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Reduce the Effect of Disturbance from Linear Unstable Second Order Systems Using Hybrid Controller Scheme

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Abstract:

A linear algebraic method was introduce in [1, 2], in this paper, this method is used to design a linear compensators controller (LCC) which used together with another suggested disturbance reduction controller (DRC) to produce hybrid controller scheme. This hybrid controller is applied on single input-single output (SISO) second order linear unstable plants with linear disturbance, some of these plants may contains zero in right half plane.
The first part of the hybrid controller scheme (the LCC) is used to stabilize the linear unstable systems by solving sets of linear algebraic equations, while the second part of the hybrid scheme (the DRC) is used to reduce the effect of the disturbance, in addition to improve the performance of LCC by reduce the oscillation, the error steady state, and the settling time of the system output response to reach the steady state. Many examples are tested to show the efficiency of this controller.

Keyword: linear algebraic method, Diephantine equation, model matching, sliding mode controller, unstable linear second order plants, disturbance reduction.

تقليل تاثير الضوضاء من الانظمة الخطية الغير مستقرة ذات الدرجة الثانية بواسطة طريقة المسيطر المزدوج

الخلاصة

الطريقة الخطية الجبرية تم تناولها في مصدر [1, 2], ففي هذا البحث تم استخدام هذه الطريقة لتصميم مسيطر خطي (LCC) يعمل مع مسيطر أخر يقلل disturbanc (DRC) ليكونان مسيطر مزدوج. هذا المسيطر تم تطبيقه على منظومات خطية غير مستقرة من الدرجة الثانية وبوجودdisturbanc وقد تضم بعض هذه المنظومات على zero في الجانب الأيمن. علما أن هذه بعض هذه المنظومات من نوع SISO (أي تتعامل مع إدخال واحد وإخراج واحد).
الجزء الأول من المسيطر مزدوج وهو (LCC) يستخدم لجعل المنظومة مستقرة بواسطة حل مجموعة من المعادلات الجبرية, بينما الجزء الأخر DRC يستخدم لتقليل تأثيرdisturbanc إضافة إلى تحسين أداء المسيطر LCC وذلك بتقليل التذبذب والخطأ عند الاستقرار وزمن الاستقرار. العديد من الأمثلة تم اختبارها لبيان دقة المسيطر.

Introduction

The linear quadratic optimal control method and design through pole-zero pattern required to choose an overall close loop system to meet design specification, then choose un appropriate feedback configuration and compute the required compensation [1].
There are many possible f/b configuration, the simplest is the unity feedback configuration as shown in Fig.(1-a). This configuration has one degree of freedom because the reference input *r* and the plant output *y* drive the same compensator to generate an actuating. A two degree of freedom configuration can be shown in Fig.(1-b) and Fig.(1-c), we can see that input *r* and the plant output *y* drive two independent compensator to generate *u*.

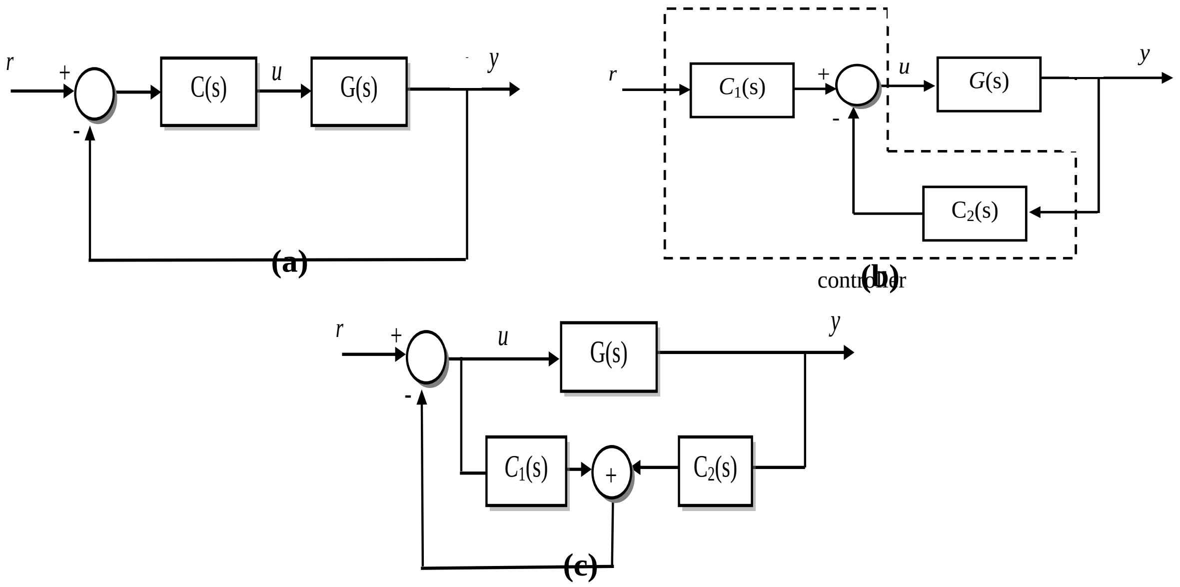


Fig. (1): control configuration.

We call Fig.(1-b) two parameter configuration (because the controller has two input *r*, *y* and one output *u*, it is also called two input, one output configuration). The other configuration shown in Fig.(1-c) is called plant input-output configuration (it is a combination of state feedback and state estimator in the state variable approach, it is also called controllable-observable configuration) [1, 2].
One way to introduce coprime fraction design is to develop the Bezout identity (Diophantine equation) and to parameterize all stabilizing compensators. The coprime fractions are used to carry out designs to achieve model matching [2].
Model matching involves pole-zero cancellation. One degree of freedom cannot be used here because we have no freedom in selecting canceled poles. Any two degree of freedom configuration can be used because we have freedom in selecting cancelled poles.

The linear algebraic method that achieve pole placement and model matching problem introduced by chen in [1] in which the basic issue of this method is introduce. Hang in [3] discussed pole zero assignment and phase lag compensator. Hang was able to improve the disturbance rejection. However, the phase lag introduced a slow pole into the system make it sluggish. Chen in [4] applied the same examples of Hang and compare between phase lag, PI controller and linear algebraic method with increasing the degree of two compensator. Chen obtained best result than Hang for disturbance rejection. Chen [4] and Hang [3] used stable system. Chen in [5] introduced the linear algebraic method in which the overall system can be designed using quadratic optimal method, H_∞ method and computer simulation.

In this paper, a hybrid controller scheme which is consists from linear compensator controller (LCC) and disturbance reduction controller (DRC) is applied for linear, unstable second order systems with disturbance. The LCC used two parameter configuration as shown in Fig(1-b). This method consists of two steps: selecting an implementable overall transfer function then the compensator can be obtained by solving sets of linear algebraic equations.

Model Matching (Linear Algebraic Method) and Stabilizing Controllers

Consider the two –parameter configuration(Fig.(1-b)) with two compensator

$$C_1(s) = \frac{L(s)}{A(s)} \qquad \text{.... (1)}$$

$$C_2(s) = \frac{M(s)}{A(s)} \qquad \text{.... (2)}$$

The closed loop transfer function of this configuration is [1, 2];

$$G_0(s) = \frac{C_1(s)G(s)}{1 + C_2(s)G(s)} \qquad \text{.... (3)}$$

Let the plant represent as a ratio of two coprime polynomials $\frac{N(s)}{D(s)}$, where the degree of $N(s)$ is less than the degree of $D(s)$ that is equal to n. The implementable transfer function $G_0(s) = \frac{N_0(s)}{D_0(s)}$(there are three constrains that must be satisfied to make the overall system is implementable for details see [1,2]). In this paper the implementable overall transfer function is chosen to minimize the performance index ITAE (integral time with absolute error) [5].

$$G_0(s) = \frac{\frac{N(s)}{D(s)} \cdot \frac{L(s)}{A(s)}}{1 + \frac{M(s)}{A(s)} \cdot \frac{N(s)}{D(s)}} = \frac{N(s)L(s)}{A(s)D(s) + M(s)N(s)} \qquad \text{.... (4)}$$

We can write the close loop transfer function as [2];

Step 1:- compute $\dfrac{G_0(s)}{N(s)} = \dfrac{N_p(s)}{D_p(s)} = \dfrac{N_0(s)}{D_0(s).N(s)}$ …. (5)

Where $N_p(s)$, $D_p(s)$ are coprime polynomials.

Step 2:- if degree of $D_p = p < 2n-1$, introduced an arbitrary $\overline{D}_p(s)$ of degree 2*n*-1-*p*, which is Hurwitz polynomial (i.e. all its pole lies in the left half-s plane). Because this polynomial can be canceled in the design, its root should be chosen inside an acceptable pole-zero cancellation region. If degree $D_p = p = 2n-1$, then set $\overline{D}_p(s) = 1$. The case in which degree $D_p > 2n-1$ will not be discussed [6].

rewrite Eq. (5) as

$$G_0(s) = \frac{N(s)N_p(s)}{D_p} \cdot \frac{\overline{D}_p}{\overline{D}_p} = \frac{N(s)N_p(s)\overline{D}_p}{D_p\overline{D}_p} \quad \text{…. (6)}$$

By comparing Eq. (6) with Eq. (4) we get

$$L(s) = N_p(s)\overline{D}_p(s) \quad \text{…. (7)}$$

$$A(s)D(s) + M(s)N(s) = D_p(s)\overline{D}_p(s) \quad \text{…. (8)}$$

The Eq.(8) is called Diaphantine or Bezout equation [1, 2, 4, and 7], the details solution of this equation explained in [1, 2].

The Suggested Hybrid Controller Scheme (HCS)

The block-diagram for the suggested controller scheme is shown in Fig.(2).

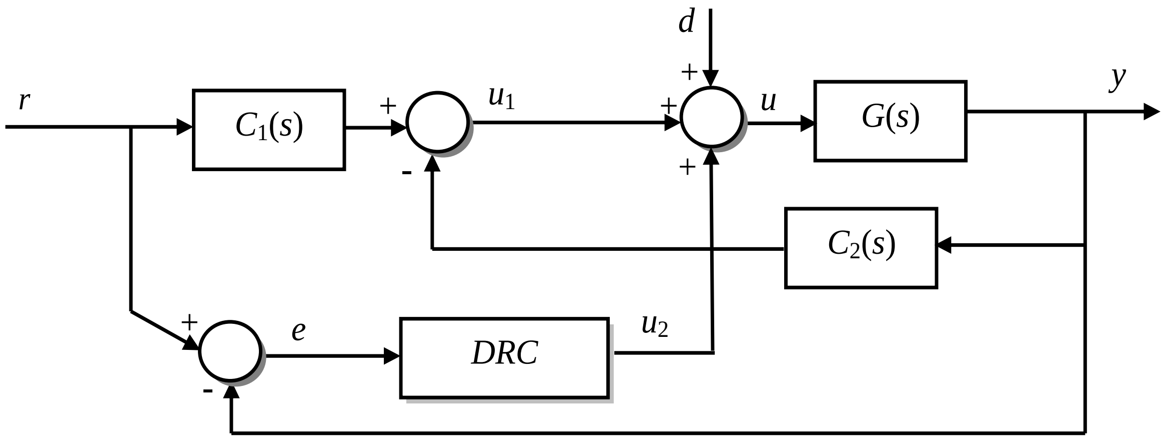


Fig. (2):the suggested hybrid controller for linear unstable system.

As shown from this figure, the suggested HCS consists from two controllers. The first controller (with control action u_1) is two –parameter configuration LCC with two compensator $C_1(s)$ and $C_2(s)$ which is used to stabilize the linear unstable system by solving sets of linear algebraic method. The second controller with control action u_2 is DRC which is used to reduce the effect of the linear disturbance *d*, in addition to improve the operation of the LCC. The total control signal $u(t)$ for the controlled system is given by the following equation;

$$u(t) = u_1(t) + u_2(t) \qquad \text{.... (9)}$$

The details for the both controller in the suggested hybrid controller scheme are explain by the following subsections.

1 Linear Compensator Design

In order to explain the procedure (which is given in section II) to design the two compensator $C_1(s)$ and $C_2(s)$ for the unstable second order plants, the following example is considered.

The open loop unstable transfer function [8]:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{2}{s^2 - 4} = \frac{N(s)}{D(s)} \qquad \text{.... (10)}$$

The implementable close loop transfer function (C.L.T.F) that minimizes the ITAE criteria is [9]:

$$G_0(s) = \frac{N_0(s)}{D_0(s)} = \frac{\omega_n^2}{s^2 + 1.4\omega_n s + \omega_n^2} \qquad \text{.... (11)}$$

The natural frequency ω_n is chosen, so that the unit step response of $\frac{G_0(s)}{G(s)}$ magnitude less than 0.5, for example let the ω_n =1.8841 rad/sec, then Eq.(11) will becomes;

$$G_0(s) = \frac{3.55}{s^2 + 2.6s + 3.55} \qquad \text{....(12)}$$

The overall transfer function is called implementable if its satisfy following constrains [2]:

(i) - All compensator used have proper rational T.F.

(ii) - The configuration selected has no plant leakage in the sense that all forward path from *r* to *y* pass through the plant.

(iii) - The closed loop transfer function of every possible input-output pair is proper and BIBO stable [1];

Compute $\frac{G_0(s)}{N(s)}=\frac{N_P(s)}{D_P(s)}=\frac{N_0(s)}{D_0(s).N(s)}$

$$\frac{N_P(s)}{D_P(s)}=\frac{1.775}{s^2+2.6s+3.55} \quad \text{.... (13)}$$

Because the degree of $D_P(s)$ is 2, then we introduced a Hurwitz polynomial $D(s)$ of degree 1, arbitrary choose it as (s+10), then

$$L(s)=1.755(s+10) \quad \text{.... (14)}$$

The solution of Diaphantine equation can obtained as;

$$\begin{bmatrix} D_0 & N_0 & 0 & 0 \\ D_1 & N_1 & D_0 & N_0 \\ D_2 & N_2 & D_1 & N_1 \\ 0 & 0 & D_2 & N_2 \end{bmatrix}\begin{bmatrix} A_0 \\ M_0 \\ A_1 \\ M_1 \end{bmatrix}=\begin{bmatrix} F_0 \\ F_1 \\ F_2 \\ F_3 \end{bmatrix} \quad \text{.... (15)}$$

Where

$$\begin{aligned} F(s) &= D\overline{D}_P = F_3s^3+F_2s^2+F_1s+F_0 \\ D(s) &= D_2s^2+D_1s+D_0 \\ N(s) &= N_2s^2+N_1s+N_0 \end{aligned} \quad \text{.... (16)}$$

According to our example, the Eq.(15) becomes;

$$\begin{bmatrix} -4 & 2 & 0 & 0 \\ 0 & 0 & -4 & 2 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} A_0 \\ M_0 \\ A_1 \\ M_1 \end{bmatrix}=\begin{bmatrix} 35.5 \\ 29.55 \\ 12.6 \\ 1 \end{bmatrix} \quad \text{.... (17)}$$

And the polynomial A(s), M(s) can be obtained as;:

$$\begin{aligned} A(s) &= A_0+A_1s = s+12.6 \\ M(s) &= M_0+M_1s = 16.75s+42.95 \end{aligned} \quad \text{.... (18)}$$

Since compensator $C_1(s)=\frac{L(s)}{A(s)}$ and $C_2(s)=\frac{M(s)}{A(s)}$, therefore

$$C_1(s)=\frac{1.755(s+10)}{s+12.6}, \quad C_2(s)=\frac{16.75s+42.95}{s+12.6} \quad \text{.... (19)}$$

2 Disturbance Reduction Controllers

The block-diagram for this controller is shown in Fig.(3).

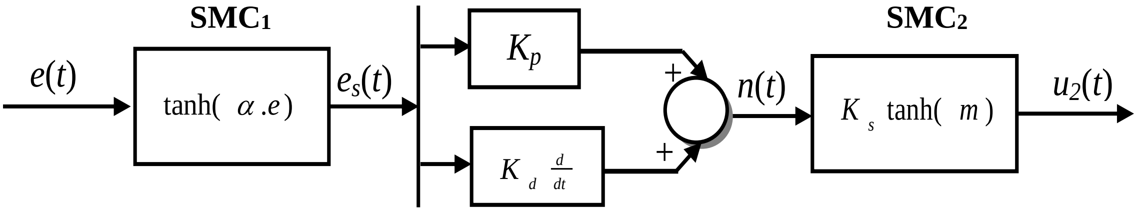


Fig. (3): The designed disturbance reduction controller.

As can be shown from this figure, the suggested disturbance reduction controller (DRC) employ two nonlinear continues sliding mode controller(SMC), the first nonlinear SMC_1 is given by:

$$e_s(t) = \tanh(\alpha . e) \qquad \text{.... (20)}$$

where α is user design positive parameter. The purpose for using the SMC_1 is to limit any input error to this SMC only between (-1 to 1). The second nonlinear continues SMC_2 is describe by:

$$u_2(t) = K_s \tanh(m) \qquad \text{.... (21)}$$

where K_s is sliding gain, selected ≤ 1 for system contain zero in the right half plane, and it is selected ≥ 1 for system contain no zero or zero lie in the left half plane.

The nonlinear function $m(t)$ is given by [10];

$$m(t) = (\beta . n^{q/p}) \qquad \text{.... (22)}$$

where $\beta > 0$; q, and p are positive integers ($p > q$); p is odd, and $n(t)$ is designed as;

$$n(t) = (K_p e_s + K_d \dot{e}_s) \qquad \text{.... (23)}$$

where the proportional gain K_p and the derivative gain K_d are design parameters, with nonlinear function $m(t)$, the sliding mode controller SMC_2 ($u_2(t)$) becomes;

$$u_2(t) = K_s \tanh(\beta . n^{q/p}) \qquad \text{.... (24)}$$

The value of K_p and K_d can be selected in this paper according to the following cases:

(1)- if the tested plant have no zeros or have small gain (less than or equal 1), then the values of K_p and K_d can selected as suitable number large than one which will make with other nonlinear SMC_2 parameters values the performance of the overall controlled system have more accurate specifications like small overshoot, small settling time,….etc.

(2)- if the tested plant have small gain (less than or equal 1) with zero in the left half plane, then the value of K_p can be selected large than one and K_d can selected (due to exist of zero) as a positive number less than one.

(3)- if the tested plant have zero in the right half plane, then the value of K_p and K_d can selected as suitable positive number less than one.

In summary, in this paper the designer can be selected the values of the DRC (α , β , K_p, K_d, q, p, and K_s) for testing the unstable plants according to the following Table(1).

Table(1): the range for the selected parameters of the DRC

Plant	α	β	K_p	K_d	q	p	K_s
Plant with no zero and/or with small gain	$1 \le \alpha \le 2$	$\beta \ge 1$	$K_p > 1$	$K_d > 1$	Integer ≥ 10	Integer odd ≥ 11	$K_s \ge 1$
Plant with zero on lift half plane	$1 \le \alpha \le 2$	$\beta \ge 1$	$K_p \ge 1$	$0 < K_d < 1$	Integer ≥ 10	Integer odd ≥ 11	$K_s \ge 1$
Plant with zero on right half plane	$1 \le \alpha \le 2$	$\beta \ge 1$	$0 < K_p < 1$	$0 < K_d < 1$	Integer ≥ 6	Integer odd ≥ 7	$K_s \le 1$

α is select $1 \le \alpha \le 2$ because if it is more than 2 this may be led to increase the oscillation in the output response.

The DRC is not reduce the effect of the disturbance only, but it also improve the performance of the first controller $u_1(t)$ by reduce the oscillation and the steady state error $E_{s.s}$ from the output response. Therefore, the control action of the disturbance reduction controller $u_2(t)$ will have zero or a very small value (when there is no disturbance, oscillation or $E_{s.s}$) and hence the total control signal $u(t)$ will still nearly equivalent to the first controller $u_1(t)$. If there is a disturbance or other problem like oscillation or $E_{s.s}$ in the system output then the control action $u_2(t)$ will add a another value to the first controller $u_1(t)$, hence the total control signal $u(t)$ will have different value from (not equivalent to) the first controller $u_1(t)$.

Simulation Results

In this section, the Matlab Simulink (version 7.0) can be used to simulated the suggested hybrid controller with different unstable examples. Five linear unstable second order plants with unit step input and linear disturbance are tested by the two parameter LCC configuration (Fig. (1.b)) and by the suggested HCS to illustrate the improve properties of the suggested approach on the controlled examples as it compare with the LCC.

The five linear unstable second order examples are given as following:

- ***<u>Ex1: Linear unstable plant with poles only (no zeros)</u>***

The open loop transfer function for this unstable example is given by;

$$G(s) = \frac{1}{(s^2 - 1)} = \frac{1}{(s-1)(s+1)} \qquad \text{.... (25)}$$

The natural frequency is chosen as 5.6 rad/sec., and $D_p = (s^2 + 7.912s + 31.9)$. The implementable closed loop transfer function

$$G_0(s) = \frac{32}{s^2 + 7.9s + 32} \qquad \text{.... (26)}$$

With the procedure discuss in section II, the compensator C_1(s) and C_2(s) for this example becomes:

$$C_1(s) = \frac{31.9s + 319}{s + 17.91}, \qquad C_2(s) = \frac{1112s + 336.9}{s + 17.91} \qquad \text{.... (27)}$$

The Suitable control parameters for the DRC are given in Table (2),

Table(2): the DRC parameters for Ex.1

Parameters	α	K_p	K_d	β	q	p	K_s
values	2	15	3	8	14	15	2

A unit step input and a disturbance(d=-1 begin at t=5 sec.) are used to test the closed loop control system with LCC and with HCS, then the output responses and the control signals are shown in Fig.(4).

- ***Ex2: Linear unstable plant with zero on left side***

A zero=-2 is add to the previous example (Ex1), therefore the unstable open loop transfer function for this example is;

$$G(s) = \frac{s+2}{(s^2-1)} = \frac{s+2}{(s-1)(s+1)} \quad \text{.... (28)}$$

The implementable closed loop transfer function

$$G_0(s) = \frac{32}{s^2+7.9s+32} \quad \text{.... (29)}$$

Following the procedure discuss in section II, the compensator $C_1(s)$ and $C_2(s)$ for this example becomes:

$$C_1(s) = \frac{32}{s+2}, \qquad C_2(s) = \frac{7.9s+33}{s+2} \quad \text{.... (30)}$$

The suitable control parameters for the DRC are given in Table (3),

Table(3): the DRC parameters for Ex.2

Parameters	α	K_p	K_d	β	q	p	K_s
values	2	15	0.1	3.8	14	15	1

This example is tested by unit step input and a disturbance (d=-0.8 begin at t=6 *sec*.), the output responses and the control signals for this simulation are shown in Fig.(5).

- **Ex3: Ex1 with *zero on right side***

Consider the following unstable plant, which is described by [2]:

$$G(s) = \frac{(s-2)}{s^2-1} \quad \text{.... (31)}$$

The implementable C.L.T.F that minimizes ITAE is:

$$G_0(s) = \frac{-(s-2)}{s^2+2s+2} \quad \text{.... (32)}$$

Br applying the procedure of section II., we get

$$C_1(s) = \frac{-(s+4)}{s+18}, \qquad C_2(s) = \frac{-(12s+13)}{s+18} \quad \text{.... (33)}$$

The parameters for the suggested DRC are given by Table(4).

Table(4): the DRC parameters for Ex.3

Parameters	α	K_p	K_d	β	q	p	K_s
values	1	0.0008	0.001	6	8	9	-3

This example is tested by unit step input and a disturbance (d=-0.5 begin at t=5 *sec*.), the output response and the control signal for this simulation are shown in Fig.(6).

- **Ex4: *Linear unstable plant with poles only (no zeros)***

Consider the example that is described in subsection III.1 with the following transfer function [8];

$$G(s) = \frac{Y(s)}{U(s)} = \frac{2}{s^2 - 4} \qquad \text{.... (34)}$$

with

$$C_1(s) = \frac{0.755\,(s + 10)}{s + 12.6}\;, \quad C_2(s) = \frac{17.025\,s + 42.95}{s + 12.6} \qquad \text{.... (35)}$$

The parameters for the suggested DRC are given by Table(5).

Table(5): the DRC parameters for Ex.4

Parameters	α	K_p	K_d	β	q	p	K_s
values	2	15	3	5	16	17	4

if unit step input and a disturbance (d=-1 begin at t=7 *sec*.) are used to test the closed loop control system with LCC and with HCS, then the output responses and the control signals are shown in Fig.(7).

- **Ex5: *Linear unstable plant with zero on right side***

Consider a second-order unstable open-loop plant, described by the transfer function [11],

$$G(s) = \frac{s - 2}{s^2 - 0.5s + 0.9286} \qquad \text{....(36)}$$

The implementable closed loop transfer function

$$G_0(s) = \frac{-16\,(s - 2)}{s^2 + 7.9s + 32} \qquad \text{....(37)}$$

(The closed loop T.F is implementable if and only if $\frac{G_0(s)}{G(s)}$ are proper and stable that's mean all zero of $N(s)$ with zero or positive real parts are retained in $N_0(s)$ [2]).

Then using the procedure of linear algebraic method, we can obtained

$L(s)$ =-16(s+10), $A(s)$ =s+97.45, M(s) =-(79.05 s+1.634)

$$C_1(s) = \frac{-16(s+10)}{s+97.45}, \qquad C_2(s) = \frac{-(79.05s+1.634)}{s+97.45} \qquad \text{....(38)}$$

The parameters for the suggested DRC are given by Table(6).

Table(6): the DRC parameters for Ex.5

Parameters	α	K_p	K_d	β	q	p	K_s
values	2	0.001	0.0015	6	6	7	-3

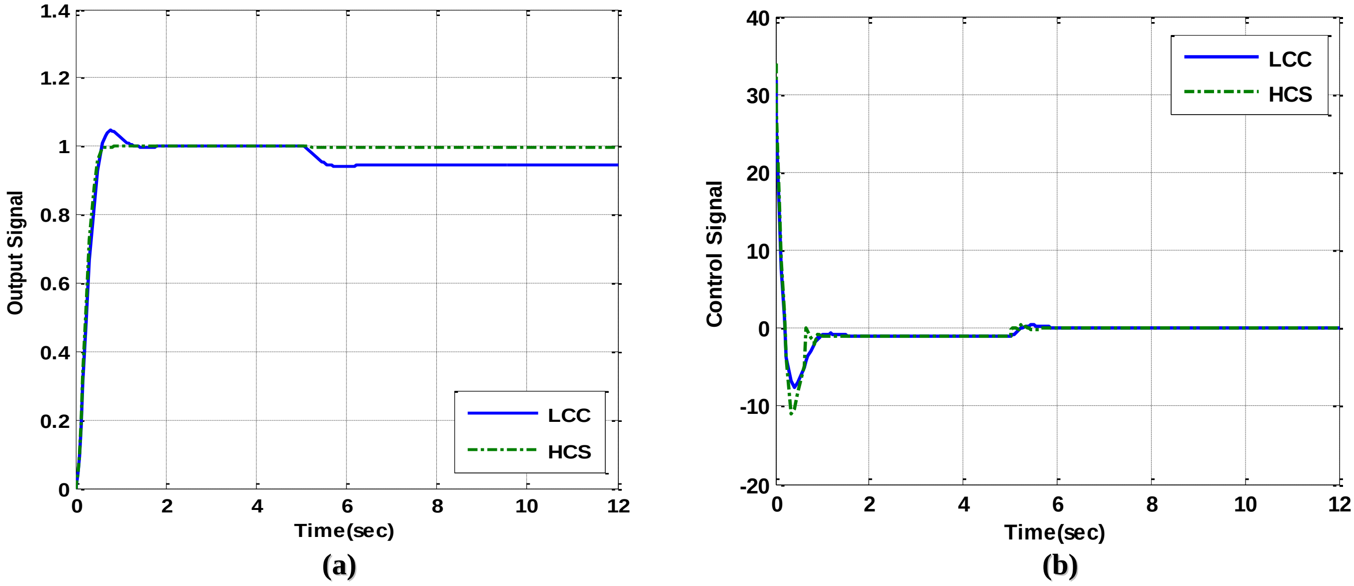
This example is tested by unit step input and a disturbance (d=-0.6 begin at t=6 *sec*.) The output response and the control signal for this simulation are shown in Fig.(8).

We can see from the above five simulation examples the following points:

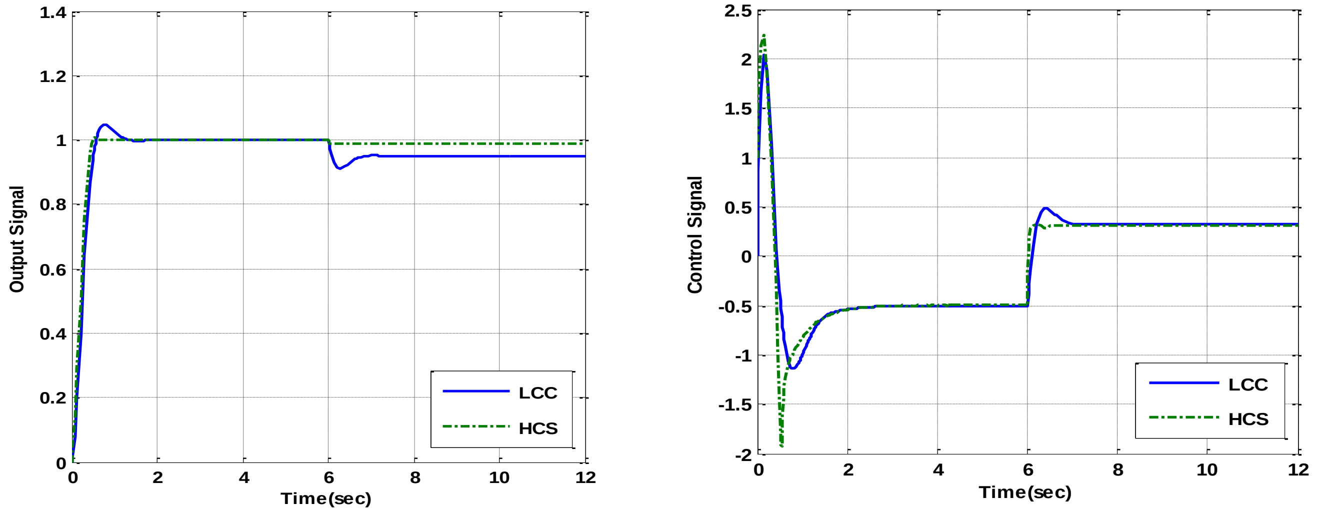
1. the LCC stabilize the five tested linear unstable plants and it still maintain the stability even a disturbance is occurs, and the output response of these test examples flow the desired input with zero or very small $E_{s.s}$ if there is no disturbance.

2. the output response of the control system flow the desired input with HCS more smoothly than with LCC, also with HCS the effect of disturbance is more reduced than with the LCC specially when the plants contain no zeros on right half plane.

3. The total control signal with the HCS is nearly equivalent to the control signal with the LCC, but it is some times increase or decrease from the control signal with LCC according to existence of the disturbance, or to improve the operation of the LCC and hence improve the performance of the output controlled system.

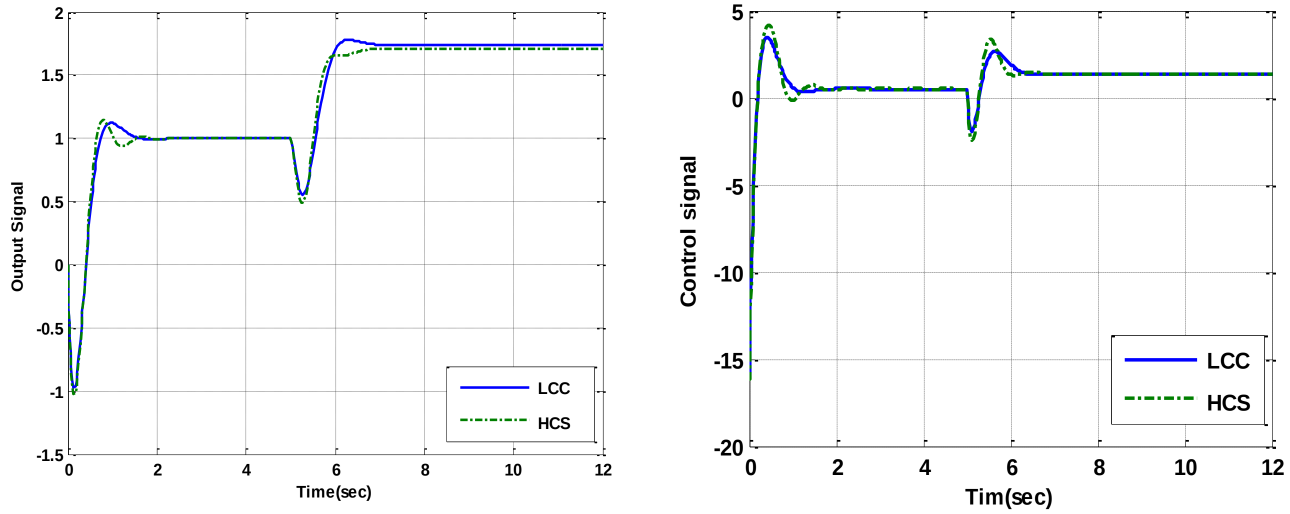


Fig(4):the response for Ex.1 with d=-1 sec. begin at t=5 sec. **(a)**: the output signal. **(b)**: the control signal.



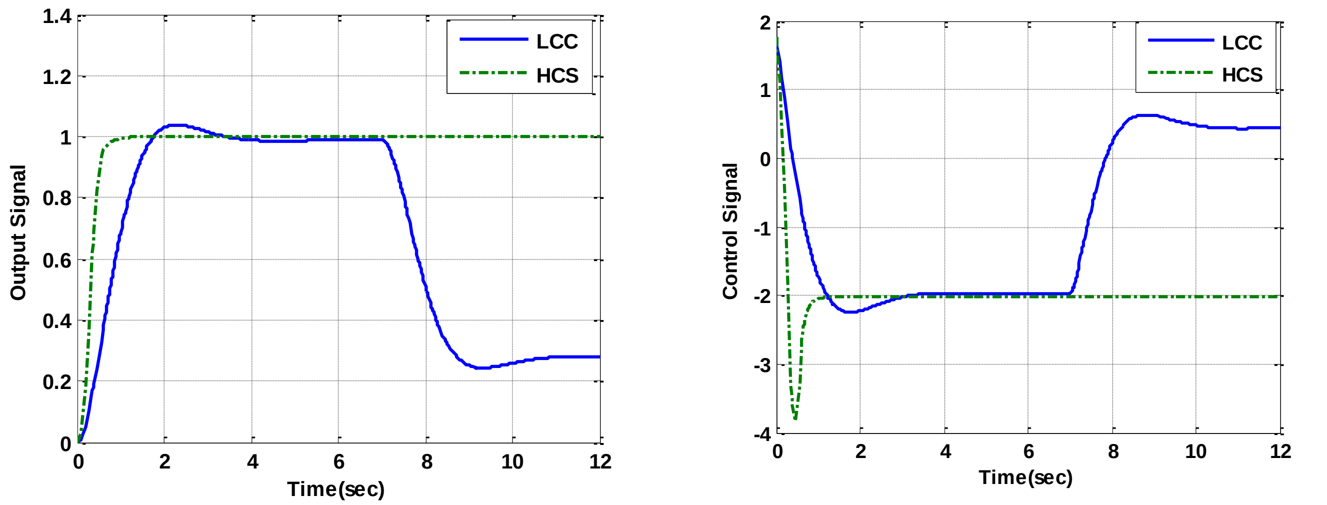
(a) **(b)**

Fig(5):the response for Ex.2. with d=-0.8 sec. begin at t=6 sec. **(a)**: the output signal. **(b)**: the control signal.



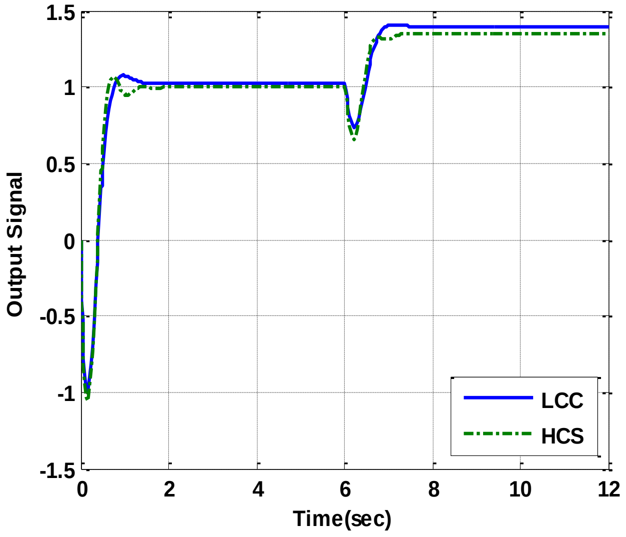
(a) **(b)**

Fig(6):the response for Ex.3 with d=-0.5 sec. begin at t=5 sec. **(a)**: the output signal. **(b)**: the control signal.

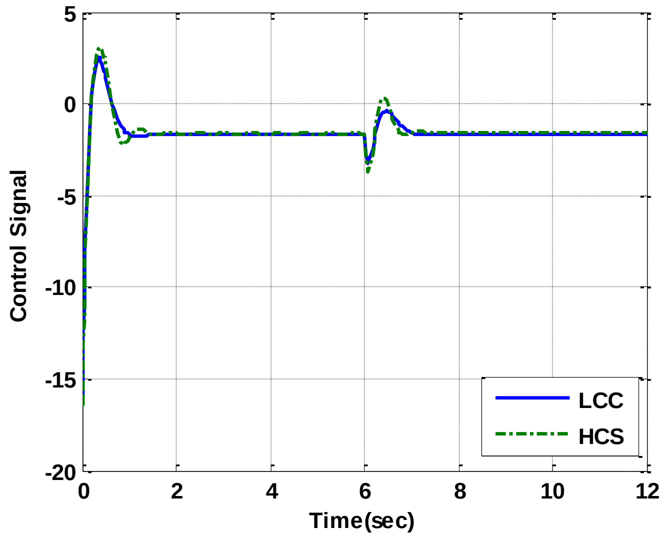


(a) **(b)**

Fig(7):the response for Ex.4 with d=-1 sec. begin at t=7 sec. **(a)**: the output signal. **(b)**: the control signal.



(a)



(b)

Fig(8):the response for Ex.5 with *d*=-0.6 sec begin at t=6 sec. **(a)**: the output signal. **(b)**: the control signal.

Conclusion

In this paper, hybrid controller scheme (HCS) for controlling the linear unstable second order plants with disturbance reduction is suggested. This controller consist from two controller, the first one is linear compensator controller (LCC) used to stabilize the unstable system, this linear compensator designs by forming set of linear equations. The procedure for the design appears to be simpler than the state variable and also appear to be simpler than conventional root locus method or frequency- domain method.

While the second controller of the HCS is disturbance reduction controller (DRC) designed by using two sliding mode controller (SMC), used to improve the operation of the LCC and to reduce the effect of the disturbance with small effected on the control signal of the LCC. The many examples that are tested by the LCC and the suggested HCS show the efficiency of our suggested scheme.

At last, we suggest testing the HCS with the nonlinear unstable systems.

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