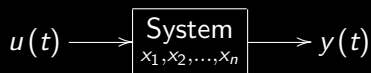


Modeling: Relationship Between State-Space Models and Transfer Functions

Xu Chen

University of Washington

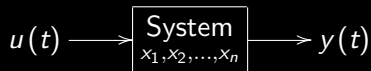
Continuous-time LTI state-space description



$$\frac{d}{dt}x(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

Recap: LTI input/output description



let $u(t) \in \mathbb{R}$ and $y(t) \in \mathbb{R}$, then

$$\begin{aligned} y(t) &= (g \star u)(t) \\ &= \int_0^t g(t - \tau) u(\tau) d\tau \end{aligned}$$

where $g(t)$ is the system's impulse response

Laplace domain:

$$Y(s) = G(s)U(s)$$

$$Y(s) = \mathcal{L}\{y(t)\}, U(s) = \mathcal{L}\{u(t)\}, G(s) = \mathcal{L}\{g(t)\}$$

From state space to transfer function

given $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times 1}$, $C \in \mathbb{R}^{1 \times n}$, $D \in \mathbb{R}$,

$$\begin{aligned}\frac{d}{dt}x(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t)\end{aligned}$$

$\xrightarrow{\mathcal{L}}$

$$\begin{aligned}sX(s) - x(0) &= AX(s) + BU(s) \\ Y(s) &= CX(s) + DU(s)\end{aligned}$$

when $x(0) = 0$, we have

$$\boxed{\frac{Y(s)}{U(s)} = C(sI - A)^{-1}B + D \triangleq G(s)}$$

–the transfer function between u and y

Analogously for discrete-time systems

for $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times 1}$, $C \in \mathbb{R}^{1 \times n}$, $D \in \mathbb{R}$,

$$x(k+1) = Ax(k) + Bu(k)$$

$$y(k) = Cx(k) + Du(k)$$

\xrightarrow{z}
 \Rightarrow

$$zX(z) - zx(0) = AX(z) + BU(z)$$

$$Y(z) = CX(z) + DU(z)$$

when $x(0) = 0$, we have

$$\boxed{\frac{Y(z)}{U(z)} = C(zI - A)^{-1}B + D \triangleq G(z)}$$

–the transfer function between u and y

From state space to transfer function: Observations

$$\begin{aligned}\frac{d}{dt}x(t) &= A_{n \times n}x(t) + B_{n \times 1}u(t) \\ y(t) &= C_{1 \times n}x(t) + Du(t)\end{aligned}$$

- ▶ dimensions:

$$G(s) = \underbrace{C}_{1 \times n} \underbrace{(sI - A)^{-1}}_{n \times n} \underbrace{B}_{n \times 1} + D$$

$$\Sigma = \left[\begin{array}{c|c} A_{n \times n} & B_{n \times 1} \\ \hline C_{1 \times n} & D_{1 \times 1} \end{array} \right]$$

- ▶ uniqueness: $G(s)$ is unique given the state-space model

Matrix inverse

$$M^{-1} = \frac{1}{\det(M)} \text{Adj}(M)$$

where $\text{Adj}(M) = \{\text{Cofactor matrix of } M\}^T$

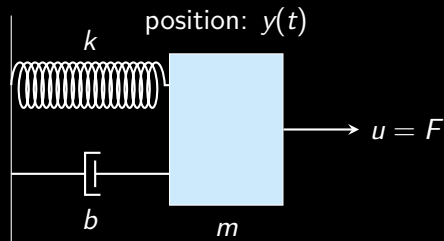
$$\text{e.g.: } M = \begin{bmatrix} 1 & 2 & 3 \\ 0 & 4 & 5 \\ 1 & 0 & 6 \end{bmatrix}, \{\text{Cofactor matrix of } M\} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$$

$$\text{where } c_{11} = \begin{vmatrix} 4 & 5 \\ 0 & 6 \end{vmatrix} = 24, c_{12} = -\begin{vmatrix} 0 & 5 \\ 1 & 6 \end{vmatrix} = 5, c_{13} = \begin{vmatrix} 0 & 4 \\ 1 & 0 \end{vmatrix} = -4,$$

$$c_{21} = -\begin{vmatrix} 2 & 3 \\ 0 & 6 \end{vmatrix} = -12, c_{22} = \begin{vmatrix} 1 & 3 \\ 1 & 6 \end{vmatrix} = 3, c_{23} = -\begin{vmatrix} 1 & 2 \\ 1 & 0 \end{vmatrix} = 2,$$

$$c_{31} = \begin{vmatrix} 2 & 3 \\ 4 & 5 \end{vmatrix} = -2, c_{32} = -\begin{vmatrix} 1 & 3 \\ 0 & 5 \end{vmatrix} = -5, c_{33} = \begin{vmatrix} 1 & 2 \\ 0 & 4 \end{vmatrix} = 4$$

Mass-spring-damper



$$\underbrace{\frac{d}{dt} \begin{bmatrix} y(t) \\ v(t) \end{bmatrix}}_{x(t)} = \underbrace{\begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix}}_A \underbrace{\begin{bmatrix} y(t) \\ v(t) \end{bmatrix}}_{x(t)} + \underbrace{\begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}}_B u(t)$$
$$y(t) = \underbrace{\begin{bmatrix} 1 & 0 \end{bmatrix}}_C \underbrace{\begin{bmatrix} y(t) \\ v(t) \end{bmatrix}}_{x(t)}$$

Mass-spring-damper

$$\frac{d}{dt} \begin{bmatrix} y(t) \\ v(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix} \begin{bmatrix} y(t) \\ v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} u(t)$$
$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} y(t) \\ v(t) \end{bmatrix}$$

$$G(s) = C(sI - A)^{-1}B + D$$

\Rightarrow

$$G(s) = \begin{bmatrix} 1 & 0 \end{bmatrix} \left[\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix} \right]^{-1} \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}$$

Mass-spring-damper

$$\begin{aligned} \left[\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix} \right]^{-1} &= \begin{bmatrix} s & -1 \\ \frac{k}{m} & s + \frac{b}{m} \end{bmatrix}^{-1} \\ &= \frac{1}{s^2 + \frac{b}{m}s + \frac{k}{m}} \begin{bmatrix} s + \frac{b}{m} & 1 \\ -\frac{k}{m} & s \end{bmatrix} \end{aligned}$$

Mass-spring-damper

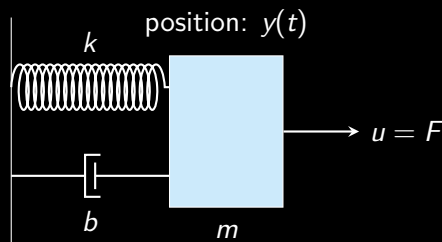
Putting the inverse in yields

$$\begin{aligned} G(s) &= [1 \quad 0] \begin{bmatrix} s & -1 \\ \frac{k}{m} & s + \frac{b}{m} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \\ &= \frac{[1 \quad 0] \begin{bmatrix} s + \frac{b}{m} & 1 \\ -\frac{k}{m} & s \end{bmatrix} \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}}{s^2 + \frac{b}{m}s + \frac{k}{m}} \end{aligned}$$

namely

$$G(s) = \frac{\frac{1}{m}}{s^2 + \frac{b}{m}s + \frac{k}{m}}$$

Numerical example in MATLAB



```
m = 1; k = 2; b = 1;  
A = [0 1; -k/m -b/m];  
B = [0; 1/m];  
C = [1 0];  
D = 0;  
sys = ss(A,B,C,D)  
[num,den] = ss2tf(A,B,C,D);  
sys_tf = tf(num,den)  
figure, step(sys)  
figure, step(sys_tf)
```

Numerical example in Python

```
import control as co
import numpy as np
m = 1
k = 2
b = 1
A = np.array([[0, 1], [-k/m, -b/m]])
B = np.array([[0], [1/m]])
C = np.array([1, 0])
D = np.array([0])
sys = co.ss(A,B,C,D)
print(sys)
sys_tf = co.ss2tf(sys)
print(sys_tf)

print(co.poles(sys))
print(co.poles(sys_tf))
```

Exercise

Given the following state-space system parameters: $A = \begin{bmatrix} 0 & -6 & 0 \\ -2 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$,

$B = \begin{bmatrix} -6 & 0 & -3 \\ -2 & 1 & 0 \\ 0 & 2 & 3 \end{bmatrix}$, $C = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$, obtain the transfer function $G(s)$.