EE 5323- Take Home Exam 2

Fall 2021

This exam has 6 pages in all. There are 4 problems.

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Almost all questions require numerical calculations to arrive at the answers. To obtain full credit, show all your work. No partial credit will be given without the supporting work.

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Pledge of honor:

"On my honor I have neither given nor received aid on this examination."

Signature: ______________________

1. Lyapunov Function

Use Lyapunov function to examine the stability of the following systems. Be clear and show all steps.

a.

$$\dot{x}_1 = x_2 \sin x_1 - x_1$$
$$\dot{x}_2 = -x_1 \sin x_1 - x_2$$

$V(x_1, x_2) = \frac{1}{2}(x_1^2 + x_2^2) > 0$

$\dot{V} = x_1 \dot{x}_1 + x_2 \dot{x}_2 = 0 \Rightarrow$

$x_1(x_2 \sin x_1 - x_1) + x_2(-x_1 \sin x_1 - x_2) = 0 \Rightarrow$

$x_1 x_2 \sin x_1 - x_1^2 - \cancel{x_1 x_2 \sin x_1} - x_2^2 = 0 \Rightarrow -(x_1^2 + x_2^2) = 0$

ep (0,0) only

$\dot{V} \leq 0$ then GAS

b.

$$\dot{x}_1 = x_2 \sin x_1 - x_1$$
$$\dot{x}_2 = -x_1 \sin x_1$$

$\dot{V} = x_1 \dot{x}_1 + x_2 \dot{x}_2 = 0 \Rightarrow$

$x_1(x_2 \sin x_1 - x_1) + x_2(-x_1 \sin x_1) = 0$

$x_1 x_2 \sin x_1 - x_1^2 - \cancel{x_1 x_2 \sin x_1} = 0$

$\dot{V} = -x_1^2$; $\dot{V} = 0$, $x_1 = 0$

$\dot{V} \leq 0$ ✓

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marginally stable because it only depends on x_1

2. LaSalle's Extension

$$\ddot{x}+k_1\dot{x}+k_2\dot{x}^3+k_3x^5=0 \Rightarrow \ddot{x} = -k_1\dot{x} - k_2\dot{x}^3 - k_3x^5$$

a. Use Lyapunov to check the stability. Hint: Use the energy as the Lyapunov function. Take the potential energy as

$$PE=\int_0^x (k_2\dot{x}^3+k_3x^5)dx \qquad V = \frac{1}{2}\dot{x}^2 + \int_0^x C(y)dy = K + U;$$

$$\dot{V} = \ddot{x}\dot{x} + \frac{d}{dt}\int_0^x C(y)dy \Rightarrow$$

Per Leibniz's theorem: $\frac{d}{dt}\int_\alpha^\beta F(x,t)dx = \dot\beta F(\beta,t) - \dot\alpha F(\alpha,t) + \int_\alpha^\beta \frac{\partial}{\partial t}F(x,t)dx$

$$\Rightarrow \dot{x}(-k_1\dot{x} - \cancel{k_2\dot{x}^3} - \cancel{k_3x^5}) + \dot{x}(\cancel{k_2x^3} + \cancel{k_3x^5}) - (0)(\ ) + (0+0)\Big|_{\alpha=0}^{\beta=x}$$

$$\Rightarrow \dot{V} = -k_1\dot{x}^2 \le 0 \text{ if } k_1 \ge 0,$$

$\dot{V} = 0 \Rightarrow \dot{x} \to 0$ or $k_1 = 0$ | SISL

↳ hints at use of LaSalle's extention

we plug this in dynamics equation.

b. Use LaSalle's extension to find a stronger type of stability for the system.

if $\dot{x} \to 0 \Rightarrow \ddot{x} \to 0$; plug in sys dynamic

$$\underbrace{\ddot{x}}_{0} + k_1\underbrace{\dot{x}}_{0} + k_2\underbrace{\dot{x}^3}_{0} + k_3x^5 = 0 \Rightarrow k_3x^5 = 0 \Rightarrow x = 0$$

⇒ thus the system is dissipative / reaches equilibrium at $x=0$; thus it is considered Global Asymptotic Stable (GAS)

3. Lyapunov Equation for Linear Systems

Use Lyapunov Equation to check the stability of the linear systems

a. $\dot{x} = Ax = \begin{bmatrix} 0 & 1 \\ 0 & -6 \end{bmatrix} x$

not stable

undetermined

$$A^T P + PA = -Q \Rightarrow \begin{bmatrix} a_1 & a_3 \\ a_2 & a_4 \end{bmatrix}\begin{bmatrix} p_1 & p_2 \\ p_3 & p_4 \end{bmatrix} + \begin{bmatrix} p_1 & p_2 \\ p_3 & p_4 \end{bmatrix}\begin{bmatrix} a_1 & a_1 \\ a_2 & a_3 \end{bmatrix} = -Q$$

$$\begin{bmatrix} a_1p_1 + a_3p_3 + a_1p_1 + a_3p_2 & a_1p_2 + a_3p_4 + a_2p_1 + a_4p_2 \\ a_2p_1 + a_4p_3 + a_1p_3 + a_3p_3 & a_2p_2 + a_4p_3 + a_2p_2 + a_4p_3 \end{bmatrix} = -Q,$$

where I test the following Q matrices

$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$

$\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 1 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}, [\ \ldots$

& a unique solution

DNE

b. $\dot{x} = Ax = \begin{bmatrix} 0 & 1 \\ -3 & -4 \end{bmatrix} x$

stable w/

$Q = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$,

$m_{11} = .8\bar{3}$
$m_{22} = .1667$

$\begin{bmatrix} .83 & .5 \\ -.5 & .5 \end{bmatrix}$

$\begin{bmatrix} \text{Same a.py matrix} \end{bmatrix} = -Q$
From 3.a.

$m_{22} = (.83 \cdot .5) - (.25)$

4. UUB

Use Lyapunov to show that the system

$$\dot{x}_1 = x_1 x_2^{\,2} - x_1(x_1^{\,2} + x_2^{\,2} - 3)$$
$$\dot{x}_2 = -x_1^{\,2} x_2 - x_2(x_1^{\,2} + x_2^{\,2} - 3)$$

is uniformly ultimately bounded UUB. That is, show that the Lyapunov derivative is NEGATIVE OUTSIDE A BOUNDED REGION. Find the radius of the bounded region outside which $\dot{V} < 0$. Any states outside this region are attracted towards the origin.

$$V(x_1, x_2) = \frac{1}{2}(x_1^2 + x_2^2 - 3)^2 > 0 \Rightarrow \dot{V} = \frac{2}{2}(x_1^2 + x_2^2 - 3)(2x_1\dot{x}_1 + 2x_2\dot{x}_2)$$

$$\Rightarrow \dot{V} = (x_1^2 + x_2^2 - 3)\left(2x_1\left(x_1x_2^2 - x_1(x_1^2 + x_2^2 - 3)\right) + 2x_2\left(-x_1^2x_2 - x_2(x_1^2 + x_2^2 - 3)\right)\right)$$

$$= (x_1^2 + x_2^2 - 3)\left[2x_1(-x_1^3 - x_1x_2^2 + 3x_1) + 2x_2(-x_1^2x_2 - x_2^3 + 3x_2)\right]$$

$$\left(-2x_1^2(x_1^2 + x_2^2 - 3) - 2x_2^2(x_1^2 + x_2^2 - 3)\right)$$

$$\Rightarrow \dot{V} = \underbrace{(x_1^2 + x_2^2 - 3)^2}_{\geq 0}\underbrace{(-2x_1^2 - 2x_2^2)}_{\leq 0} = 0 \Rightarrow \text{Per Cauchy Schwartz}$$

$$\Rightarrow \|\dot{V}\| \leq \|x_1^2 + x_2^2 - 3\|^2 \, \|(-2)\| \, \underbrace{\|x_1^2 + x_2^2\|}_{\geq 0}$$

$\|x^T y\| \leq \|x\| \cdot \|y\|$ given an orthonormal space

creates boundary where the radius is $\underline{\sqrt{3}}$