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Techniques used to Control Nonlinear Systems using linear Feedback, Slip Mode Control, and back-Rotation

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الملخص:

تتناول هذه الورقة المبادئ الأساسية للتقنيات المستخدمة في التحكم بالأنظمة غير الخطية (في أنظمة التحكم الالي) وقد تم تطبيق هذا التقنيات المستخدمة في هذه الورقة البحثية على ثلاثة أمثلة غير خطية مختلفة للتحقق من أدائها والية التحكم في الانظمة وقيودها و الطرق هي كالاتي: خطية التغذية الراجعة، والتحكم بالنمط المنزلق، والتدوير الخلفي.

Abstract:

The basic principles of this paper about the techniques that used to apply control on nonlinear systems. These methods were applied to three different nonlinear examples in order to check the performance of these techniques. These methods are Feedback Linearization, Sliding mode Control and Backstepping.

Key words: Nonlinear systems, sliding mode control, Back-stepping control, feedback linearization control, Van der Pol system, linearization, Close-Loop-system, Open-Loop-system, Feedback Linearization.

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Introduction:

The basic principles of this paper about the techniques that used to apply control on Nonlinear systems. These methods were applied to three different Nonlinear examples in order to check the performance of these techniques. These methods are Feedback Linearization, Sliding mode Control and Backstepping. Moreover, nonlinear dynamical equations are difficult to solve, Nonlinear systems are commonly approximated by linear equations (linearization). While this works well up to some accuracy and some range for the input values, but some interesting phenomena such as solutions, chaos, and singularities are hidden by linearization. In addition, in follows that some aspects of the dynamic behavior of a nonlinear system can appear to be counterintuitive, unpredictable or even chaotic.

1- First system differential equation and controller design:

The system differential Equation as follows: -

$$\dot{x}_1 = x_2 + a x_1 sin x_1$$
$$\dot{x}_2 = b x_1 x_2 + u$$

And the system following by:

$$\overline{f}(x) = \begin{bmatrix} x_2 + ax_1 sinx_1 \\ bx_1x_2 \end{bmatrix} \quad ; \quad \overline{g}(x) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$we\ need\ to\ find\ z = T(x)\ satisfying:$

$$(1)\ \frac{\partial T_1}{\partial x}\overline{g} = 0 \qquad (2)\ \frac{\partial T_2}{\partial x}\overline{g} \neq 0 \qquad (3)\ T_2 = \frac{\partial T_1}{\partial x}\overline{f}$$

$Writing\ all\ conditions:$

$$(1)\ \frac{\partial T_1}{\partial x}\overline{g} = 0 \rightarrow \begin{bmatrix} \frac{\partial T_1}{\partial x_1} & \frac{\partial T_1}{\partial x_2} \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} = 0 \ \rightarrow\ \frac{\partial T_1}{\partial x_2} = 0 \ \rightarrow T_1 = T_1(x_1)$$

$$(2)\ \frac{\partial T_2}{\partial x}\overline{g} \neq 0 \rightarrow \begin{bmatrix} \frac{\partial T_2}{\partial x_1} & \frac{\partial T_2}{\partial x_2} \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} \neq 0 \ \rightarrow\ \frac{\partial T_2}{\partial x_2} \neq 0 \ \rightarrow T_2 = T_2(x_1, x_2)$$

$$(3)\ T_2 = \frac{\partial T_1}{\partial x}\overline{f} = \begin{bmatrix} \frac{\partial T_1}{\partial x_1} & \frac{\partial T_1}{\partial x_2} \end{bmatrix}\begin{bmatrix} x_2 + ax_1 sinx_1 \\ bx_1x_2 \end{bmatrix} = \frac{\partial T_1}{\partial x_1}\ (x_2 + ax_1 sinx_1)$$

$$From\ (1)\ let\ \ T_1 = x_1\ \ - - - \rightarrow\ \frac{\partial T_1}{\partial x_2} = 0 \quad - - - \rightarrow (Satisfies\ condition)$$

$$From\ (3)\ \ T_2 = \frac{\partial T_1}{\partial x}\overline{f} = \begin{bmatrix} \frac{\partial T_1}{\partial x_1} & \frac{\partial T_1}{\partial x_2} \end{bmatrix}\begin{bmatrix} x_2 + ax_1 sinx_1 \\ bx_1x_2 \end{bmatrix} = \frac{\partial T_1}{\partial x_1}\ (x_2 + ax_1 sinx_1)$$

$$as\ \frac{\partial T_1}{\partial x_1} = 1 \quad \rightarrow T_2 = (x_2 + ax_1 sinx_1) \rightarrow (Satisfies\ condition\ (2)\ \&\ (3))$$

$So\ all\ condition\ are\ true:$

$$z = T(x) = \begin{bmatrix} x_1 \\ x_2 + ax_1 sinx_1 \end{bmatrix} \quad - - \rightarrow \quad \begin{matrix} z_1 = x_1 \\ z_2 = x_2 + ax_1 sinx_1 \end{matrix}$$

$Now\ we\ need\ to\ find\ x = T^{-1}(z)$

$x_1 = z_1$

$z_2 = x_2 + ax_1 sinx_1\ \rightarrow z_2 = x_2 + az_1 sinz_1 \rightarrow x_2 = z_2 - az_1 sinz_1$

$$x = T^{-1}(z) = \begin{bmatrix} z_1 \\ z_2 - az_1 sinz_1 \end{bmatrix}$$

Verifying:

$\dot{z}_1 = \dot{x}_1 = \ x_2 + ax_1 sinx_1 = z_2 - az_1 sinz_1 + az_1 sinz_1 = z_2$

$\dot{z}_2 = \dot{x}_2 + a\dot{x}_1 sinx_1 + ax_1 cosx_1 \dot{x}_1$

$\dot{z}_2 = bx_1x_2 + u + a(x_2 + ax_1 sinx_1)sinx_1 + ax_1 cosx_1 (x_2 + ax_1 sinx_1)$

$\dot{z}_2 = bx_1x_2 + u + \ ax_2 sinx_1 + a^2x_1 sin^2x_1 + ax_1x_2 cosx_1 + a^2x_1^2 sinx_1 cosx_1$

$$\dot{z}_2 = bz_1(z_2 - az_1 sinz_1) + u + a\ sinz_1(z_2 - az_1 sinz_1) + a^2 z_1 sin^2 z_1 + az_1 cosz_1(z_2 - az_1 sinz_1) + a^2 z_1^2 sinz_1 cosz_1$$

$$\dot{z}_2 = bz_1 z_2 - abz_1^2 sinz_1 + u + a\ z_2 sinz_1 - a^2 z_1 sin^2 z_1 + a^2 z_1 sin^2 z_1 + az_1 z_2\ cosz_1 - a^2 z_1^2 sinz_1 cosz_1 + a^2 z_1^2 sinz_1 cosz_1$$

$$\dot{z}_2 = bz_1 z_2 - abz_1^2 sinz_1 + a\ z_2 sinz_1 + az_1 z_2\ cosz_1 + u$$

$To\ design\ SFL\ controller\ that\ regulates\ z\ \to 0$

$$u = \frac{1}{g(z)}[-f(z) + v] \qquad v = -(k_1 z_1 + k_2 z_2)$$

k_1 & k_2 have to selected to make the location for system poles in the left hand side

thus the system is state feed back linearizable.

By simulating the above controller with Malab at $a = \hat{a} = 1$ and $b = \hat{b} = 1.5$. we get the response shown in Fig.1. It's clear from the result that the controller regulates the system states to zero effectively

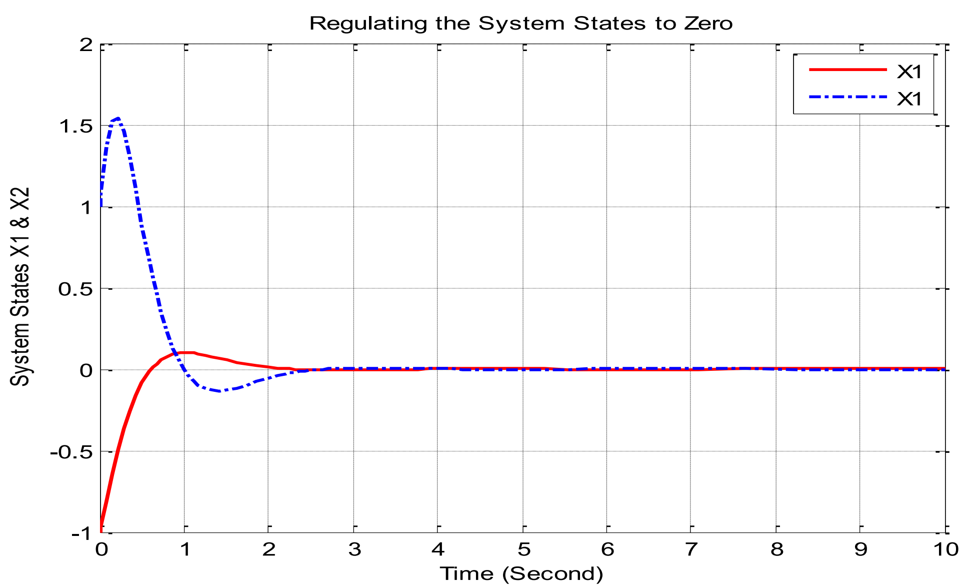

Fig.1. The feedback linearization controller regulates the system states to zero

By setting $a = -1\ and\ b = 2$ in simulation with the same u and diffeomorphism. It is not possible to control the system. We can notice that from figure (2).

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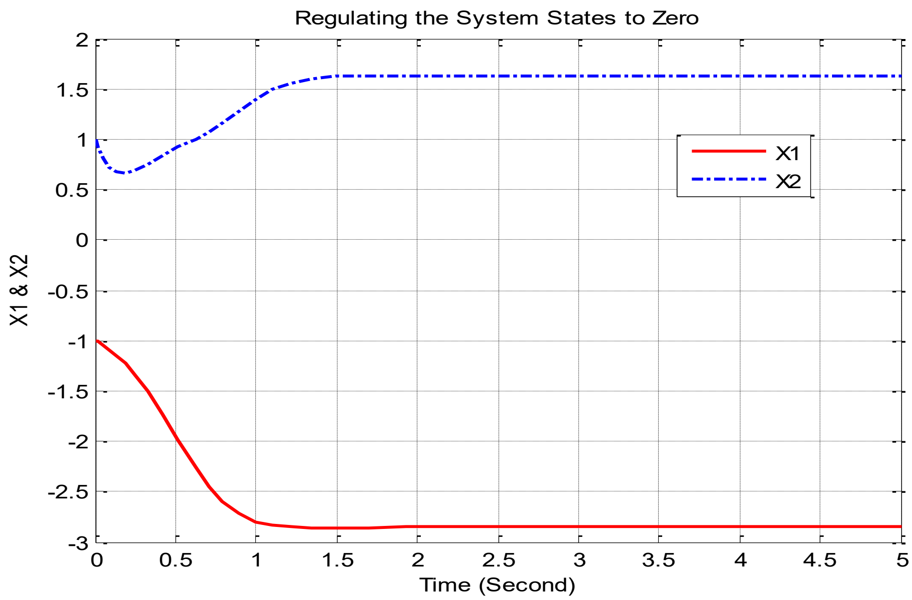


Fig.2. The feedback linearization controller does not regulates the system states to zero

Applying Sliding Mode Control Approach:

$\dot{x}_1 = x_2 + ax_1 sinx_1$

By selecting $\boldsymbol{x_2}$ that stabilizes the origin $x_1 = 0$. This can be reached by assuming the Lyapunove candidate function:

$v_1 = \frac{1}{2}x_1^2$ for $\dot{x}_1 = x_2 + ax_1 sinx_1$

$\dot{v}_1 = x_1\dot{x}_1$

$= x_1(x_2 + ax_1 sinx_1)$

$= x_1x_2 + ax_1^2 sinx_1 \le x_1x_2 + 2x_1^2$

$0 \le |a| \le 2$ and $x_2 = -3x_1$

$x_1 = 0$ is GAS

$\dot{v}_1 \le x_1(-3x_1) + 2x_1^2$

$\dot{v}_1 \le -3x_1^2 + 2x_1^2$

$\dot{v}_1 \le -x_1^2$

$s = 3x_1 + x_2$

$$\dot{s} = 3\dot{x}_1 + \dot{x}_2 \quad = 3(x_2 + ax_1 sinx_1) + bx_1x_2 + u \; = 3x_2 + 3ax_1 sinx_1 + bx_1x_2 + u$$

$$u = -3x_2 - 3x_1 sinx_1 - x_1x_2 + v$$

$$\dot{s} = \; 3x_2 + 3ax_1 sinx_1 + bx_1x_2 - 3x_2 - 3x_1 sinx_1 - x_1x_2 + v$$

$$= -3x_1 sinx_1(a-1) + x_1x_2(b-1) + v$$

$$= |-3x_1 sinx_1(a-1) + x_1x_2(b-1)| \leq 3|x_1| + 2|x_1||x_2|$$

$$\leq |x_1|(3 + 2|x_2|)$$

$$v = \; -[1 + |x_1|(3 + 2|x_2|)]sat(\frac{S}{\epsilon})$$

Figures (3) and (4) shows the Matlab simulation of the time response and phase portrait for x_1 and x_2

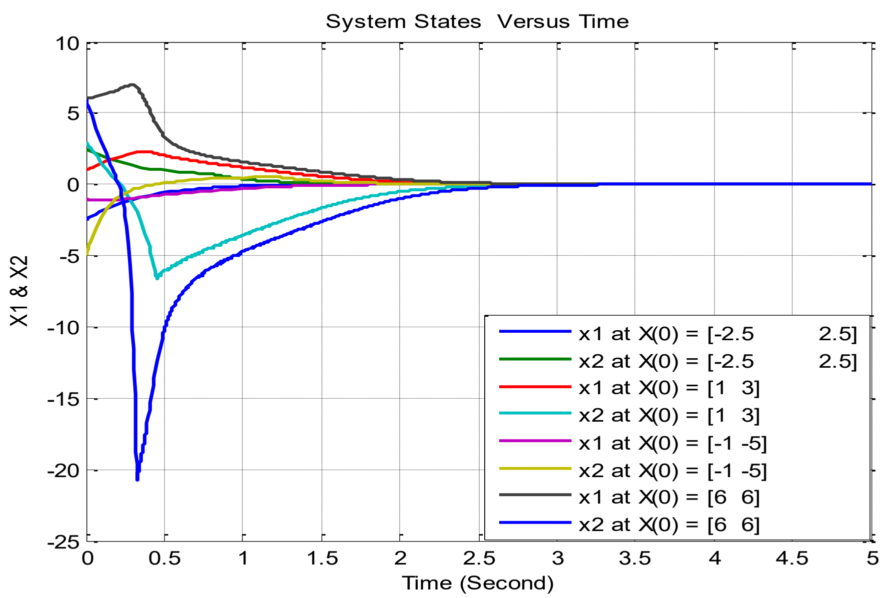


Fig.3. The system states response versus time with different initial condition

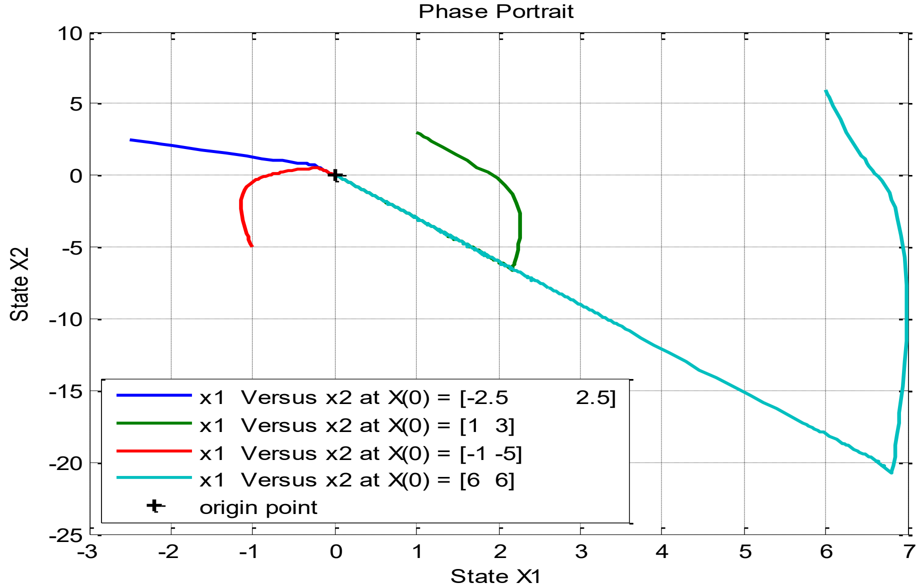


Fig.4. Displays the portrait for states $\boldsymbol{x_1}$ *and* $\boldsymbol{x_2}$

2- Sliding Mode control for a Pendulum:

The Sliding Mode Control for a pendulum, whose suspension point is subjected to a time-varying, bounded, horizontal acceleration, is given by

$$ml\ddot{\theta} + mg\,sin\theta + kl\dot{\theta} = \frac{T}{l} + mh(t)cos\theta$$

Where h is the horizontal acceleration, and T is the torque (control) input. Assume that g = 9.81 and

$$0.9 \le l \le 1.1 \le, \quad 0.5 \le m \le 1.5, \quad 0 \le k \le 0.2, \qquad |h(t)| \le 1$$

It is desired to stabilize the pendulum at θ=0 for arbitrary initial conditions $\theta(0)$ and $\dot{\theta}$ (0). And Designing a continuous sliding mode feedback controller to achieve ultimate convergence of the states to $|\theta| \le 0.01$ and $|\dot{\theta}| \le 0.01$. And finally verifying the controller design with a simulation.

$$Let \quad x_1 = \theta \qquad x_2 = \dot{\theta}$$

$$\begin{cases} \dot{x}_1 = \dot{\theta} = x_2 \\ \dot{x}_2 = \ddot{\theta} = -\frac{g}{l}\,sin\theta - \frac{k}{m}\dot{\theta} + \frac{1}{ml^2}T + \frac{h(t)}{l}cos\theta \end{cases}$$

$$Let \;\; a = \frac{g}{l} \qquad b = \frac{k}{m} \qquad c = \frac{1}{ml^2} \qquad T = u \qquad \boldsymbol{\zeta(t)} = \frac{h(t)}{l}$$

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -a\,sinx_1 - bx_2 + cu + \boldsymbol{\zeta(t)}cosx_1 \end{cases}$$

$$x_2 = -x_1$$

$$s = x_1 + x_2$$

$$\dot{s} = \dot{x}_1 + \dot{x}_2 = x_2 - a\,sinx_1 - bx_2 + cu + \boldsymbol{\zeta}(\boldsymbol{t})cosx_1 = (1-b)x_2 - a\,sinx_1 + cu + \boldsymbol{\zeta}(\boldsymbol{t})cosx_1$$

$$\dot{s} = c[u + \ \delta]$$

$$Assuming\ \ \delta = \frac{1}{c}[(1-b)x_2 - a\,sinx_1 + \boldsymbol{\zeta}(\boldsymbol{t})cosx_1]$$

$$|\delta| \leq \left|\frac{a}{c}\right||x_1| + \left|\frac{1-b}{c}\right||x_2| + \left|\frac{\boldsymbol{\zeta}(\boldsymbol{t})}{c}\right| \leq 16.186|x_1| + 1.815|x_2| + 1.111$$

$$u = -[16.186|x_1| + 1.815|x_2| + 2]sat(\frac{s}{\epsilon})$$

Figure (5) and (6) shows the Matlab simulation of the time response and phase portrait for x_1 and x_2 with different initial value

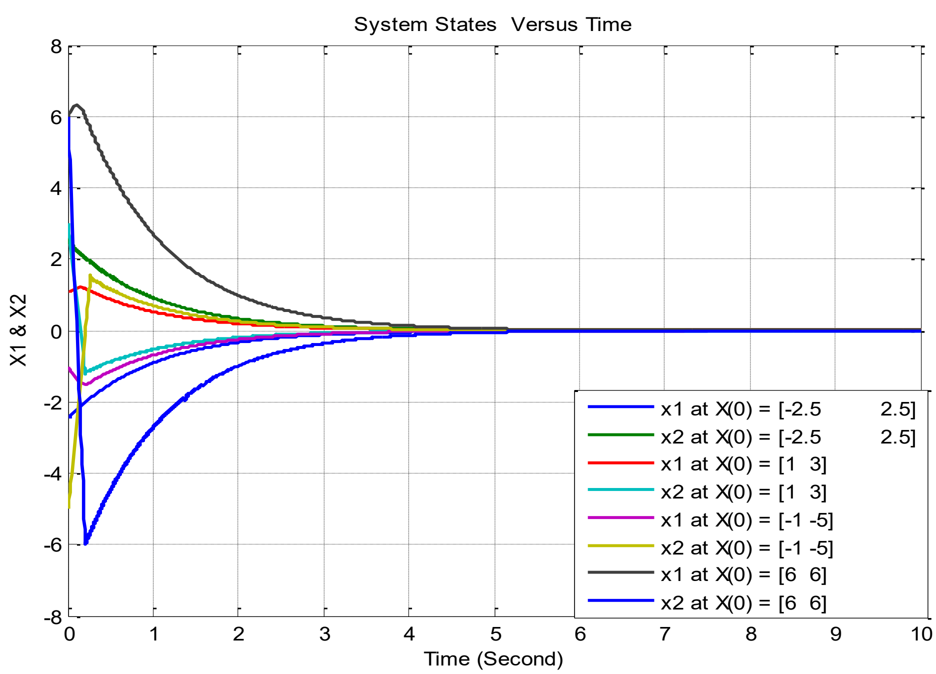


Fig.5. The system states response versus time with different initial condition

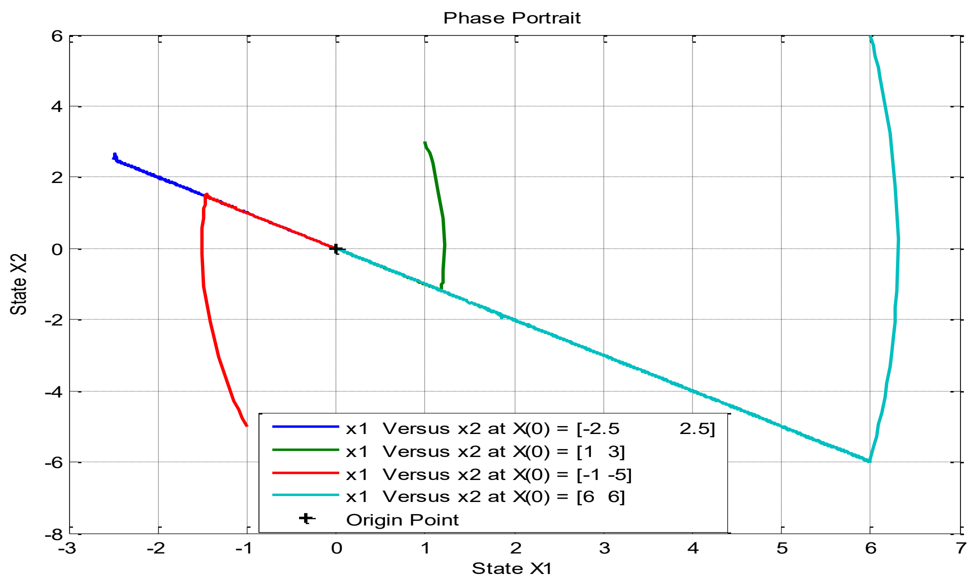


Fig.6. Displays the portrait for states x_1 and x_2

3- Back stepping of Wing Rock Regulation:

Aircraft wing rock is a limit cycling oscillation in the roll angle $\emptyset$ and the roll rate $\dot{\emptyset}$ which can occur in high performance aircraft with delta wings when flying at high angles of attack. See Figure (8) for further clarification.

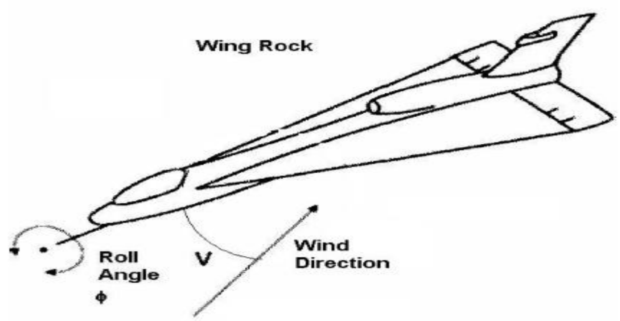
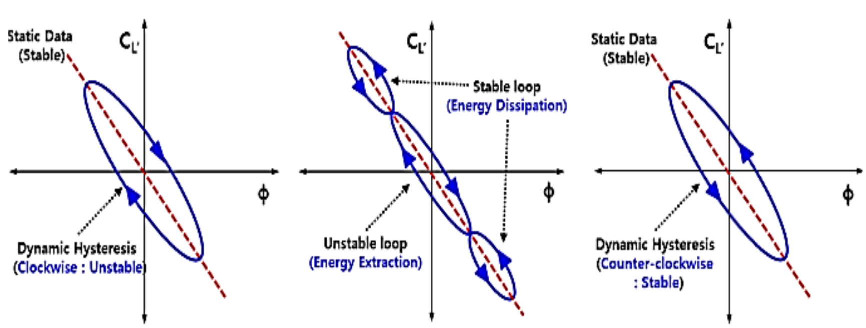


Fig.7. Aircraft wing rock



(a) Wing rock build-up phase (b) Wing rock limit cycle phase (c) Wing rock decay phase

Fig.8. Wing rock build –up phase, limit cycle phase, and decay phase

A model of wing rock based on wind tunnel experiment is given by

$$\ddot{\emptyset} = -\omega^2 + \mu_1\dot{\emptyset} + b_1\dot{\emptyset}^3 + \mu_2\emptyset^2\dot{\emptyset} + b_2\,\emptyset\dot{\emptyset}^2 + g\delta_a$$

Parameter and constants for the model:

$$\omega^2 = -c_1a_1 \qquad \mu_1 = c_1a_2 - c_2 \qquad b_1 = c_1a_3 \qquad \mu_2 = c_1a_4$$
$$b_2 = c_1a_5 \qquad c_1 = 0.354 \qquad c_2 = 0.001$$

When the angle of attack $v = 25$, the values of the parameters $a_1\ to\ a_5$ are given in the following table:

$V\text{: the angle of attack and } a\text{: the values of the parameters}$

Table 1: Parameters for the coefficients in the wing rock model:

v	a_1	a_2	a_3	a_4	a_5
25	-0.05686	0.03254	0.07334	-0.3597	1.4681

The state space representation of the wing rock phenomenon is written, where g is a constant and δ_a is a force applied on the wing by an actuator with linear dynamics given by :

$$\dot{\delta}_a = -\frac{1}{\tau}\delta_a + \frac{1}{\tau}u$$

Let $x_1 = \emptyset \rightarrow$ Roll angle $x_2 = \dot{\emptyset}$ → Roll velocity → $\ddot{\emptyset}$ = Roll acceleration $x_3 = \delta_a$

The state space representation of the wing rock phenomenon is derived as follow:

$$\dot{x}_1 = \dot{\emptyset} = x_2$$

$$\dot{x}_2 = \ddot{\emptyset} = -\omega^2x_1 + \mu_1x_2 + b_1x_2^3 + \mu_2x_1^2x_2 + b_2x_1x_2^2 + gx_3$$

$$\dot{x}_3 = \dot{\delta}_a = -\tfrac{1}{\tau}x_3 + \tfrac{1}{\tau}u$$

$$y = x_1$$

Simulating the system in open loop → $(u = 0)$ Initial conditions $\emptyset(0) = -4$ $\dot{\emptyset}(0) = 0$ $\dot{\delta} = 0$

$$\tau = \frac{1}{15} \qquad g = 1.5$$

The simulation with initial conditions $\emptyset(\mathbf{0}) = -4\,, \dot{\emptyset}(0) = 0\,, \dot{\boldsymbol{\delta}} = 0$ without control for states $x1$ versus $x2$ we observe a limit cycle as shown in figure(9).

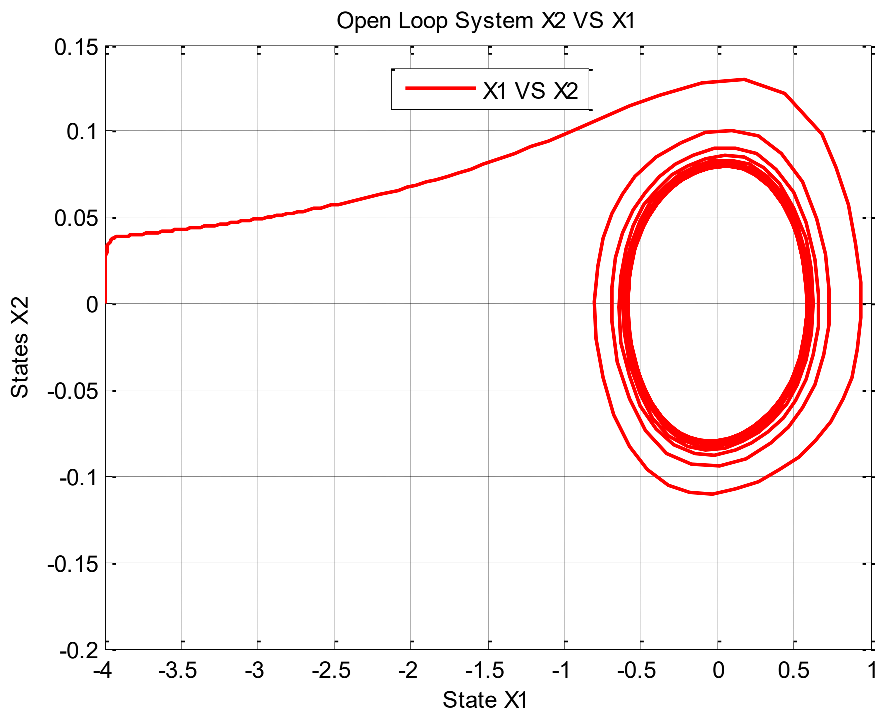


Fig.9. Open loop system state X1 versus X2

4- A backstopping controller Design and simulation for closed loop system:

A backstopping controller was designed for this system to regulate the states to zero, and simulating it by Matlab software.

$\dot{x}_1 = x_2$

$\dot{x}_2 = -\omega^2 x_1 + \mu_1 x_2 + b_1 x_2^3 + \mu_2 x_1^2 x_2 + b_2 x_1 x_2^2 + g x_3$

$\dot{x}_3 = -\frac{1}{\tau} x_3 + \frac{1}{\tau} u$

$z_1 = x_1$

$z_2 = x_2 - \propto_1$

$\dot{z}_1 = \dot{x}_1 = x_2 = (z_2 + \propto_1) \quad \leftarrow \propto_1 = -k_1 z_1$

$\dot{z}_1 = z_2 - k_1 z_1$

$v_1 = \frac{1}{2} z_1^2$

$\dot{v}_1 = z_1 \dot{z}_1 = z_1 z_2 - k_1 z_1^2$

$z_2 = x_2$

$z_3 = x_3 - \propto_2$

$\dot{z}_2 = \dot{x}_2 - \dot{\propto}_1$

$= -\omega^2 x_1 + \mu_1 x_2 + b_1 x_2^3 + \mu_2 x_1^2 x_2 + b_2 x_1 x_2^2 + g(z_3 + \propto_2) - \dot{\propto}_1$

$\propto_2 = \frac{1}{g}(\omega^2 x_1 - \mu_1 x_2 - b_1 x_2^3 - \mu_2 x_1^2 x_2 - b_2 x_1 x_2^2 + \dot{\propto}_1 - k_2 z_2 - z_1)$

By substituting $\propto_2$ in $\dot{z}_2$

$\dot{z}_2 = -\omega^2 x_1 + \mu_1 x_2 + b_1 x_2^3 + \mu_2 x_1^2 x_2 + b_2 x_1 x_2^2 + g z_3 + \omega^2 x_1 - \mu_1 x_2 - b_1 x_2^3 - \mu_2 x_1^2 x_2 - b_2 x_1 x_2^2 + \dot{\propto}_1 - k_2 z_2 - z_1 - \dot{\propto}_1$

$\dot{z}_2 = g z_3 - k_2 z_2 - z_1$

$v_2 = v_1 + \frac{1}{2} z_2^2$

$\dot{v}_2 = \dot{v}_1 + z_2 \dot{z}_2 = z_1 z_2 - k_1 z_1^2 + g z_2 z_3 - k_2 z_2^2 - z_1 z_2$

$= -k_1 z_1^2 + g z_2 z_3 - k_2 z_2^2$

$\dot{z}_3 = \dot{x}_3 - \dot{\propto}_2$

$= -\frac{1}{\tau} x_3 + \frac{1}{\tau} u - \dot{\propto}_2$

Let $u = \tau\left(\frac{1}{\tau} x_3 + \dot{\propto}_2 - k_3 z_3 - g z_2\right)$

$\dot{z}_3 = -k_3 z_3 - g z_2$

$v_3 = \frac{1}{2} z_1^2 + \frac{1}{2} z_2^2 + \frac{1}{2} z_3^2$

$\dot{v}_3 = z_1 \dot{z}_1 + z_2 \dot{z}_2 + z_3 \dot{z}_3$

$= z_1 z_2 - k_1 z_1^2 + g z_2 z_3 - k_2 z_2^2 - z_1 z_2 - k_3 z_3^2 - g z_2 z_3$

$= -k_1 z_1^2 - k_2 z_2^2 - k_3 z_3^2 \quad \rightarrow z^* = 0 \; is \; GAS$

$\rightarrow x^* = 0 \; is \; GAS$

$\propto_2 = \frac{1}{g} \omega^2 x_1 - \frac{1}{g} \mu_1 x_2 - \frac{1}{g} b_1 x_2^3 - \frac{1}{g} \mu_2 x_1^2 x_2 - \frac{1}{g} b_2 x_1 x_2^2 - \frac{1}{g} k_1 \dot{z}_1 - \frac{1}{g} k_2 z_2 - \frac{1}{g} z_1)$

$z_1 = x_1 \quad , \quad \dot{z}_1 = \dot{x}_1 = x_2 \quad , \quad z_2 = x_2$

$$\propto_2 = \frac{1}{g}\omega^2 x_1 - \frac{1}{g}\mu_1 x_2 - \frac{1}{g}b_1 x_2^3 - \frac{1}{g}\mu_2 x_1^2 x_2 - \frac{1}{g}b_2 x_1 x_2^2 - \frac{1}{g}k_1 x_2 - \frac{1}{g}k_2 x_2 - \frac{1}{g}x_1)$$

$$\dot{\propto}_2 = \frac{1}{g}\omega^2 \dot{x}_1 - \frac{1}{g}\mu_1 \dot{x}_2 - \frac{3}{g}b_1 x_2^2 \dot{x}_2 - (\frac{2}{g}\mu_2 x_1 x_2 \dot{x}_1 + \frac{1}{g}\mu_2 x_1^2 \dot{x}_2) - (\frac{1}{g}b_2 \dot{x}_1 x_2^2 + \frac{2}{g}b_2 x_1 x_2 \dot{x}_2) - \frac{1}{g}k_1 \dot{x}_2 - \frac{1}{g}k_2 \dot{x}_2 - \frac{1}{g}\dot{x}_1$$

$$\dot{\propto}_2 = \frac{1}{g}\omega^2 \dot{x}_1 - \frac{1}{g}\mu_1 \dot{x}_2 - \frac{3}{g}b_1 x_2^2 \dot{x}_2 - \frac{2}{g}\mu_2 x_1 x_2 \dot{x}_1 - \frac{1}{g}\mu_2 x_1^2 \dot{x}_2 - \frac{1}{g}b_2 \dot{x}_1 x_2^2 - \frac{2}{g}b_2 x_1 x_2 \dot{x}_2 - \frac{1}{g}k_1 \dot{x}_2 - \frac{1}{g}k_2 \dot{x}_2 - \frac{1}{g}\dot{x}_1$$

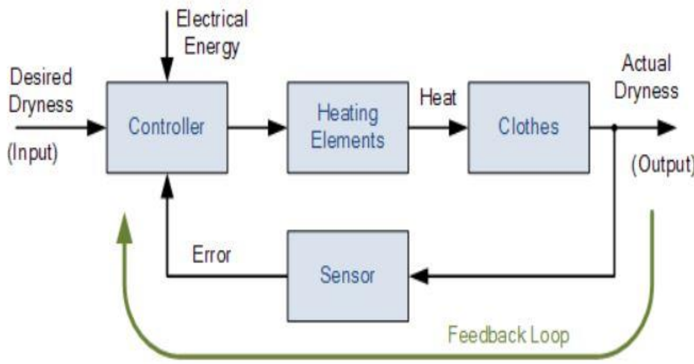


Fig.10. Design and simulation for closed loop system

By using the controller designed by backstopping the system states regulated to zero as shown in the results in fig.11.

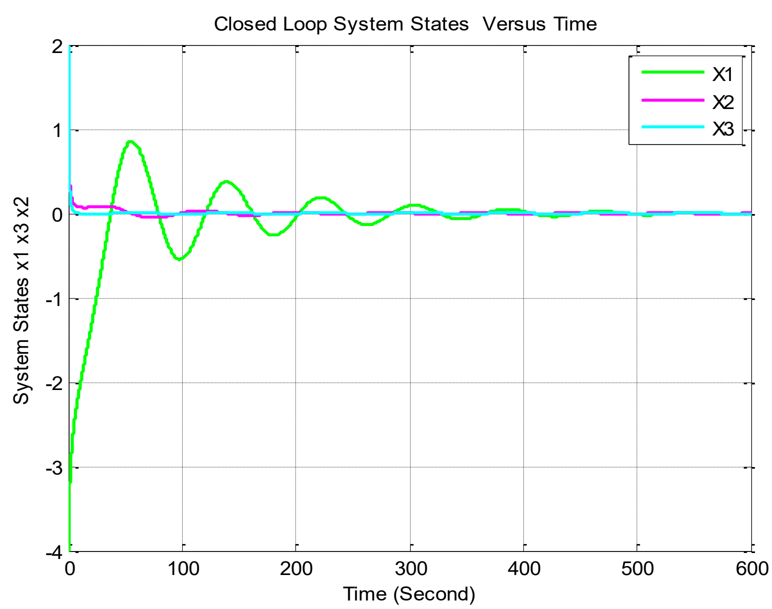


Fig.11. Closed loop system states versus time

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Conclusion:

According to the results we got from these papers, we found that the feedback linearization technique controls the system only within the certain constrains. The open loop system states for Air craft wing rock form a limit cycle. By designing backstopping controller, we successfully regulate the system states to zero. Also Sliding mode control satisfy the required performance in both models.

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