Teoria dei Sistemi e Controllo Ottimo e Adattativo (C. I.)
Teoria dei Sistemi (Mod. A)

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Lez. 10: Modi di un sistema lineare, risposta libera e forzata
(tempo discreto)

Corso di Laurea Magistrale in Ingegneria Meccatronica

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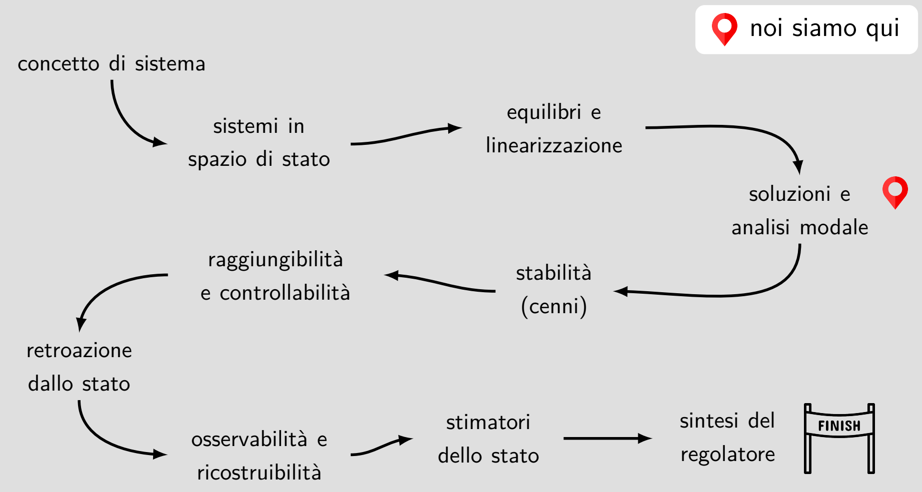
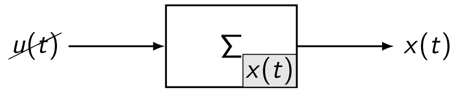


In questa lezione

- ▷ Analisi modale ed evoluzione libera di un sistema lineare a t.d.
- ▷ Evoluzione complessiva di un sistema lineare a t.d.

Soluzioni di un sistema lineare autonomo?



Caso vettoriale $\quad x(t) = y(t) \in \mathbb{R}^n$

$$x(t+1) = Fx(t), \qquad x(0) = x_0$$

$$x(t) = F^t x_0$$

Calcolo di F^t tramite Jordan

1. $F = TF_J T^{-1} \quad \Longrightarrow \quad F^t = TF_J^t T^{-1}$

2. $$F_J = \begin{bmatrix} J_{\lambda_1} & 0 & \cdots & 0 \\ 0 & J_{\lambda_2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & J_{\lambda_k} \end{bmatrix} \quad \Longrightarrow \quad F_J^t = \begin{bmatrix} J_{\lambda_1}^t & 0 & \cdots & 0 \\ 0 & J_{\lambda_2}^t & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & J_{\lambda_k}^t \end{bmatrix}$$

3. $$J_{\lambda_i} = \begin{bmatrix} J_{\lambda_i,1} & 0 & \cdots & 0 \\ 0 & J_{\lambda_i,2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & J_{\lambda_i,g_i} \end{bmatrix} \quad \Longrightarrow \quad J_{\lambda_i}^t = \begin{bmatrix} J_{\lambda_i,1}^t & 0 & \cdots & 0 \\ 0 & J_{\lambda_i,2}^t & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & J_{\lambda_i,g_i}^t \end{bmatrix}$$

Calcolo di F^t tramite Jordan

4(i). $$J_{\lambda_i,j} = \begin{bmatrix} \lambda_i & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & 1 \\ 0 & \cdots & 0 & \lambda_i \end{bmatrix} \in \mathbb{R}^{r_{ij}\times r_{ij}} \overset{\lambda_i \neq 0}{\Longrightarrow} J_{\lambda_i,j}^t = (\lambda_i I + N)^t, \quad N = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & 1 \\ 0 & \cdots & 0 & 0 \end{bmatrix}$$

$$\Longrightarrow J_{\lambda_i,j}^t = \begin{bmatrix} \binom{t}{0}\lambda_i^t & \binom{t}{1}\lambda_i^{t-1} & \binom{t}{2}\lambda_i^{t-2} & \cdots & \binom{t}{r_{ij}-1}\lambda_i^{t-r_{ij}+1} \\ 0 & \binom{t}{0}\lambda_i^t & \binom{t}{1}\lambda_i^{t-1} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \binom{t}{2}\lambda_i^{t-2} \\ \vdots & \ddots & \ddots & \ddots & \binom{t}{1}\lambda_i^{t-1} \\ 0 & \cdots & \cdots & 0 & \binom{t}{0}\lambda_i^t \end{bmatrix}$$

Calcolo di F^t tramite Jordan

4(ii). $$J_{\lambda_i,j} = \begin{bmatrix} \lambda_i & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & 1 \\ 0 & \cdots & 0 & \lambda_i \end{bmatrix} \in \mathbb{R}^{r_{ij}\times r_{ij}} \overset{\lambda_i = 0}{\Longrightarrow} J_{\lambda_i,j}^t = N^t, \quad N = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & 1 \\ 0 & \cdots & 0 & 0 \end{bmatrix}$$

$$\Longrightarrow J_{\lambda_i,j}^t = \begin{bmatrix} \delta(t) & \delta(t-1) & \delta(t-2) & \cdots & \delta(t-r_{ij}+1) \\ 0 & \delta(t) & \delta(t-1) & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \delta(t-2) \\ \vdots & \ddots & \ddots & \ddots & \delta(t-1) \\ 0 & \cdots & \cdots & 0 & \delta(t) \end{bmatrix}$$

Modi elementari

$$\left.\begin{array}{l} \binom{t}{0}\lambda_i^t,\ \binom{t}{1}\lambda_i^{t-1},\ \binom{t}{2}\lambda_i^{t-2},\ \ldots,\ \binom{t}{r_{ij}-1}\lambda_i^{t-r_{ij}+1} \\ \delta(t),\ \delta(t-1),\ \delta(t-2),\ \ldots,\ \delta(t-r_{ij}+1) \end{array}\right\} = \text{modi elementari del sistema}$$

1. $\lambda_i \neq 0$: $\binom{t}{k}\lambda_i^{t-k} \sim t^k \lambda_i^t = t^k e^{t(\ln \lambda_i)}$ (**N.B.** $\ln(\cdot)$ = logaritmo naturale complesso)

2. $\lambda_i = 0$: modi elementari si annullano dopo un numero finito di passi !

Non esiste una controparte modale a tempo continuo !!

Evoluzione libera

$$x(t+1) = Fx(t) + \cancel{Gu(t)}, \qquad x(0) = x_0$$

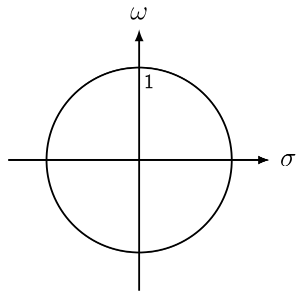
$$y(t) = Hx(t) + \cancel{Ju(t)}$$

$$y(t) = y_\ell(t) = HF^t x_0 = \sum_{i,j} t^j \lambda_i^t v_{ij} + \sum_j \delta(t-j) w_j$$

$= \text{combinazione lineare dei modi elementari}$

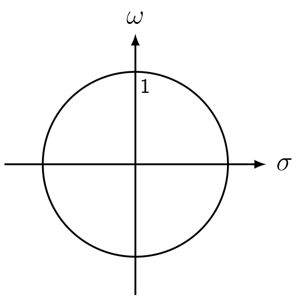
Carattere dei modi elementari

$$\lambda_i = \sigma_i + i\omega_i \in \mathbb{C}, \lambda_i \neq 0 : \binom{t}{k_i}\lambda_i^{t-k_i} \sim t^{k_i}\lambda_i^t = t^{k_i} e^{t(\ln \lambda_i)} = t^{k_i} e^{t(\ln|\lambda_i| + i\arg(\lambda_i))}$$



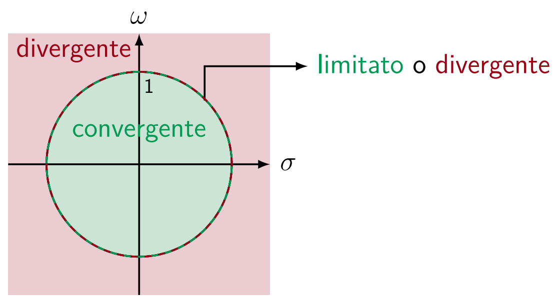
Carattere dei modi elementari

$\lambda_i = 0$: $\delta(t - k_i)$



Carattere dei modi elementari

modo associato a $\lambda_i = \sigma_i + i\omega_i$



Comportamento asintotico

$$F \in \mathbb{R}^{n \times n} \text{ con autovalori } \{\lambda_i\}_{i=1}^{k}$$

$|\lambda_i| < 1, \forall i \iff F^t \xrightarrow{t\to\infty} 0 \implies y(t) = HF^t x_0 \xrightarrow{t\to\infty} 0$

$F^t = 0$ per t finito se $\lambda_i = 0$!!

$|\lambda_i| \leq 1,\ \forall i$ e $\nu_i = g_i$ se $|\lambda_i| = 1 \iff F^t$ limitata $\Rightarrow y(t) = HF^t x_0$ limitata

$\exists\, \lambda_i$ tale che $|\lambda_i| > 1$ o $|\lambda_i| = 1$ e $\nu_i > g_i \iff F^t$ non limitata $\Rightarrow y(t) = HF^t x_0$?

Evoluzione complessiva (libera + forzata)

$$x(t+1) = Fx(t) + Gu(t), \qquad x(0) = x_0$$

$$y(t) = Hx(t) + Ju(t)$$

$$x(t) = x_\ell(t) + x_f(t), \qquad x_\ell(t) = F^t x_0, \qquad x_f(t) \ ??$$

$$y(t) = y_\ell(t) + y_f(t), \qquad y_\ell(t) = HF^t x_0, \qquad y_f(t) \ ??$$

Evoluzione complessiva (libera + forzata)

$$x(t+1) = Fx(t) + Gu(t), \qquad x(0) = x_0$$

$$y(t) = Hx(t) + Ju(t)$$

$$x(t) = \underbrace{F^t x_0}_{=x_\ell(t)} + \underbrace{\sum_{k=0}^{t-1} F^{t-k-1} Gu(k)}_{=x_f(t)}$$

$$y(t) = \underbrace{HF^t x_0}_{=y_\ell(t)} + \underbrace{\sum_{k=0}^{t-1} HF^{t-k-1} Gu(k) + Ju(t)}_{=y_f(t)}$$

$$w(t) = \text{ risposta impulsiva } = \begin{cases} J, & t = 0 \\ HF^t G, & t \geq 1 \end{cases}$$

Evoluzione complessiva (libera + forzata)

$$x(t+1) = Fx(t) + Gu(t), \qquad x(0) = x_0$$

$$y(t) = Hx(t) + Ju(t)$$

$$x(t) = \underbrace{F^t x_0}_{=x_\ell(t)} + \underbrace{\sum_{k=0}^{t-1} F^{t-k-1} Gu(k)}_{=x_f(t)} = \underbrace{F^t x_0}_{=x_\ell(t)} + \underbrace{\mathcal{R}_t u_t}_{=x_f(t)} \qquad u_t \triangleq \begin{bmatrix} u(t-1) \\ u(t-2) \\ \vdots \\ u(0) \end{bmatrix}$$

$$y(t) = \underbrace{HF^t x_0}_{=y_\ell(t)} + \underbrace{\sum_{k=0}^{t-1} HF^{t-k-1} Gu(k) + Ju(t)}_{=y_f(t)} = \underbrace{HF^t x_0}_{=y_\ell(t)} + \underbrace{H\mathcal{R}_t u_t + Ju(t)}_{=y_f(t)}$$

$\mathcal{R}_t \triangleq \left[\ G \mid FG \mid F^2 G \mid \cdots \mid F^{t-1} G\ \right]$ = matrice di raggiungibilità in t passi

Evoluzione complessiva con Zeta

$$zX(z) - zx_0 = FX(z) + GU(z)$$

$$Y(z) = HX(z) + JU(z)$$

$$V(z) \triangleq \mathcal{Z}[v(t)] = \sum_{t=0}^{\infty} v(t) z^{-t}$$

$$X(z) = \underbrace{z(zI - F)^{-1}x_0}_{=X_\ell(z)} + \underbrace{(zI - F)^{-1}GU(z)}_{=X_f(z)}$$

$$Y(z) = \underbrace{Hz(zI - F)^{-1}x_0}_{=Y_\ell(z)} + \underbrace{[H(zI - F)^{-1}G + J]U(z)}_{=Y_f(z)}$$

Equivalenze dominio temporale/Zeta

1. $W(z) = \mathcal{Z}[w(t)] = H(zI - F)^{-1}G + J =$ matrice di trasferimento

2. $\mathcal{Z}[F^t] = z(zI - F)^{-1} =$ metodo alternativo per calcolare F^t !!