

Lecture 7: Anti-windup and friction compensation

- ▶ Compensation for saturations (anti-windup)
- ▶ Friction models
- ▶ Friction compensation

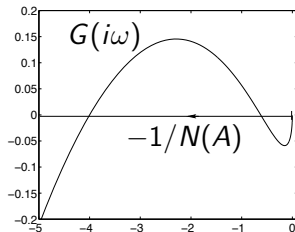
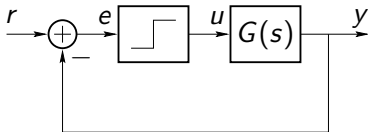
Material

- ▶ Lecture slides

Course Outline

- Lecture 1-3 Modelling and basic phenomena
(linearization, phase plane, limit cycles)
- Lecture 2-6 Analysis methods
(Lyapunov, circle criterion, describing functions)
- Lecture 7-8 Common nonlinearities
(Saturation, friction, backlash, quantization)
- Lecture 9-13 Design methods
(Lyapunov methods, Backstepping, Optimal control)
- Lecture 14 Summary

Last lecture: Stable periodic solution

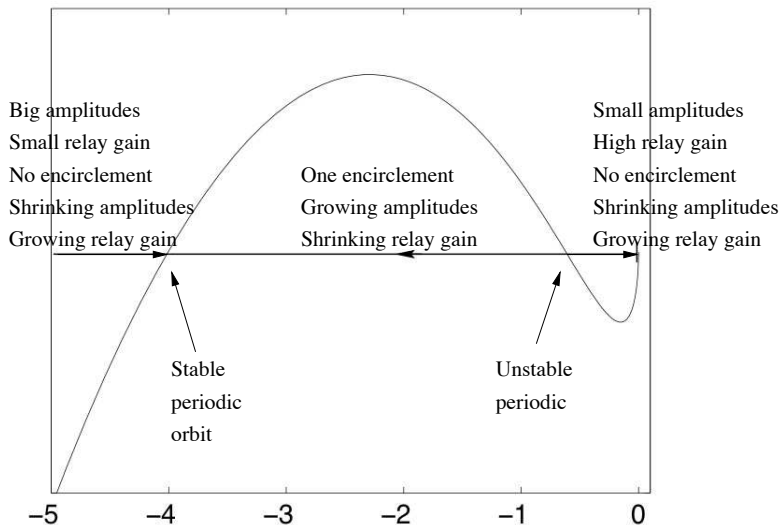


$$G(s) = \frac{(s+10)^2}{(s+1)^3} \quad \text{with feedback} \quad u = -\text{sgn } y$$

gives one stable and one unstable limit cycle. The left most intersection corresponds to the stable one.

Periodic Solutions in Relay System

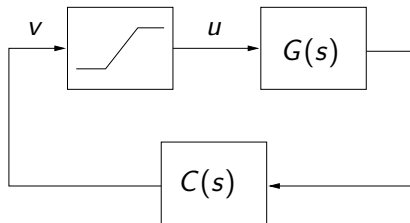
The relay gain $N(A)$ is higher for small A :



Today's Goal

- ▶ *To be able to design and analyze antiwindup schemes for*
 - ▶ *PID*
 - ▶ *state-space systems*
 - ▶ *and Kalman filters (observers)*
- ▶ *To understand common models of friction*
- ▶ *To design and analyze friction compensation schemes*

Windup – The Problem



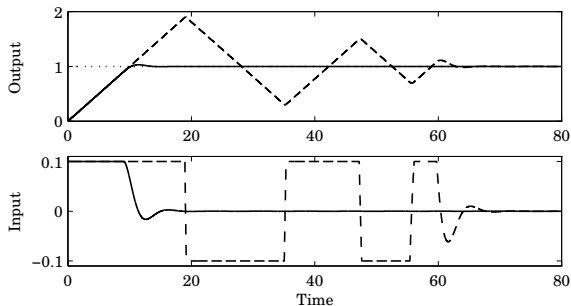
The feedback path is broken when u saturates

The controller $C(s)$ is a dynamic system

Problems when controller is unstable (or stable but not AS)

Example: I-part in PID-controller

Example-Windup in PID Controller

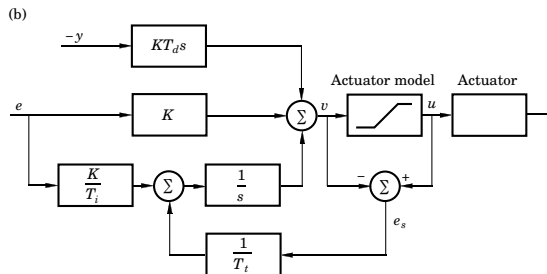
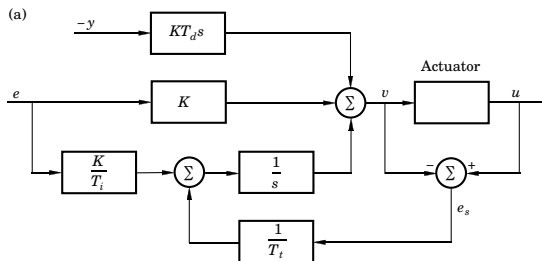


Dashed line: ordinary PID-controller

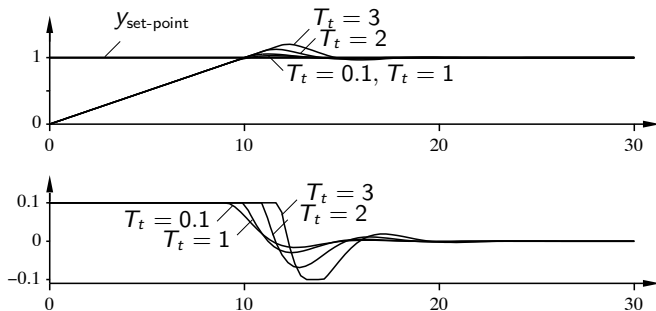
Solid line: PID-controller with anti-windup

Anti-windup for PID-Controller ("Tracking")

Anti-windup (a) with actuator output available and (b) without



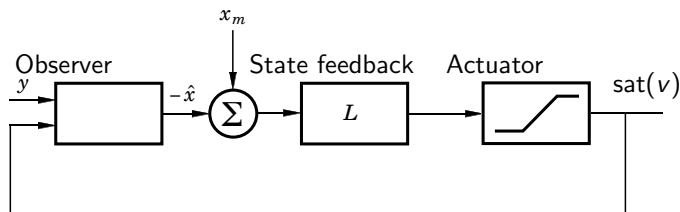
Choice of Tracking Time T_t



With very small T_t (large gain $1/T_t$), spurious errors can saturate the output, which leads to accidental reset of the integrator. Too large T_t gives too slow reaction (little effect).

The tracking time T_t is the design parameter of the anti-windup. Common choices: $T_t = T_i$ or $T_t = \sqrt{T_i T_d}$.

State feedback with Observer



$$\dot{\hat{x}} = A\hat{x} + B \text{sat}(v) + K(y - C\hat{x})$$

$$v = L(x_m - \hat{x})$$

\hat{x} is estimate of process state, x_m desired (model) state.
Need model of saturation if $\text{sat}(v)$ is not measurable

Antiwindup – General State-Space Controller

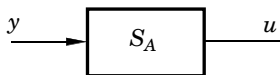
State-space controller:

$$\dot{x}_c(t) = Fx_c(t) + Gy(t)$$

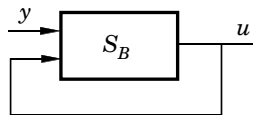
$$u(t) = Cx_c(t) + Dy(t)$$

Windup possible if F is unstable and u saturates.

(a)



(b)



Idea:

Rewrite representation of control law from (a) to (b) such that:

(a) and (b) have same input-output relation

(b) behaves better when feedback loop is broken, if S_B stable

Antiwindup – General State-Space Controller

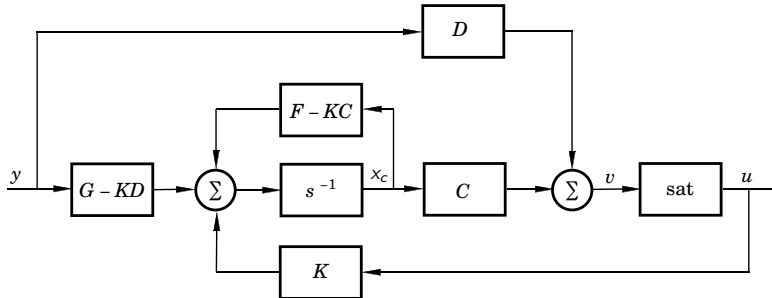
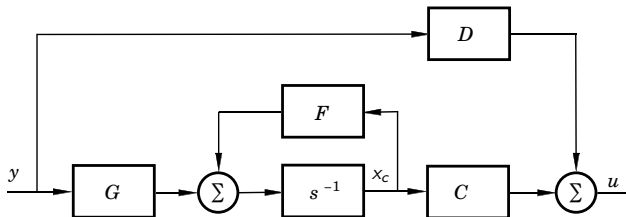
Mimic the observer-based controller:

$$\begin{aligned}\dot{x}_c &= Fx_c + Gy + K \underbrace{(u - Cx_c - Dy)}_{=0} \\ &= (F - KC)x_c + (G - KD)y + Ku \\ &= F_0x_c + G_0y + Ku\end{aligned}$$

Design so that $F_0 = F - KC$ has desired stable eigenvalues
Then use controller

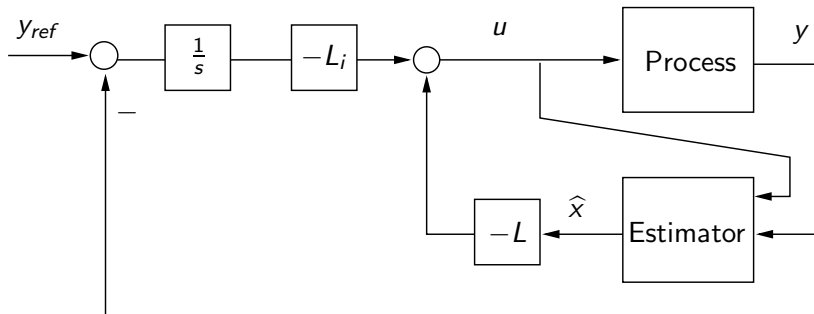
$$\begin{aligned}\dot{x}_c &= F_0x_c + G_0y + Ku \\ u &= \text{sat}(Cx_c + Dy)\end{aligned}$$

State-space controller without and with anti-windup:



5 Minute Exercise

How would you do antiwindup for the following state-feedback controller with observer and integral action ?



Saturation

Optimal control theory (later)

Multi-loop Anti-windup (Cascaded systems):

Difficult problem, several suggested solutions

Turn off integrator in outer loop when inner loop saturates

Friction

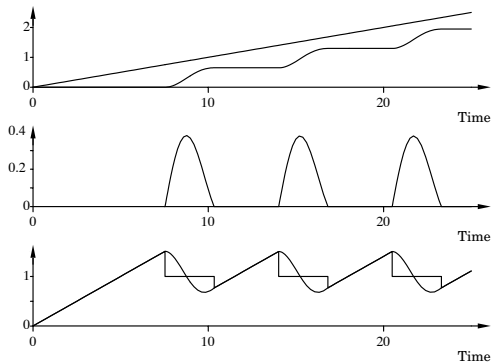
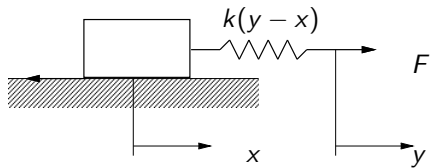
Present almost everywhere

- ▶ Often bad
 - ▶ Friction in valves and mechanical constructions
- ▶ Sometimes good
 - ▶ Friction in brakes
- ▶ Sometimes too small
 - ▶ Earthquakes

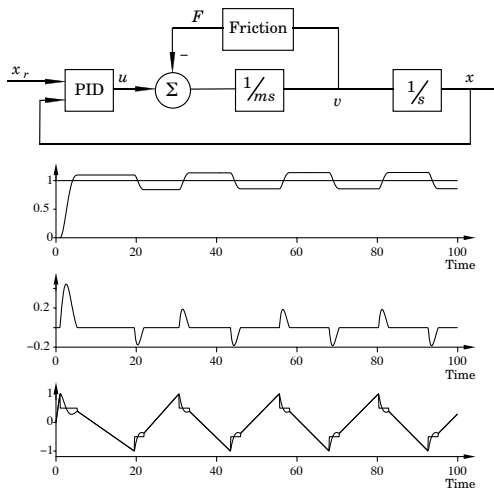
Problems

- ▶ How to model friction
- ▶ How to compensate for friction

Stick-slip Motion



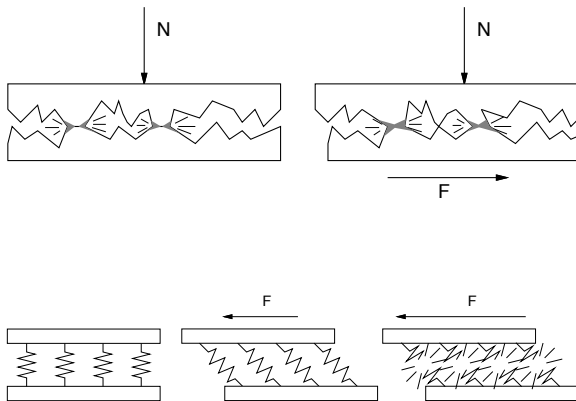
Position Control of Servo with Friction – Hunting



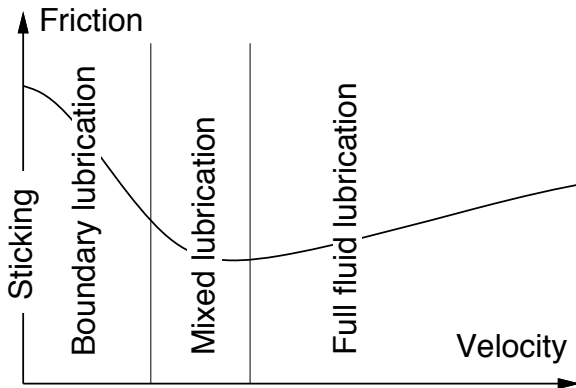
3 Minute Exercise

What are the signals in the previous plots? What model of friction has been used in the simulation?

Friction



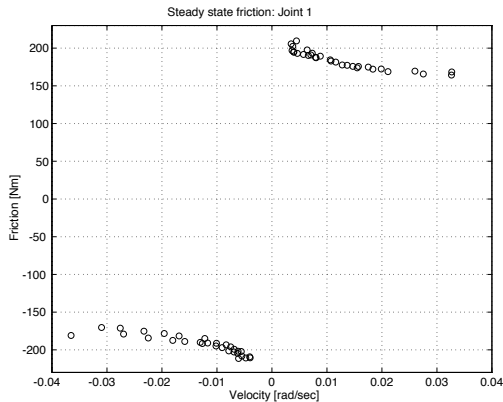
Lubrication Regimes



Hard to get good model at $v = 0$

Stribeck Effect

For low velocity: friction increases with decreasing velocity
Stribeck (1902)



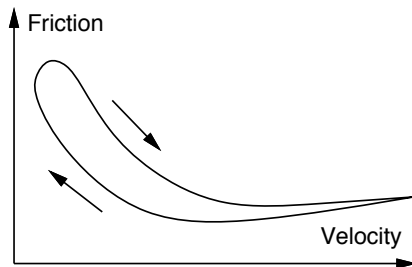
Frictional Lag

Dynamics are important also outside sticking regime

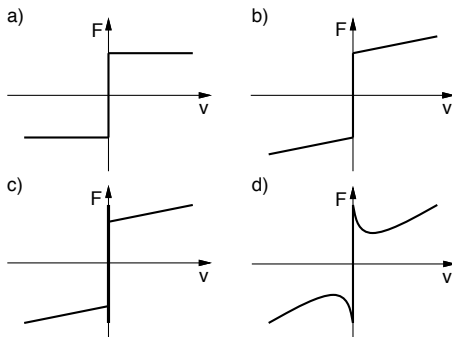
Hess and Soom (1990)

Experiment with unidirectional motion $v(t) = v_0 + a \sin(\omega t)$

Hysteresis effect!



Classical Friction Models



$$c) \quad F(t) = \begin{cases} F_c \operatorname{sign} v(t) + F_v v(t) & v(t) \neq 0 \\ \max(\min(F_e(t), F_s), -F_s) & v(t) = 0 \end{cases}$$

$F_e(t)$ = external applied force , F_c, F_v, F_s constants

Advanced Friction Models

See PhD-thesis by Henrik Olsson

- ▶ Karnopp model
- ▶ Armstrong's seven parameter model
- ▶ Dahl model
- ▶ Bristle model
- ▶ Reset integrator model
- ▶ Bliman and Sorine
- ▶ Wit-Olsson-strm

Demands on a model

To be useful for control the model should be

- ▶ sufficiently accurate,
- ▶ suitable for simulation,
- ▶ simple, few parameters to determine.
- ▶ physical interpretations, insight

Pick the simplest model that does the job! If no stiction occurs the $v = 0$ -models are not needed.

Friction Compensation

- ▶ Lubrication
- ▶ Integral action (beware!)
- ▶ Dither
- ▶ Non-model based control
- ▶ Model based friction compensation
- ▶ Adaptive friction compensation

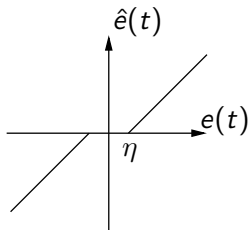
Integral Action

- The integral action compensates for any external disturbance
- Good if friction force changes slowly ($v \approx \text{constant}$).
- To get fast action when friction changes one must use much integral action (small T_i)
- Gives phase lag, may cause stability problems etc

Deadzone - Modified Integral Action

Modify integral part to $I = \frac{K}{T_i} \int_0^t \hat{e}(t) d\tau$

$$\text{where input to integrator } \hat{e} = \begin{cases} e(t) - \eta & e(t) > \eta \\ 0 & |e(t)| < \eta \\ e(t) + \eta & e(t) < -\eta \end{cases}$$

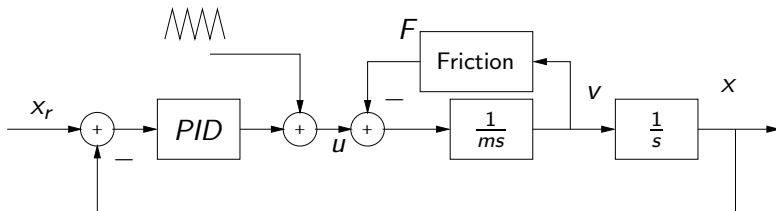


Advantage: Avoid that small static error introduces limit cycle

Disadvantage: Must accept small error (will not go to zero)

Mechanical Vibrator–Dither

Avoids sticking at $v = 0$ where there usually is high friction by adding high-frequency mechanical vibration (dither)

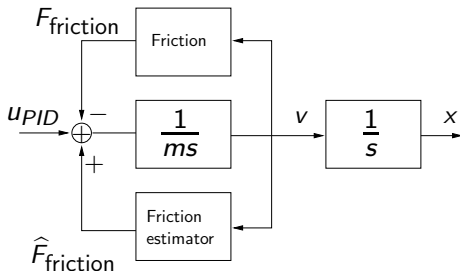


Cf., mechanical maze puzzle
(labyrinthspiel)



Adaptive Friction Compensation

Coulomb Friction $F = a \operatorname{sgn}(v)$



Assumption: v measurable.

Friction estimator:

$$\begin{aligned}\dot{z} &= k u_{PID} \operatorname{sgn}(v) \\ \hat{a} &= z - k m |v| \\ \hat{F}_{\text{friction}} &= \hat{a} \operatorname{sgn}(v)\end{aligned}$$

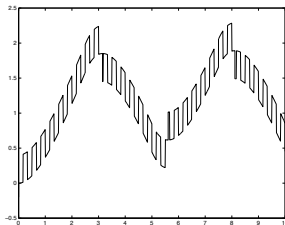
Result: $e = a - \hat{a} \rightarrow 0$ as $t \rightarrow \infty$,
since

$$\begin{aligned}\frac{de}{dt} &= -\frac{d\hat{a}}{dt} = -\frac{dz}{dt} + km\frac{d}{dt}|v| \\ &= -ku_{PID} \operatorname{sgn}(v) + km\dot{v} \operatorname{sgn}(v) \\ &= -k \operatorname{sgn}(v)(u_{PID} - m\dot{v}) \\ &= -k \operatorname{sgn}(v)(F - \hat{F}) \\ &= -k(a - \hat{a}) \\ &= -ke\end{aligned}$$

Remark: Careful with $\frac{d}{dt}|v|$ at $v = 0$.

The Knocker

Combines Coulomb compensation and square wave dither



Tore Hgglund, Innovation Cup winner + patent 1997

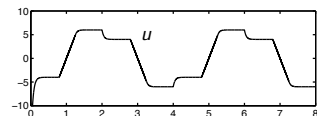
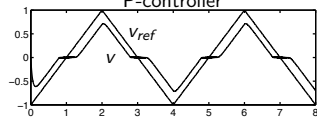
Example—Friction Compensation

Velocity control with

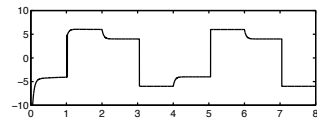
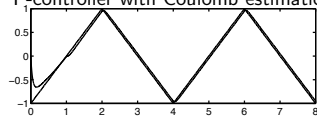
- a) P-controller
- b) PI-controller
- c) $P + \text{Coulomb estimation}$

Results

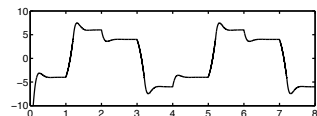
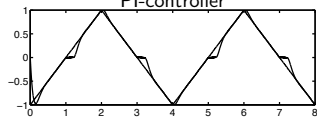
P-controller



P-controller with Coulomb estimation



PI-controller



Next Lecture

- ▶ Backlash
- ▶ Quantization