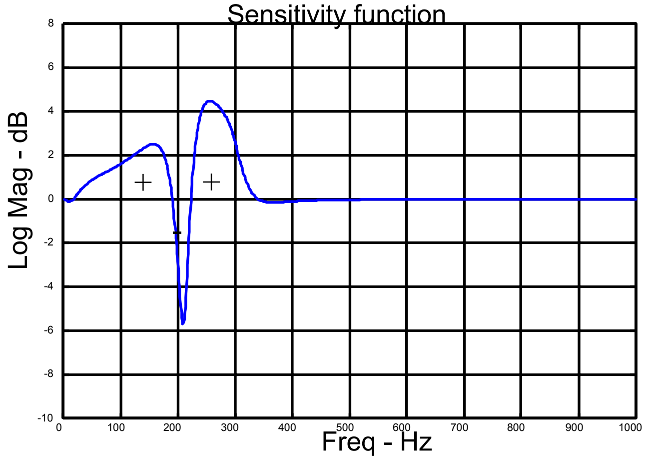
σ - STD of Gaussian component of valve command

A - amplitude of limit cycle in valve command

$N(\sigma)$ - Random Input Describing Function

$S(j\ \omega)$ is a nonlinear analog of sensitivity function

Conservation Principle: are under logarithm of sensitivity function is preserved => peak splitting will occur

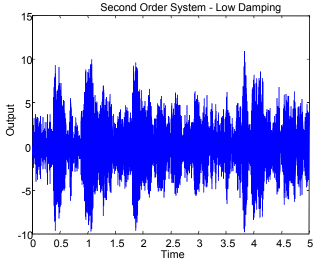


Peak splitting can occur in nonlinear systems, even limit cycling!

Combustion Dynamics & Control:Role of Dynamic Analysis in Modeling/Design Cycle

Alter system dynamics to obtain acceptable behavior

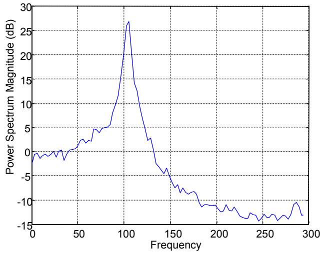
Observed Unacceptable Time Response Behavior



Model description capturing system dynamics

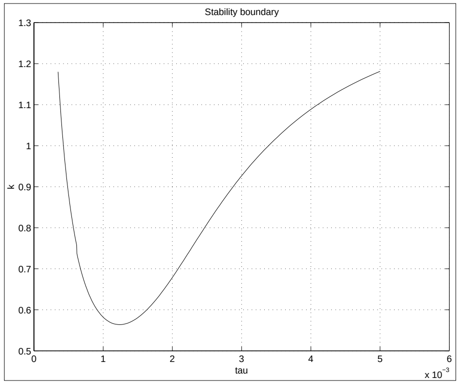
Evaluation of Design Options

- •Evaluation of model sensitivities
- •Development of experimental protocols and model calibration
- •Evaluation of paths to mitigate undesirable behavior



System Level Model Showing Feedback Coupling

Effects of Parameter Variation on Stability Boundary



Enabling effective use of dynamic model

Parametric analysis of system model

Conclusions

Aerospace Applications of Control

- Control (feedback) analysis is useful beyond control system design.

- Modeling plays a central role.
  - Nominal plant
  - Uncertainty, disturbance signals,

- Modeling is done for a well-defined purpose.

Backup

Aerospace Applications of Control

Modeling and Analysis - Nyquist Criterion(2)

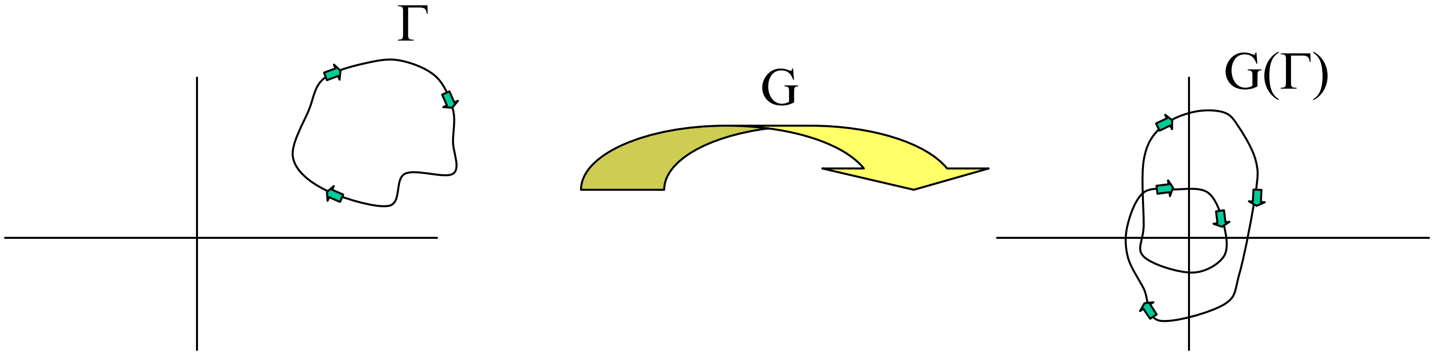
Nyquist criterion: translate closed loop properties into open loop properties

Observation: closed loop stability is equivalent to all poles of the closed loop transfer function lie in the open left half of the complex plane

Now use complex variable theory on the relevant transfer function - specifically use the so called principle of the argument

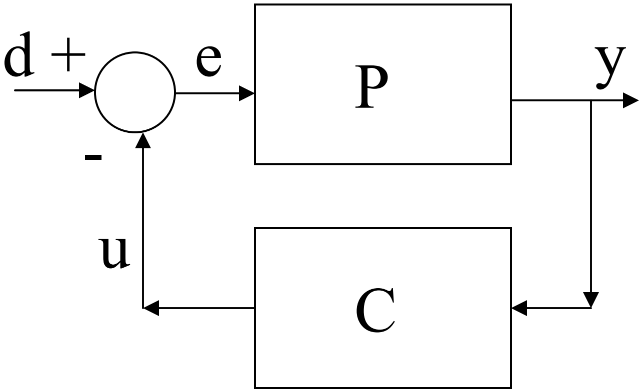
Principle of the argument: # of poles - # of zeros of a rational function inside Γ = winding number about the origin of the map $G(\Gamma)$

Graphically this is a mapping result (and a fancy way to count!)



Modeling and Analysis - Nyquist Criterion(3)

system shown is stable iff the zeros of 1+PC are in the open left half plane



$$\frac{\widehat{u}}{\widehat{d}} = PC = \frac{n_p n_c}{d_p d_c}$$ Open-loop TF

$$\frac{\widehat{u}}{\widehat{d}} = \frac{PC}{1+PC} = \frac{n_p n_c}{d_p d_c + n_p n_c}$$ Closed-loop TF

closed loop poles

But examine 1+PC:

$$1 + PC = 1 + \frac{n_p}{d_p}\frac{n_c}{d_c} = \frac{d_p d_c + n_p n_c}{d_p d_c}$$

open loop poles

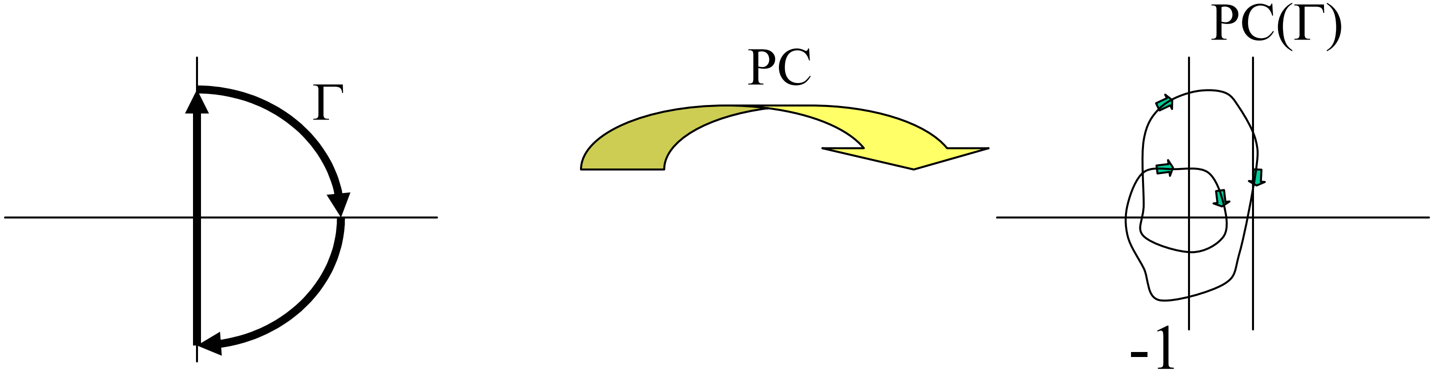
Now map the RHP under 1+PC and count encirclements of the origin

or

Map the RHP under PC and count encirclements of -1

Modeling and Analysis - Nyquist Criterion(4)

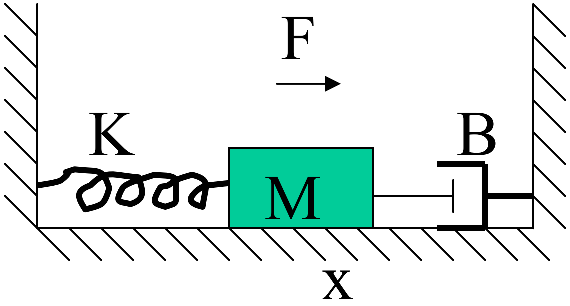
of OL poles - # of CL poles inside Γ = winding number of $P\,(j\omega)\;C(j\omega)$ about -1



Nyquist Criterion: closed loop feedback system is stable <=> the number of encirclements of -1 is equal to the number of open loop poles

Special case: If the open loop system is stable then the closed loop system will be stable <=> the Nyquist plot of the open loop system does not encircle or touch -1

Modeling and Analysis - Nyquist Example



Consider making the applied force a function of the velocity and choosing the function to add damping

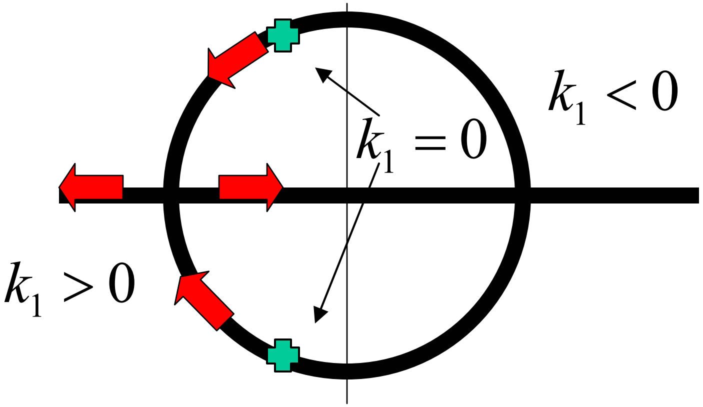
$$F = -k_1\dot{x}$$

Approach I: Compute. Form the “closed loop system” and use computation to determine the closed loop eigenvalues (poles) and plot them as a function of the gain

Results for all gain (positive and negative) shown by the “root locus” plot

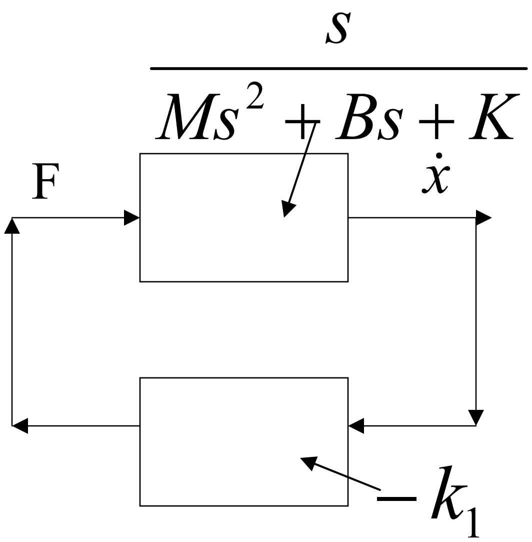
$$M\ddot{x} + B\dot{x} + Kx = -k_1\dot{x}$$

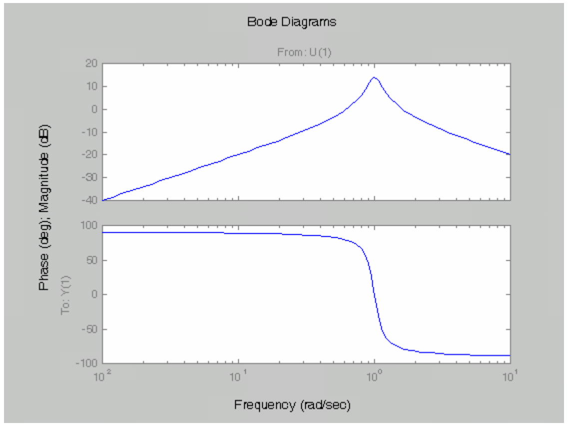
$$M\ddot{x} + \left(B + k_1\right)\dot{x} + Kx = 0$$

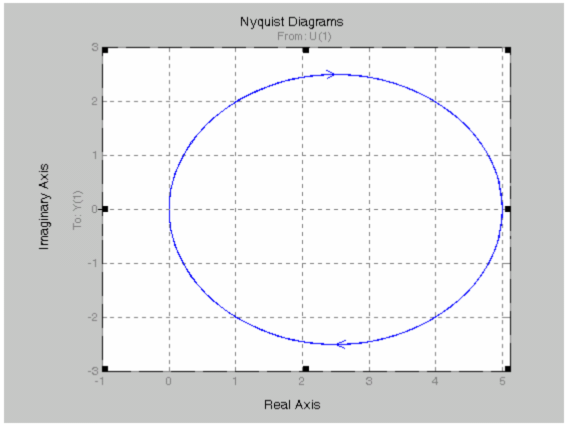


Modeling and Analysis - Nyquist Example(2)

Approach II: Use Nyquist theorem. Form the block diagram of the "closed loop system" and use open loop properties to determine the closed loop stability as a function of the gain



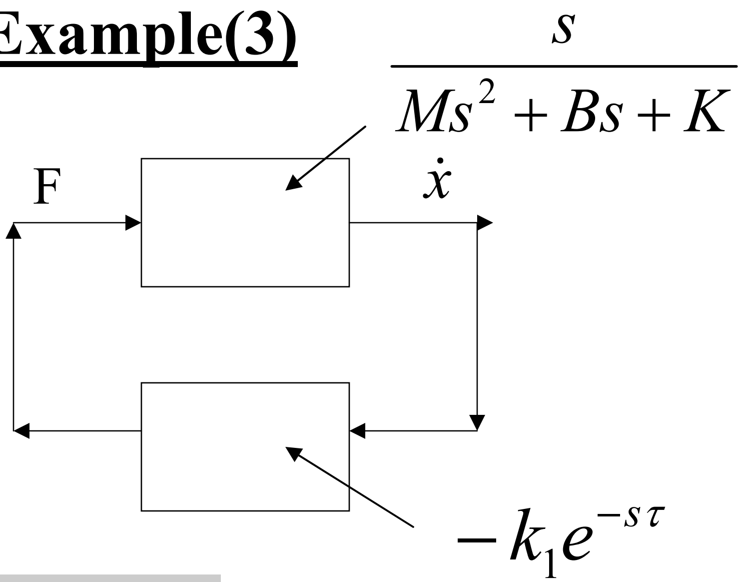




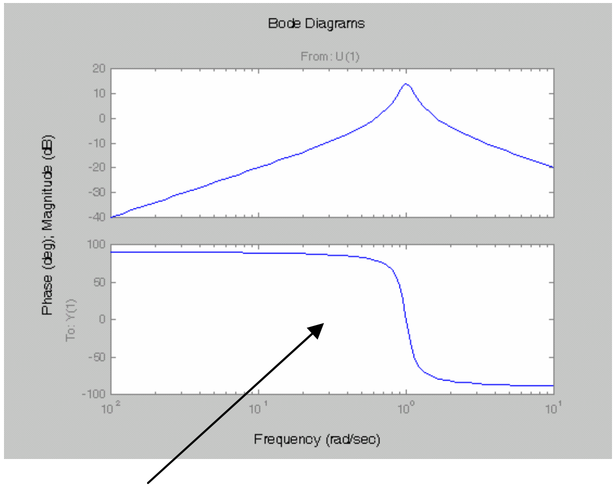
Nyquist plot shows no encirclements of -1 point (for positive gain) so system is closed loop stable (but for increasing gain plot comes close and so there is decreasing margin) - for negative gain there are always two encirclements (unstable)

Modeling and Analysis - Nyquist Example(3)

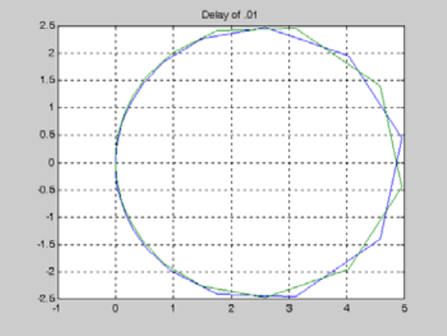
Approach II: A bit of realism - suppose that the sensor for the rate (tachometer) has a small delay - what will be the effect on the stability of the closed loop system?

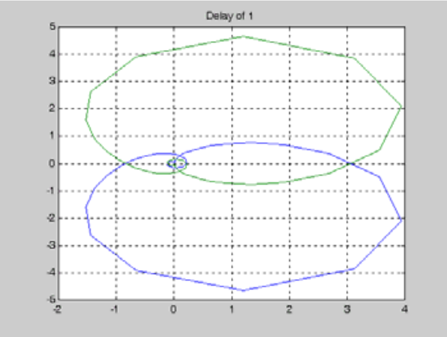


$$M\ddot{x}(t)+B\dot{x}(t)+Kx(t)=-k_1x(t-\tau)$$



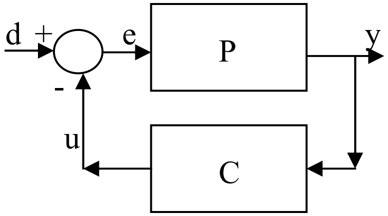
Effect of delay: subtracts ωτ from the phase response of oscillator





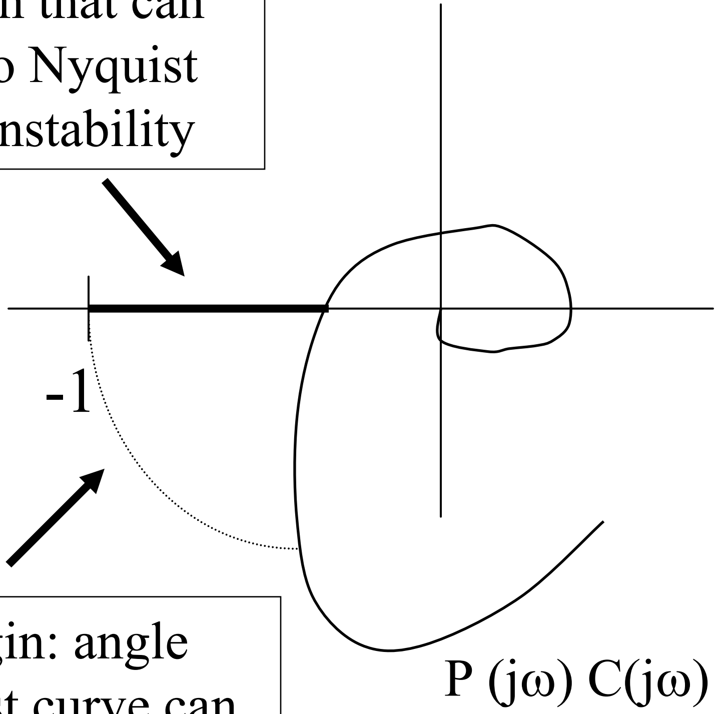
For small delays the Nyquist plot is unchanged but for large delays (or large frequencies) the plot is significantly different and the presence of a delay may alter stability - easily seen in the frequency domain!

Synthesis for Linear Systems - Nominal Stability



- Nominal stability of the closed loop system can be easily ascertained using the Nyquist plot as shown,
- Typical values for gain margin are 6 dB and for phase margin 45-60 degrees

Gain margin: amplification that can be applied to Nyquist curve until instability

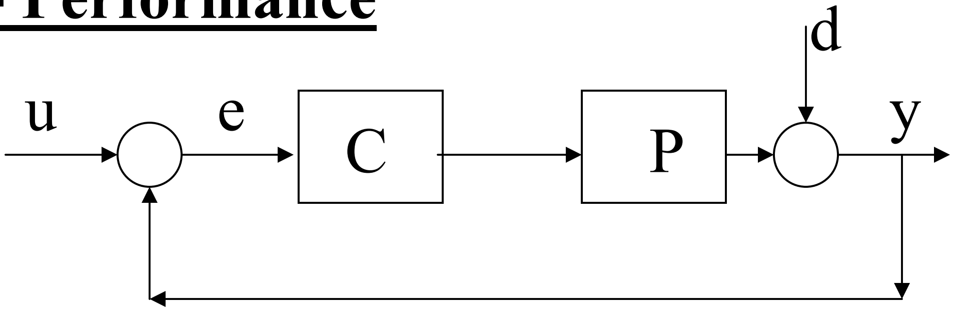


Phase margin: angle that Nyquist curve can be rotated until instability

Synthesis for Linear Systems - Performance

- Performance typically refers to tracking where the output (y) is required to (asymptotically) follow the input (u) or disturbance rejection where the output (y) is made to be insensitive to the disturbance (d) - both over a range of frequencies

- Both problems are the same (single degree of freedom feedback structure) and require that the sensitivity function S be small over the range of frequencies where performance is required



sensitivity

$$S = \frac{1}{1+PC}$$

complementary sensitivity

$$T = \frac{PC}{1+PC}$$

$$y = Sd\,, e = Su\,, y = Tu$$

so performance(tracking or disturbance rejection requires):

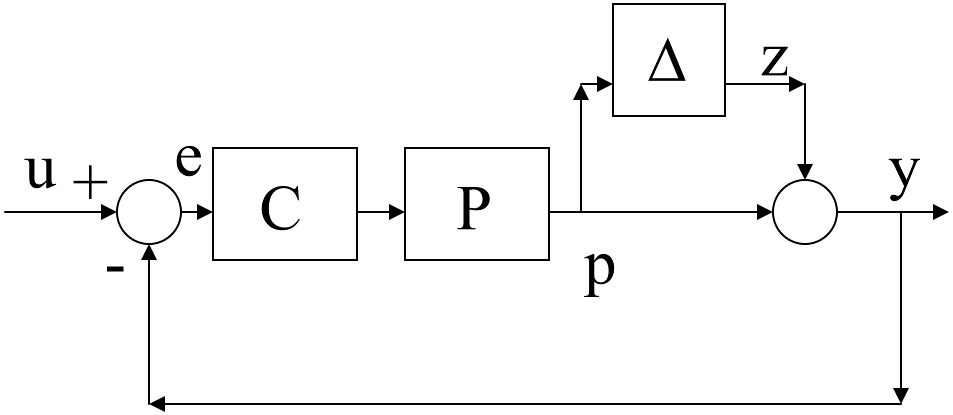
$$\left|S\left(i\omega\right)\right| << 1$$

over the range of frequencies for which tracking and disturbance rejection is desired

Synthesis for Linear Systems - Robustness

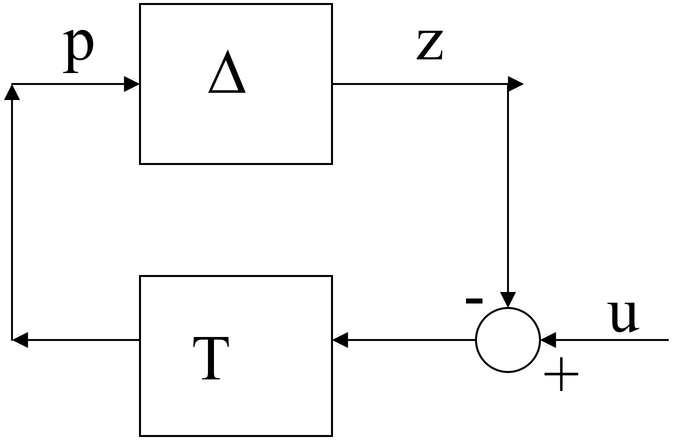
Problem: consider the perturbed system (for example only shown perturbed at output - analysis could be done for other cases). What conditions on the open loop ensure that the closed loop will be robustly stable where robustly means for all Δ that is norm bounded (say by δ)?

Solution: first redraw the block diagram to illustrate what the uncertainty "sees"



$$z = \Delta p,\ y = p + z,\ \ p = PCe,\ \ e = u - y$$

$$p = \frac{PC}{1+PC}(u - z) = T(u - z)$$



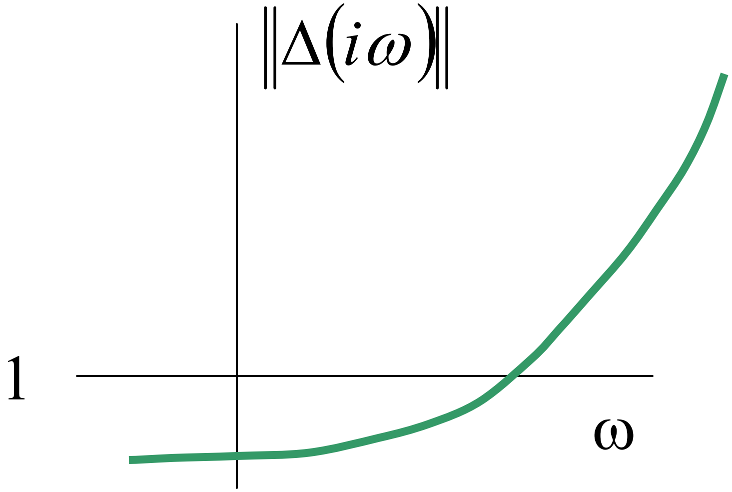
Synthesis for Linear Systems - Robustness(2)

Solution (continued):

•if the uncertainty is unknown (phase) then the TΔ loop is stable iff the "loop gain" is strictly < 1,

•recognize that the "loop gain" is the complementary sensitivity function and then this requires that the loop "roll off" at high frequencies

Typical shape for uncertainty (percentage of output) is small at low frequency and increasingly uncertain (especially phase) at high frequency



Robust stability then implies that the complementary sensitivity function "roll off" or to preserve robustness performance is sacrificed

$$\left|T(i\omega)\right| \le \frac{1}{\left|\Delta(i\omega)\right|} \;\forall\, \omega$$