PID Tuning for Temperature Control of Heated Plates Using the Waterbed Effect

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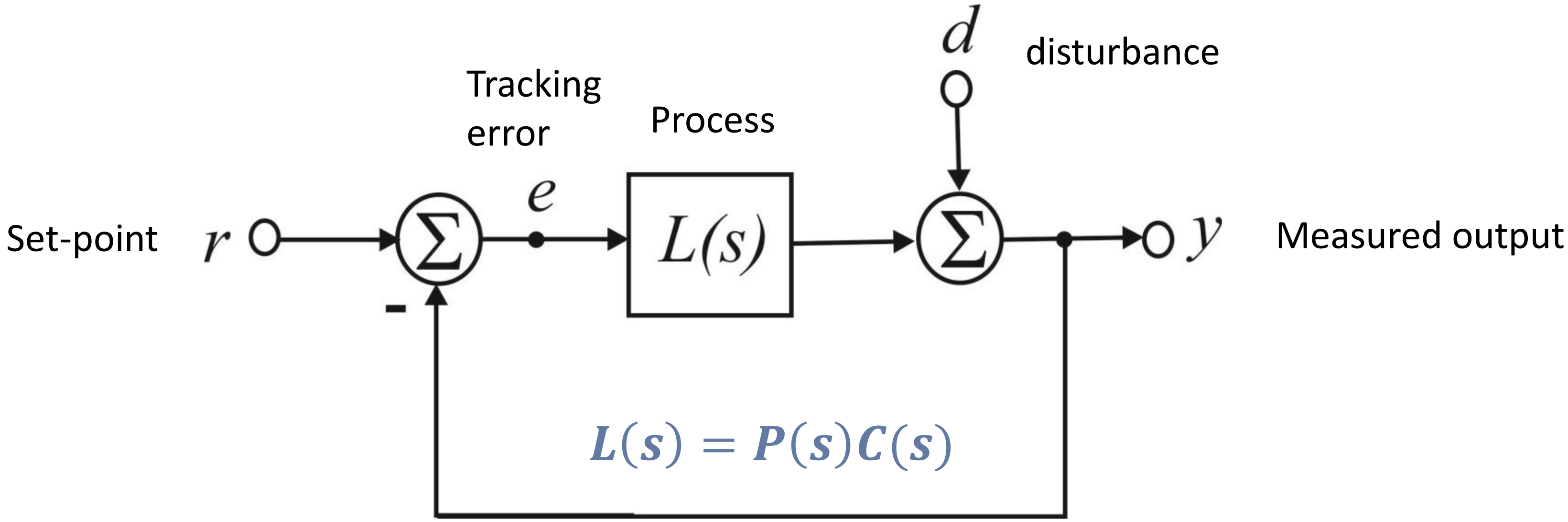
Overview

- ❑ The Waterbed Effect Theory
- ❑ Using the Theory for PID Tuning
- ❑ Application to a Heated Plate
- ❑ Summary & Conclusions

The Waterbed Effect

- There is a fundamental and inescapable limitation on achievable design specifications in feedback control systems
- The sensitivity function, $|S(s)|$ is the transfer function from the reference input r (Set-point) to the tracking error e
- The overall transfer function gain is less sensitive to variations in the process gain by a factor of $|S|$

$$E(s) = \left(I + L(s)\right)^{-1} R(s) = S(s)R(s)$$



$$L(s) = P(s)C(s)$$

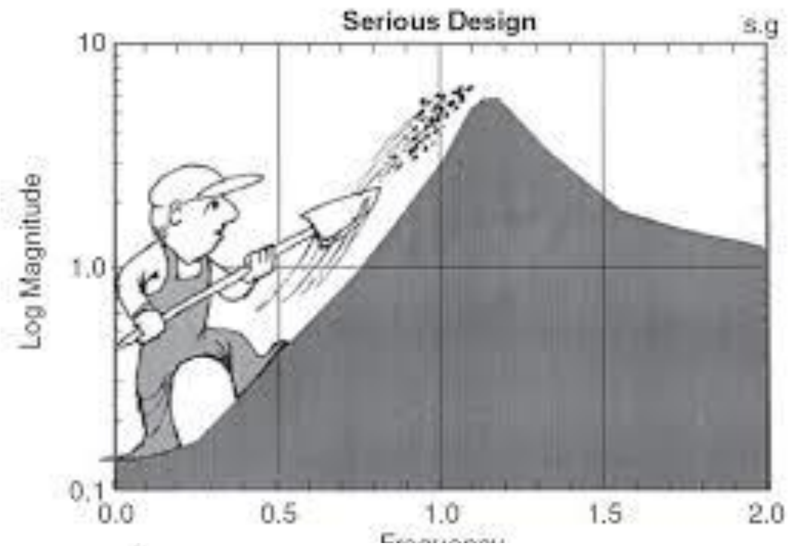
Unity feedback control system

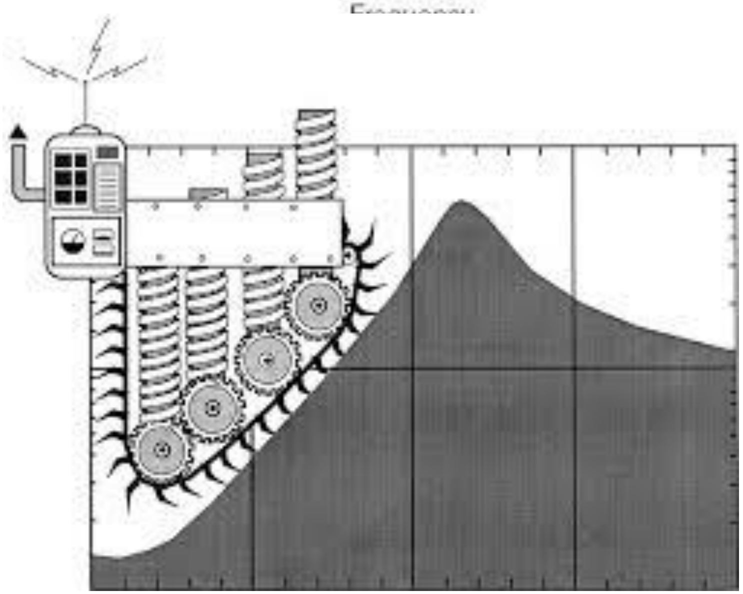
The Waterbed Effect

- Bode showed that for a system with an excess of at least two more poles than zeros and no right-half plane (RHP) poles, $\int_0^\infty ln(|S|)d\omega = 0$
- This means that if the sensitivity is to be reduced in a certain frequency range, then of it must be increased in another frequency range. This is referred to as the waterbed effect.
- If the system has n_p unstable poles then, $\int_0^\infty ln(|S|)d\omega = \sum_{i=1}^{n_p} Re\{p_i\}$
- Recently [Emami-Naeini, D. de Roover, 2015] we have derived a new fundamental result that has been seemingly masked by previous derivations :

$$\int_0^\infty \ln|s(j\omega)|d\omega = \begin{cases} -\frac{\pi}{2}\left(\sum_{i=1}^{n}(\tilde{p}_i - p_i)\right), OLS \\ -\frac{\pi}{2}\left(\sum_{i=1}^{n}(\tilde{p}_i - p_i) + \sum_{i=1}^{np} 2p_i\right), OLU \end{cases}$$

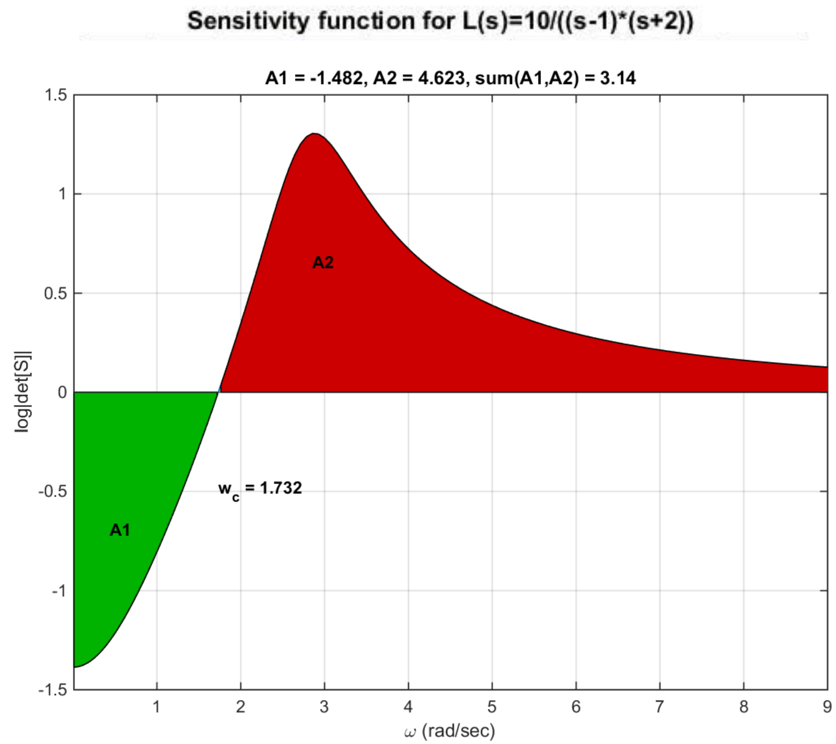
- The fundamental relationship is that the sum of areas underneath the ln(|S|) is related to the difference in speeds of the closed-loop system and the open-loop system. This makes much intuitive sense.





- The Waterbed Effect can be viewed as a "sensitivity dirt," **conservation** law for control systems.

Gunter Stein, "Respect the Unstable", IEEE Control Systems Magazine, Aug. 2003.



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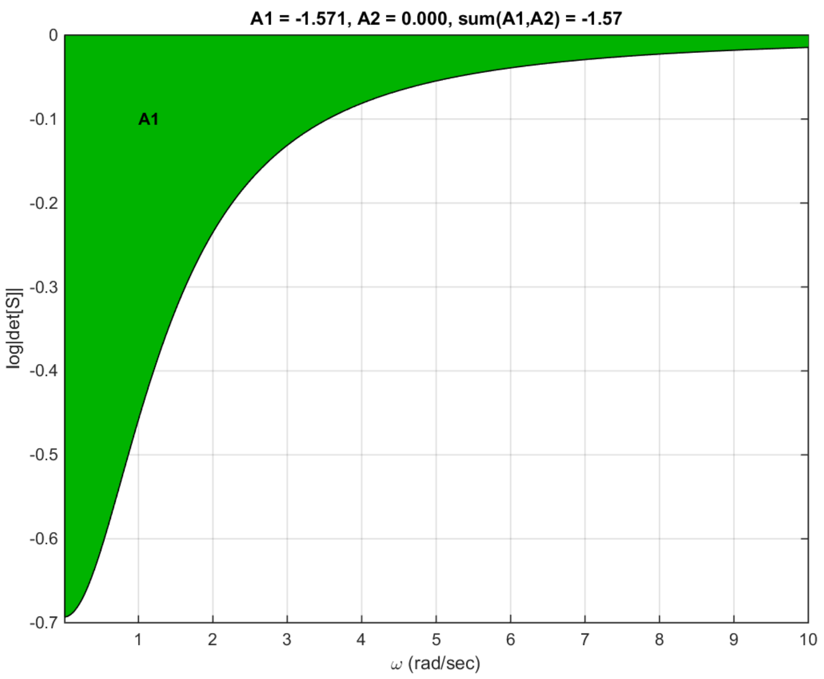
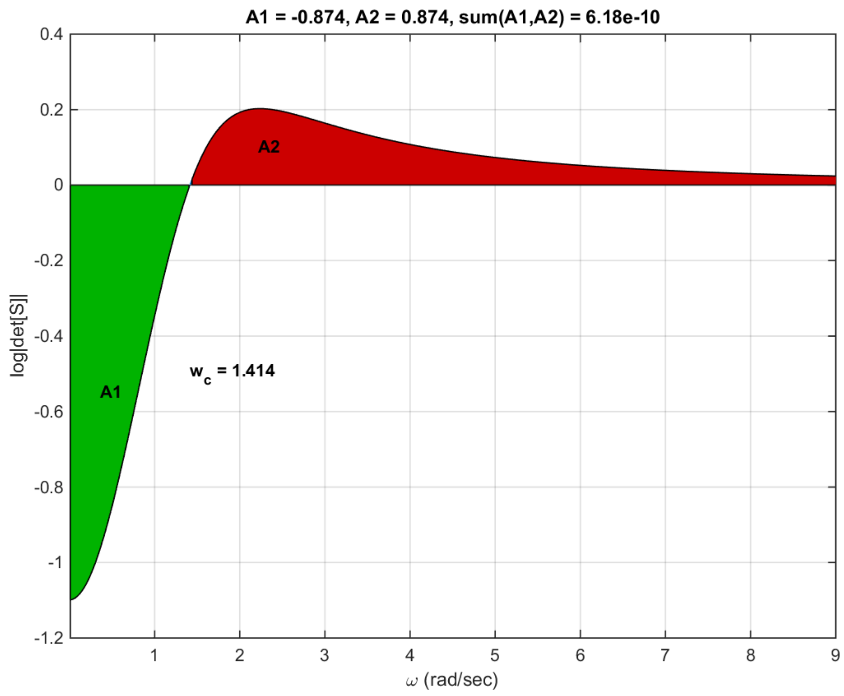
The Waterbed Effect: Examples

$$L(s) = \frac{1}{(s+1)}$$



$$L(s) = \frac{2}{(s+1)^2}$$



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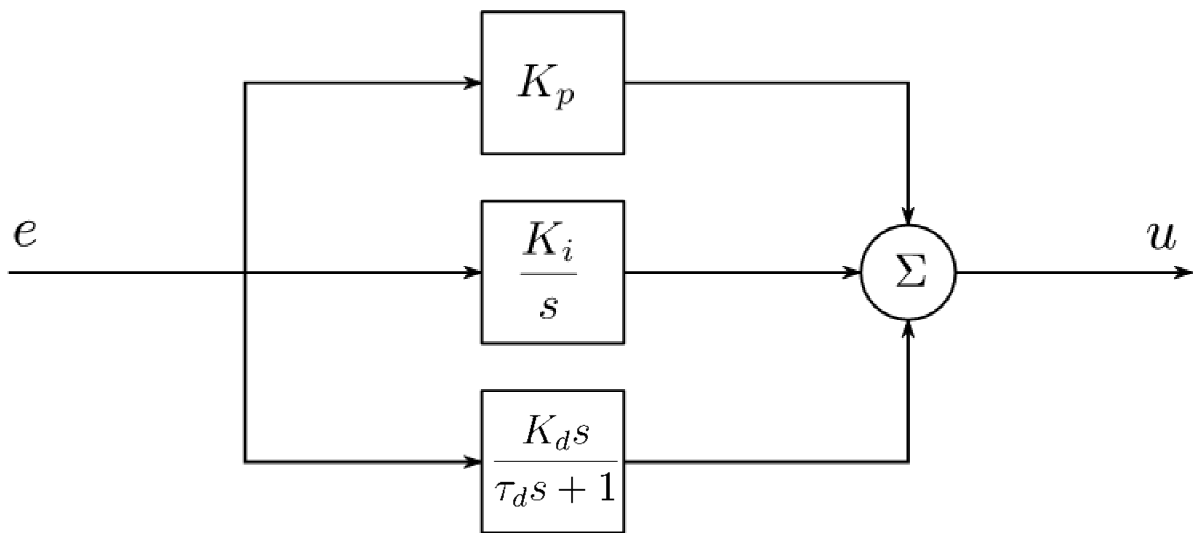
PID Control Structure

Proportional Gain | Integral Gain | Derivative Gain

$$C(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{\tau_d s + 1},$$



G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*, 7th ed. Prentice-Hall, 2015.

- Assume the plant can be approximated by:

$$P(s) = \frac{K}{(\tau_1 s + 1)(\tau_2 s + 1)}$$

- Assume the desired closed-loop transfer function is given by:

$$T_{des}(s) = \frac{\omega_{des}^2}{\left(s^2 + 2\beta\omega_{des}s + \omega_{des}^2\right)}$$

- Then the following selection of PID tuning parameters will yield the desired closed loop:

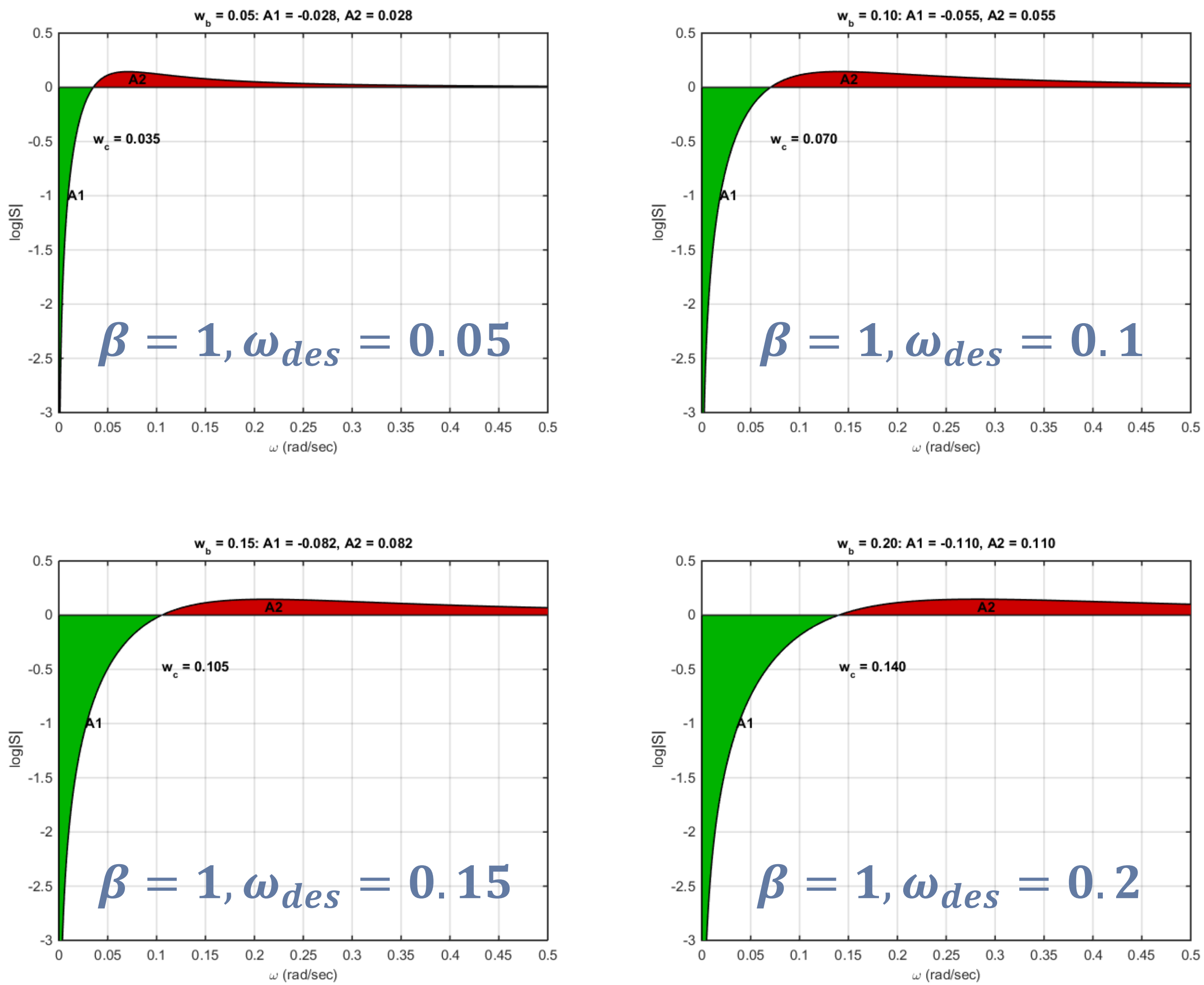
$$K_p = \frac{(2\beta\omega_{des}(\tau_1 + \tau_2) - 1)}{4K\beta^2}, \quad K_i = \frac{\omega_{des}}{2K\beta}$$

$$K_d = \frac{(2\beta\omega_{des}\tau_1 - 1)(2\beta\omega_{des}\tau_2 - 1)}{8K\beta^3\omega_{des}}, \quad \tau_d = \frac{1}{2\beta\omega_{des}}$$

Only 2 tuning knobs: β and ω_{des}! (desired closed-loop damping and bandwidth)

Sensitivity Function Tuning

Varying the tuning parameters and inspecting the Waterbed Effect allows for efficient tuning of the desired closed-loop



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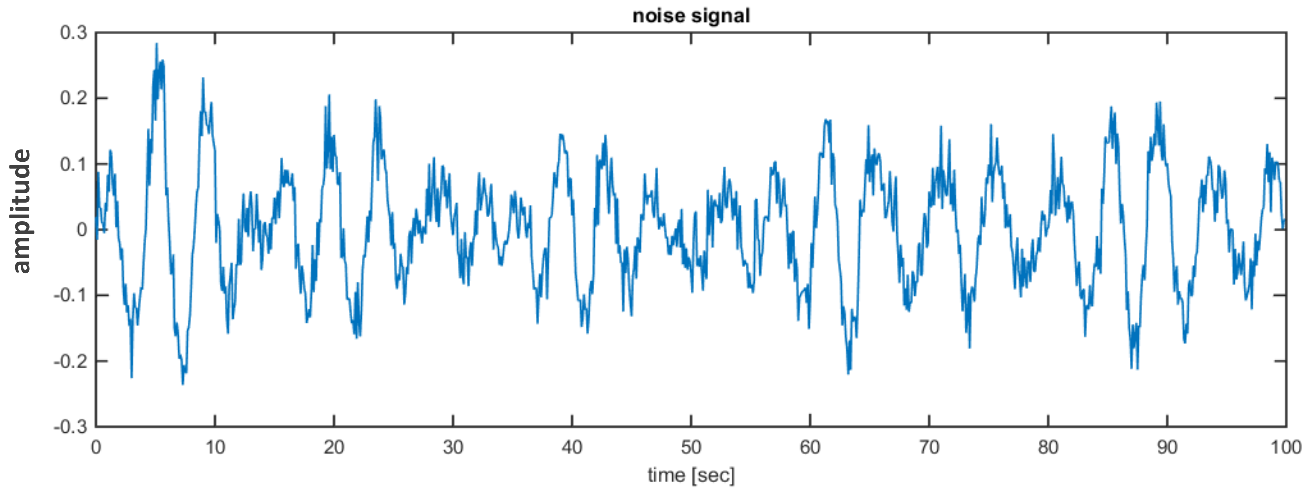
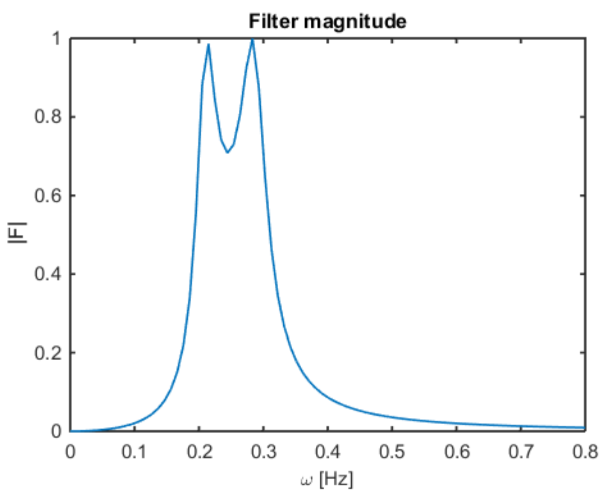
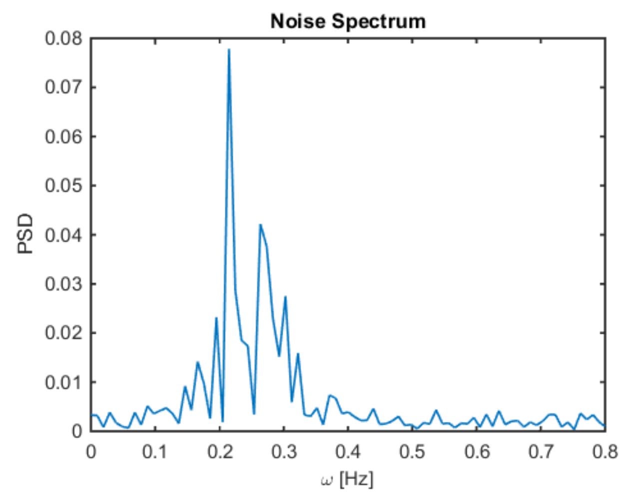
Example Noise Signal



The Sensitivity Area A2 amplifies the noise spectrum





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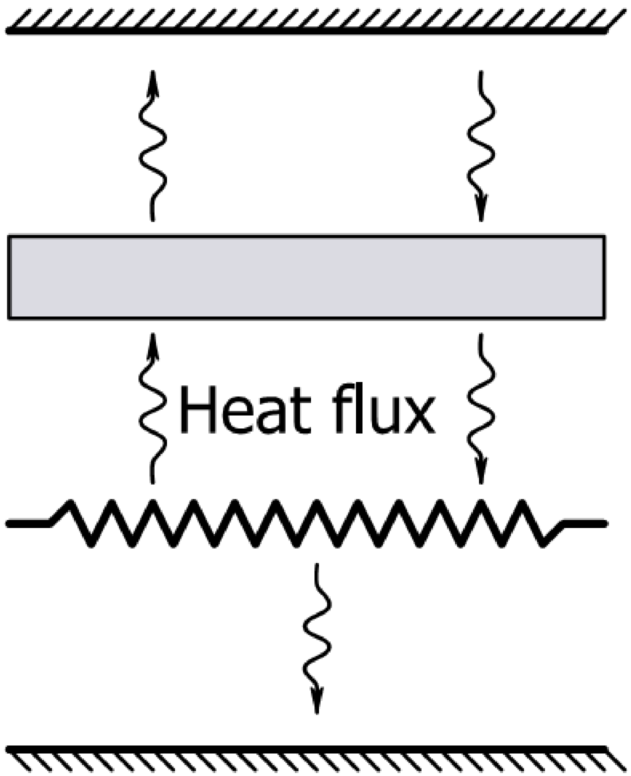
Temperature Control of Heated Plates

- Temperature control of heated plates is important in many thermal processing systems (RTP, Etch, Bake, MOCVD, etc.)
- The dynamic response of the system can change considerably depending on operating temperature, wafer types, and/or process conditions
- Ideally one would like to get the exact same closed-loop temperature response *(performance)* despite these system variations *(robustness)*
- In this example we will look how changes in system parameters affect the closed-loop dynamics in terms of the waterbed effect

Thermal Model of Heated Plate

- A tungsten-halogen lamp is shown heating a plate from below
- The plate radiates, conducts, and convects heat to the walls and surroundings
- The system can be divided into a number of control volumes and the heat equation can be written for the net rate of temperature change:



$$\dot{T} = f(T, u), \qquad y = g(T),$$

Dynamic System of Equations — Sensed Temperature

For each control volume, i

$$m_i(T)\dot{T}_i = Q_i^r(T) + Q_i^c(T) + Q_i^v(T) + b_i u,$$

Thermal mass — Radiation — Conduction — Convection — Electrical Power In

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Plate Heat Loss – 1D Example

- **The heat loss from the plate to the surroundings**

$$q_s = \epsilon\sigma(T_s^4 - T_\infty^4) + h(T_s - T_\infty),$$

Effective emissivity — Effective heat transfer coefficient

Effective emissivity for infinite parallel surfaces

$$\epsilon = \frac{1}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}.$$

Surface 1 — Surface 2

We will look at control performance when these two parameters (ε and *h*) vary.

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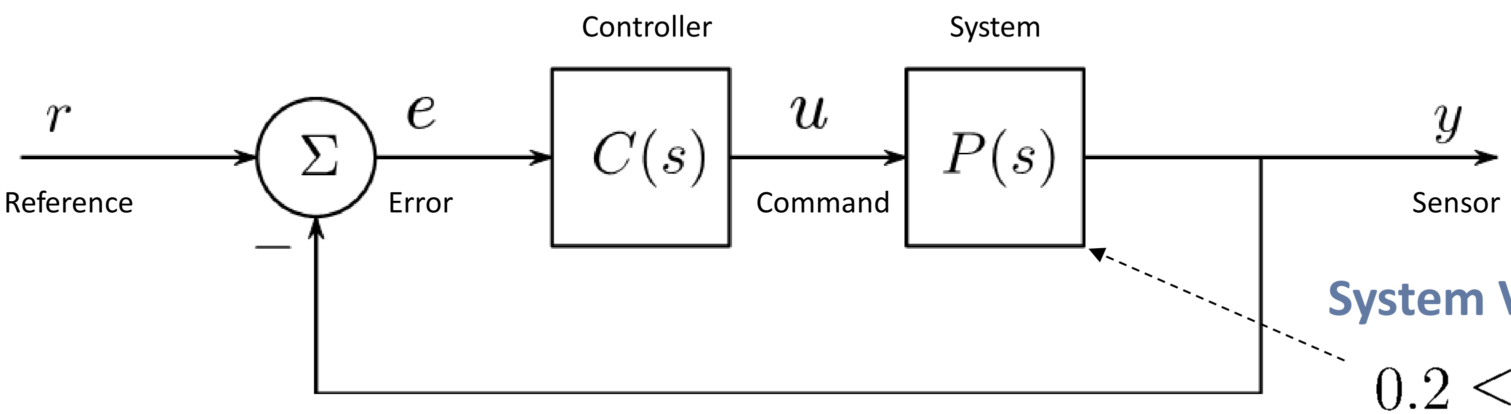
Process Variations and Robust Control

- Plate emissivity can change in ways that are difficult to predict
- Changes in gas flows or gas chemistry can change the heat losses
- Changes can be “wafer-to-wafer” or during processing (dynamic)
- If you knew how the losses changed, you could tune the controller for a specific process condition
- But often you cannot know about changes so the controller must be robust
- Robustness here is defined as good performance for a wide range of process conditions

- Consider the following closed-loop system, where P denotes the heated plate, and C denotes the PID feedback controller



System Variations:

$$0.2 \le \epsilon \le 0.8$$
$$5 \le h \le 100$$

Heat loss from plate to surroundings:

$$q_s = \epsilon\sigma(T_s^4 - T_\infty^4) + h(T_s - T_\infty),$$

Effective emissivity (ϵ)

Effective heat transfer coefficient (h)

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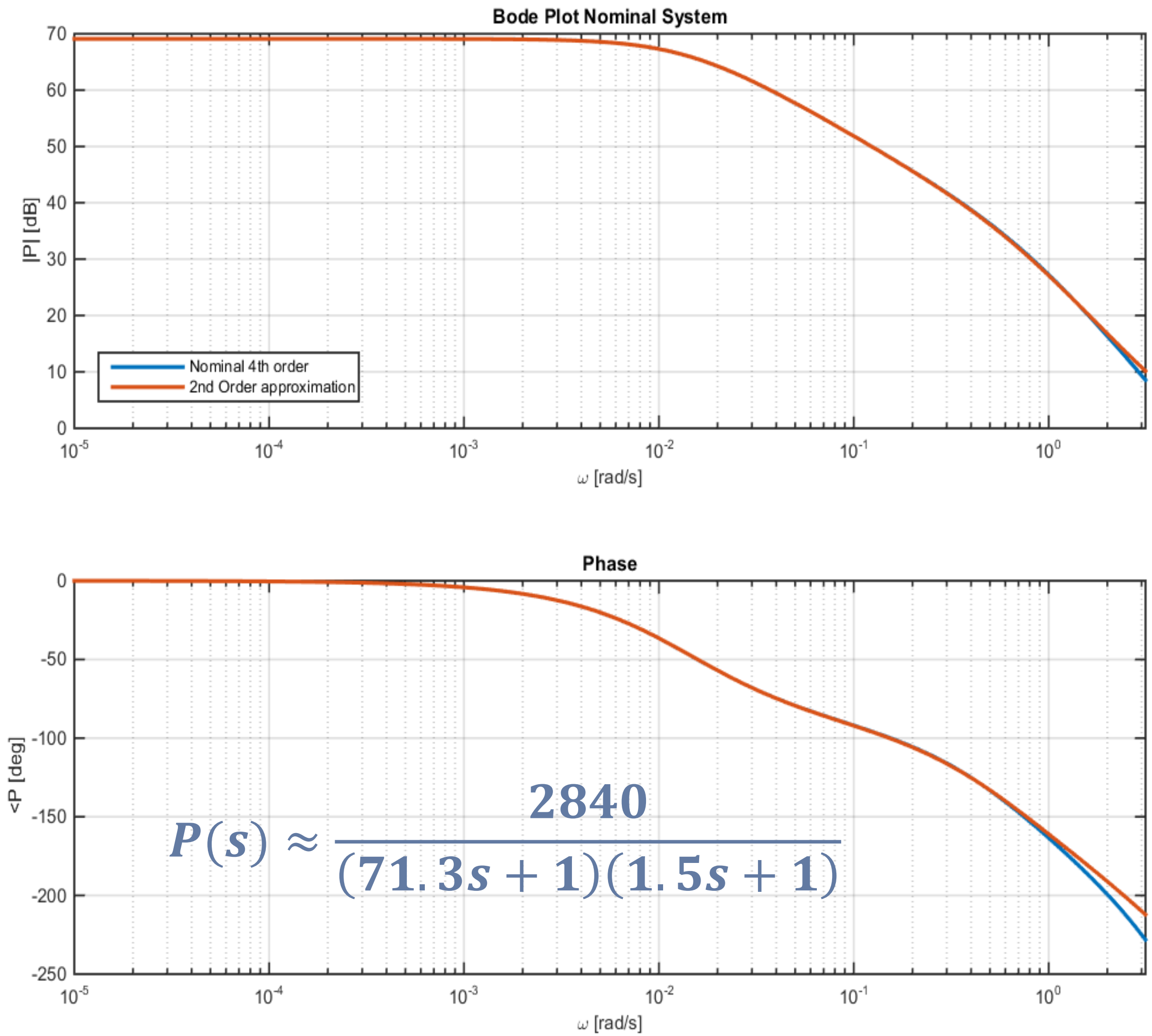
Bode Plot of Nominal Plant

- **Nominal plant is obtained by linearizing non-linear thermal system at operating point e_0 = 0.6, h_0 = 50, and T_0 = 600C**

- **Nominal plant can be well approximated by 2nd order system**



$$P(s) \approx \frac{2840}{(71.3s + 1)(1.5s + 1)}$$

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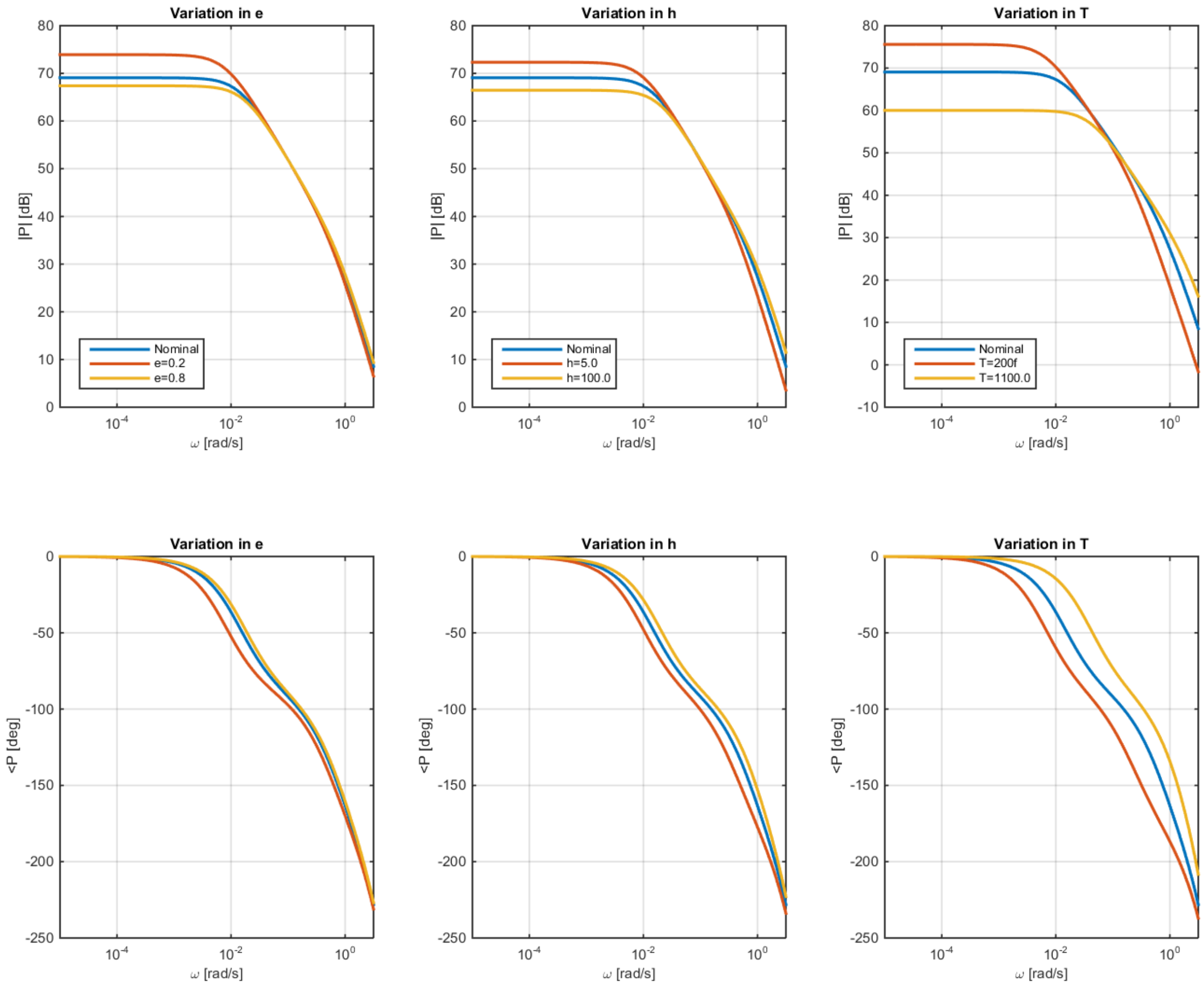
Bode Plots for Varying System Conditions

Variation in *e* | Variation in *h* | Variation in *T*

Magnitude

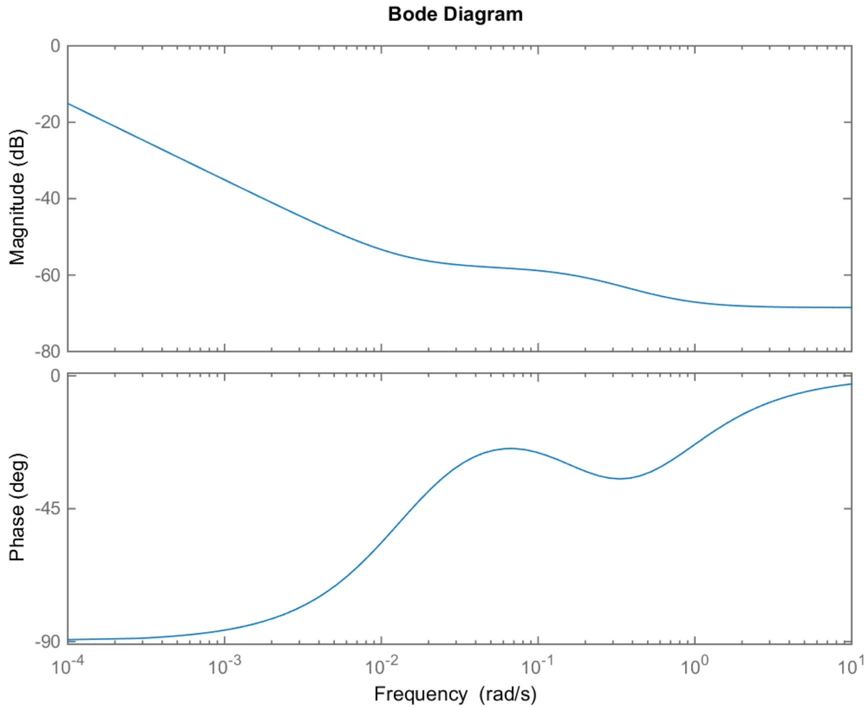
Phase



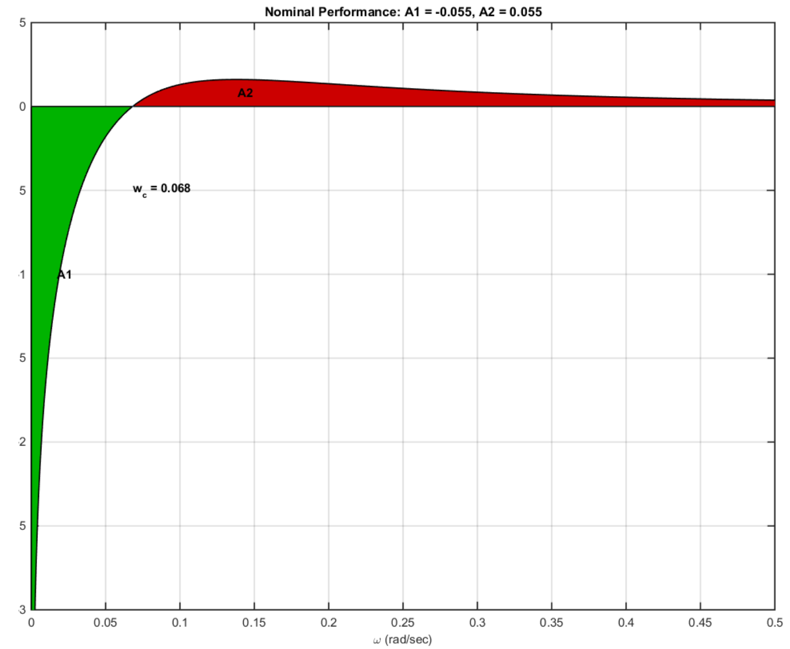
Control Design for Nominal Plant

- Using the presented PID tuning procedure, a controller was obtained based on the 2nd order plant parameters from the previous slide, and tuning parameters $\beta = 1, \omega_{des} = 0.1$ [rad/s]

Bode Plot of PID Controller



Corresponding Sensitivity Function



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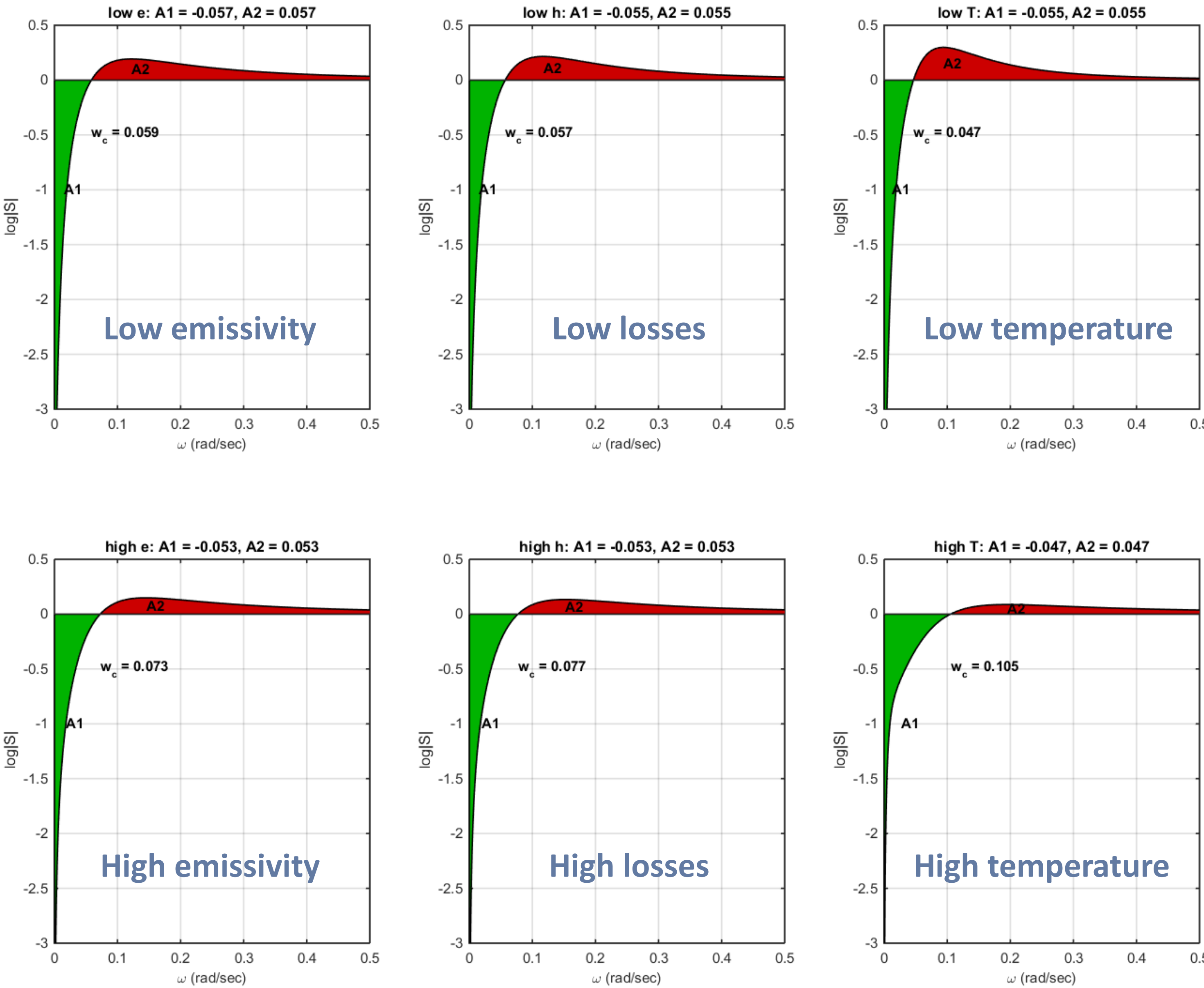
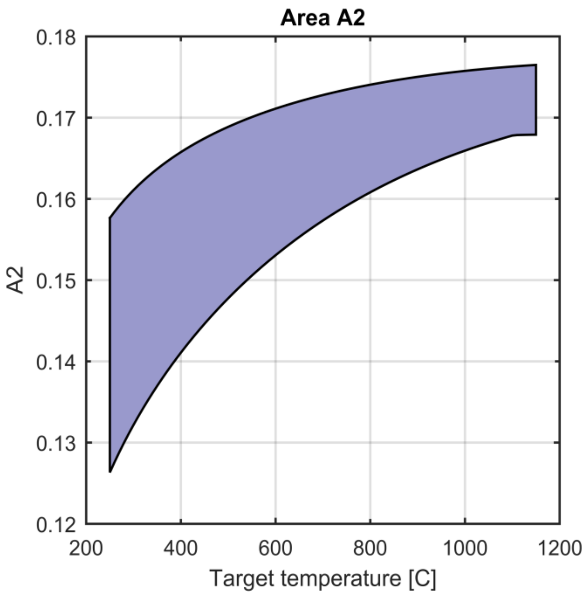
Sensitivity Functions for Varying Process Conditions



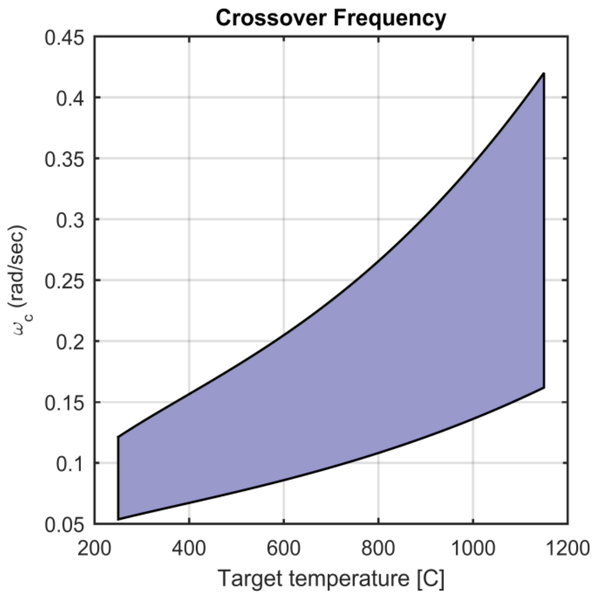
Waterbed Parameters for Varying Process Conditions

Critical 'waterbed' characteristics of a nominal set of PID parameters for a range of plate properties and operating conditions of a heated plate.

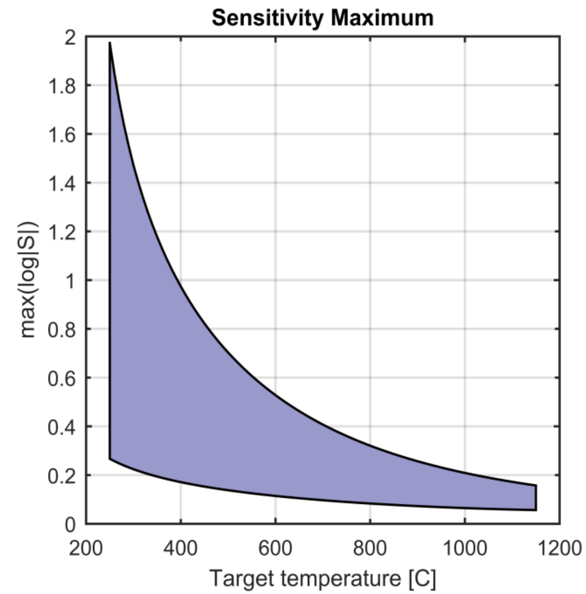
Area A2



Crossover w_c



max|S|



- Summary of 3000 simulations where three critical waterbed parameters were calculated for variations in emissivity and heat transfer coefficient over the entire operating range from 250°C to 1150°C
- As the target temperature increases, the area for disturbance rejection and corresponding cross-over frequency increases, but so does the area for noise amplification

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Summary & Conclusions

- PID controllers are ubiquitous in semiconductor process control
- We proposed a new method of tuning PID controllers using the fundamental waterbed effect from control systems theory
- We applied the new methodology to heating of a plate used in semiconductor process control
- Use of the waterbed effect allows for efficient tuning of PID controllers