CDS 101: Lecture 4.1
Linear Systems

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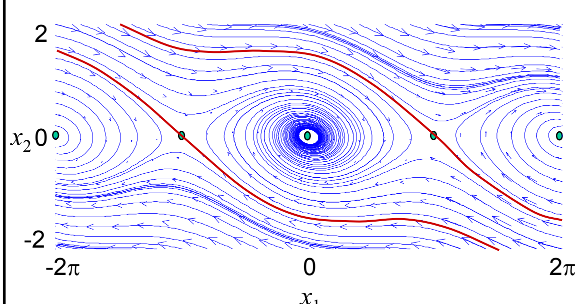
Goals:

- Describe linear system models: properties, examples, and tools
- Characterize the stability and performance of a linear system in terms of eigenvalues
- Compute linearization of a nonlinear systems around an equilibrium point

Reading:

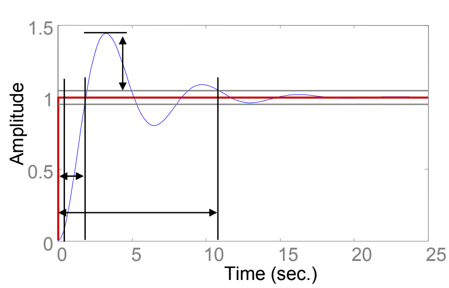
- Packard, Poola and Horowitz, *Dynamic Systems and Feedback,* Sections 19, 20, 22
- *Optional*: Astrom, Section 3.6, 3.7 (pp 125-134)

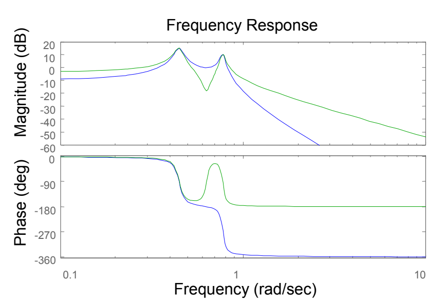
Review from Last Week



Key topics for this lecture

- Stability of equilibrium points
- Local versus global behavior
- Performance specification via step and frequency response





What is a *linear* system?

Linearity of functions: $f : \mathbb{R}^n \to \mathbb{R}^m$

- Zero at the origin: $f(0) = 0$
- Addition: $f(x+y) = f(x) + f(y)$
- Scaling: $f(\alpha x) = \alpha f(x)$

$\Bigg\}$ $f(\alpha x + \beta y) = \alpha f(x) + \beta f(y)$

Canonical example: $f(x) = Ax$

Linearity of *systems*: sums of *solutions*

Dynamical system

$$\dot{x} = Ax$$

$x(0) = x_{10} \to x(t) = x_1(t)$ $\quad$ $x(0) = x_{20} \to x(t) = x_2(t)$

$$\Downarrow$$

$$x(0) = \alpha x_1 + \beta x_2 \to x(t) = \alpha x_1(t) + \beta x_2(t)$$

Control system

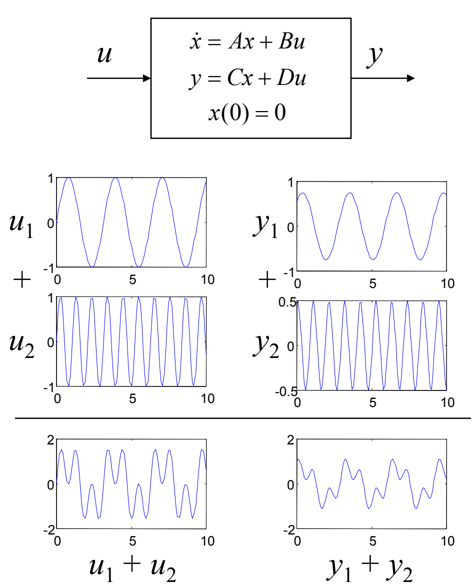
$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

$x(0) = 0,\; u(t) = u_1(t) \to y(t) = y_1(t)$ $\quad$ $x(0) = 0,\; u(t) = u_2(t) \to y(t) = y_2(t)$

$$\Downarrow$$

$$x(0) = 0,\; u(t) = \alpha u_1(t) + \beta u_2(t) \to y(t) = \alpha y_1(t) + \beta y_2(t)$$

Linear input/output systems



Input/output linearity at x(0) = 0

- Linear systems are linear in initial condition *and* input ⇒ need to use x(0) = 0 to add the outputs together
- For different initial conditions, you need to be more careful (sounds like a good midterm question)

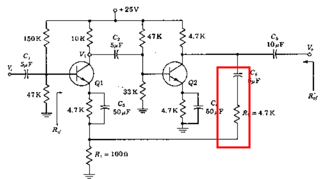
Linear system ⇒ step response and frequency response scale with input amplitude

- 2X input ⇒ 2X output
- This is why we look at *ratios* and *percentages* in step/freq response. These are *independent* of input amplitude
- Limitation: input saturation ⇒ only holds up to certain input amplitude

Why are linear systems important?

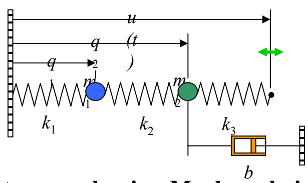
Many important *examples*

Electronic circuits



- Especially true after feedback
- Frequency response is key performance specification (think telephones)

Many mechanical systems



Quantum mechanics, Markov chains, …

Many important *tools*

Frequency response, step response, etc

- Traditional tools of control theory
- Developed in the 1930's at Bell Labs; intercontinental telecommunications

Classical control design toolbox } CDS 101/110a

- Nyquist plots, gain/phase margin
- Loop shaping

Optimal control/estimator design } CDS 110b

- Linear quadratic regulators
- Kalman estimators

Robust control design } CDS 110b/212

- H_∞ control design
- μ analysis for structured uncertainty

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Solutions of linear systems: the matrix exponential

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx + Du\end{aligned} \longrightarrow y(t) = ???$$

Scalar linear system, with no input

$$\begin{aligned}\dot{x} &= ax \\ y &= cx\end{aligned} \quad x(0) = x_0 \longrightarrow x(t) = e^{at}x_0 \longrightarrow y(t) = ce^{at}x_0$$

Matrix version, with no input

$$\begin{aligned}\dot{x} &= Ax \\ y &= Cx\end{aligned} \quad x(0) = x_0 \longrightarrow x(t) = e^{At}x_0 \longrightarrow \boxed{y(t) = Ce^{At}x_0}$$

initial(A,B,C,D,x0);

Matrix exponential

- Analog to the scalar case; defined by series expansion:

$$e^M = I + M + \frac{1}{2!}M^2 + \frac{1}{3!}M^3 + \cdots$$

P = exp(M)

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Stability of linear systems

$$\dot{x} = Ax + \cancel{Bu}^{\,0}$$
~~$y = Cx + Du$~~

$$x(t) = e^{At}x_0$$

Q: when is the system asymptotically stable?

$$\lim_{t\to\infty} x(t) = 0$$

Stability is determined by the *eigenvalues* of the matrix *A*

- Simple case: diagonal system

$$\dot{x} = \begin{bmatrix} \lambda_1 & & 0 \\ & \ddots & \\ 0 & & \lambda_n \end{bmatrix} x \quad \Rightarrow \quad x(t) = \begin{bmatrix} e^{\lambda_1 t} & & 0 \\ & \ddots & \\ 0 & & e^{\lambda_n t} \end{bmatrix} x_0$$

Stable if $\lambda_i \le 0$
Asy stable if $\lambda_i < 0$
Unstable if $\lambda_i > 0$

- More generally: transform to "Jordan" form

$$\dot{x} = T^{-1}JTx \qquad J = \begin{bmatrix} J_1 & & 0 \\ & \ddots & \\ 0 & & J_k \end{bmatrix} \qquad J_i = \begin{bmatrix} \lambda_i & 1 & 0 \\ & \ddots & 1 \\ 0 & & \lambda_i \end{bmatrix}$$

Stable if $\mathrm{Re}(\lambda_i) \le 0$
Asy stable if $\mathrm{Re}(\lambda_i) < 0$
Unstable if $\mathrm{Re}(\lambda_i) > 0$

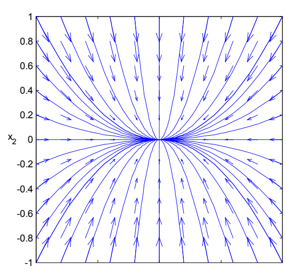
Form of eigenvalues determines system behavior

Linear systems are automatically *globally* stable or unstable

Eigenstructure of linear systems

Real e-values

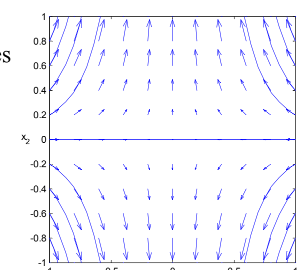
$\mathrm{Re}(\lambda_i) < 0$



Real e-values

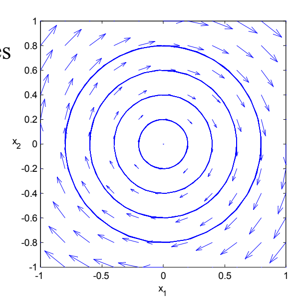
$\mathrm{Re}(\lambda_i) < 0$

$\mathrm{Re}(\lambda_j) > 0$



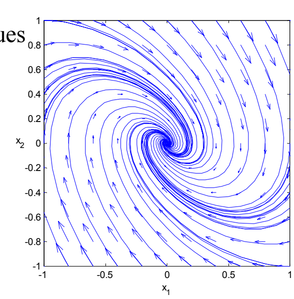
Complex e-values

$\mathrm{Re}(\lambda_i) = 0$



Complex e-values

$\mathrm{Re}(\lambda_i) < 0$



Impluse, step and frequency response

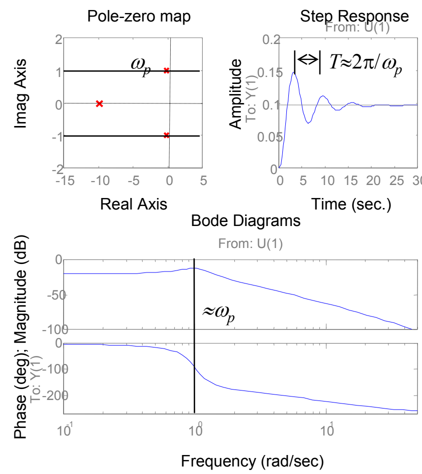
$$\dot{x} = Ax + Bu \qquad u(t) = 1(t) \qquad u(t) = A\sin(\omega t)$$
$$y = Cx + Du$$

Effect of eigenstructure on impulse and step response

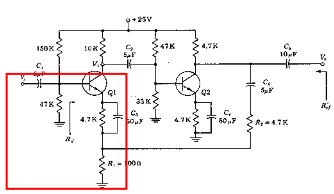
- Complex eigenvalues with small real part lead to oscillatory response
- Frequency of oscillations ≈ ω_i

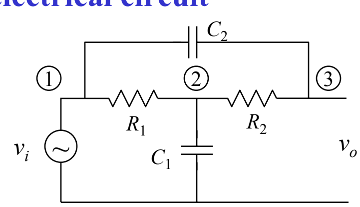
Effects of eigenstructure on frequency response

- Eigenvalues determine "break points" for frequency response
- Complex eigenvalues lead to peaks in response function near ω_i



Example: electrical circuit





"Bridged Tee Circuit"

Derivation based on Kirchoff's laws for electrical circuits (Ph 2)

- Sum of currents at nodes = 0:

$$C_1 \frac{dv_2}{dt} = \frac{v_1 - v_2}{R_1} - \frac{v_2 - v_3}{R_2} \qquad C_2 \frac{d(v_3 - v_1)}{dt} = -\frac{v_3 - v_2}{R_2}$$

- Rewrite in terms of new states: $v_{c1}=v_2$, $v_{c1}=v_1 - v_3$

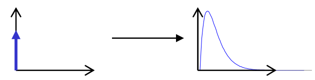
$$\frac{d}{dt}\begin{bmatrix} v_{c1} \\ v_{c2} \end{bmatrix} = \begin{bmatrix} -\frac{1}{C_1}\left(\frac{1}{R_1}+\frac{1}{R_2}\right) & -\frac{1}{C_1 R_2} \\ -\frac{1}{C_2 R_2} & -\frac{1}{C_2 R_2} \end{bmatrix} \begin{bmatrix} v_{c1} \\ v_{c2} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1}\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \\ V_{c2} \end{bmatrix} v_i \qquad v_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} v_{c1} \\ v_{c2} \end{bmatrix} + v_i$$

Linear control systems and convolution

$$\dot{x} = Ax + Bu \qquad y = Cx + Du \quad \longrightarrow \quad y(t) = \underbrace{Ce^{At}x(0)}_{\text{homogeneous}} + ???$$

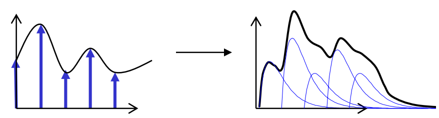
Impulse response, $h(t) = Ce^{At}B$

- Response to input "impulse"
- Equivalent to "Green's function"



Linearity ⇒ compose response to arbitrary $u(t)$ using *convolution*

- Decompose input into "sum" of shifted impulse functions
- Compute impulse response for each
- "Sum" impulse response to find $y(t)$



Complete solution: use integral instead of "sum"

$$y(t) = Ce^{At}x(0) + \int_{\tau=0}^{t} Ce^{A(t-\tau)}Bu(\tau)d\tau + Du(t)$$

- linear with respect to initial condition *and* input
- 2X input ⇒ 2X output when $x(0) = 0$

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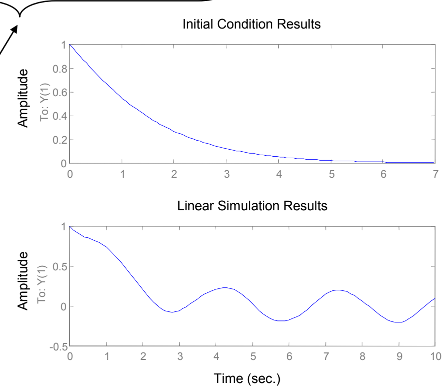
Matlab tools for linear systems

$$y(t) = Ce^{At}x(0) + \int_{\tau=0}^{t} Ce^{A(t-\tau)}Bu(\tau)d\tau + Du(t)$$

```
A = [-1 1; 0 -1];   B = [0; 1];
C = [1 0]; D = [0];
x0 = [1; 0.5];

sys = ss(A,B,C,D);
initial(sys, x0);
impulse(sys);

t = 0:0.1:10;
u = 0.2*sin(5*t) + cos(2*t);
lsim(sys, u, t, x0);
```



Other MATLAB commands

- gensig, square, sawtooth – produce signals of different types
- step, impulse, initial, lsim – time domain analysis
- bode, freqresp, evalfr – frequency domain analysis

ltiview – linear time invariant system plots

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Linearization around an equilibrium point

$$\dot{x} = f(x,u) \quad y = h(x,u) \longrightarrow \dot{z} = Az + Bv \quad w = Cz + Dv$$

"Linearize" around $x = x_e$

$$f(x_e, u_e) = 0 \quad y_e = h(x_e, u_e)$$

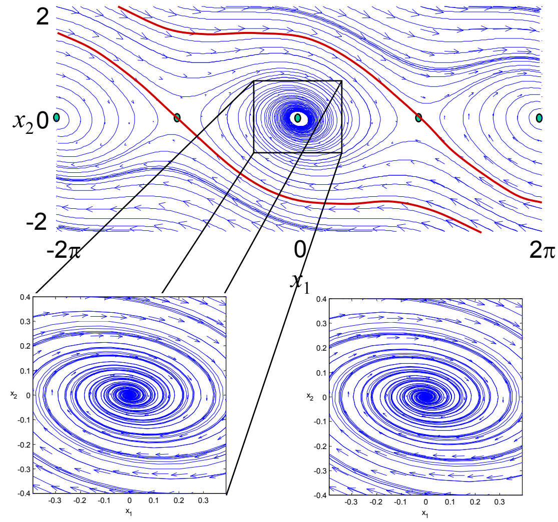
$$z = x - x_e \quad v = u - u_e \quad w = y - y_e$$

$$A = \frac{\partial f}{\partial x} \quad B = \frac{\partial f}{\partial u}$$

$$C = \frac{\partial h}{\partial x} \quad D = \frac{\partial h}{\partial u}$$

Remarks

- In examples, this is often equivalent to small angle approximations, etc
- Only works *near* to equilibrium point



Full nonlinear model

Linear model (honest!)

Local stability of nonlinear systems

Asymptotic stability of the linearization implies *local* asymptotic stability of eq pt

- Linearization around equilibrium point captures "tangent" dynamics

$$\dot{x} = f(x) = A \cdot (x - x_e) + o(x - x_e) \longleftarrow \text{higher order terms}$$

- If linearization is *unstable,* can conclude that nonlinear system is locally unstable
- If linearization is *stable* but not *asymptotically stable,* can't conclude anything about nonlinear system:

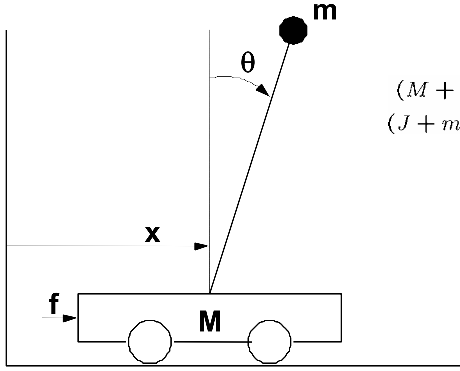
$$\dot{x} = \pm x^3 \xrightarrow{\text{linearize}} \dot{x} = 0$$

- linearization is stable (but not asy stable)
- nonlinear system can be asy stable or unstable

Local approximation particularly appropriate for control systems design

- Control often used to *ensure* system stays near desired equilibrium point
- If dynamics are well-approximated by linearization near equilibrium point, can use this to design the controller that keeps you there (!)

Example: inverted pendulum on a cart



$$(M+m)\ddot{x} + ml\cos\theta\ddot{\theta} = -b\dot{x} + ml\sin\theta\dot{\theta}^2 + f$$
$$(J+ml^2)\ddot{\theta} + ml\cos\theta\ddot{x} = -mgl\sin\theta$$

- State: $x, \theta, \dot{x}, \dot{\theta}$
- Input: $u = F$
- Output: $y = x$
- Linearize according to previous formula around $\theta = \pi$

$$\frac{d}{dt}\begin{bmatrix} x \\ \theta \\ \dot{x} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{m^2gl^2}{J(M+m)+Mml^2} & \frac{-(J+ml^2)b}{J(M+m)+Mml^2} & 0 \\ 0 & \frac{mgl(M+m)}{J(M+m)+Mml^2} & \frac{-mlb}{J(M+m)+Mml^2} & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \frac{J+ml^2}{J(M+m)+Mml^2} \\ \frac{ml}{J(M+m)+Mml^2} \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

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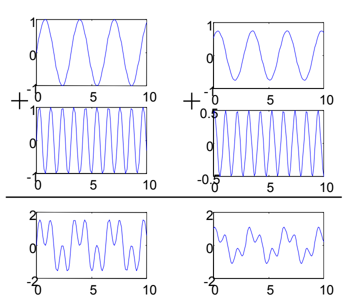
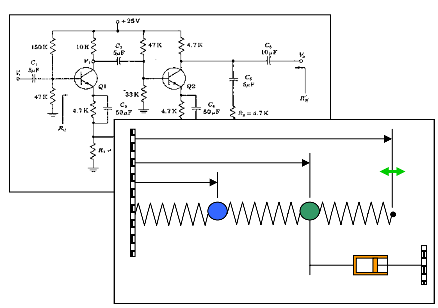
Summary: Linear Systems

u → $\dot{x} = Ax + Bu$, $y = Cx + Du$, $x(0) = 0$ → y





$$y(t) = Ce^{At}x(0) + \int_{\tau=0}^{t} Ce^{A(t-\tau)}Bu(\tau)d\tau + Du(t)$$

Properties of linear systems

- Linearity with respect to initial condition and inputs
- Stability characterized by eigenvalues
- Many applications and tools available
- Provide local description for nonlinear systems

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