FEAT JOURNAL
FARM ENGINEERING AND AUTOMATION TECHNOLOGY JOURNAL
วารสารวิศวกรรมฟาร์มและเทคโนโลยีการควบคุมอัตโนมัติ

Robust Tracking Control Scheme for a Ship Maneuvering with Uncertain Dynamics Using Modified Fuzzy Logic Variable Structure Controller Approach

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Received: 5 June 2022
Revised: 6 October 2022
Accepted: 16 November 2022
Available online: 23 June 20223

Abstract

In this paper, the tracking control of ship maneuvering by a Modified Fuzzy Logic Variable Structure Control with an integral compensator or MFLVSC is investigated. The MFLVSC structure consists of an integrator and variable structure system. The integrator ensure the elimination of steady state error due to step and ramp command inputs, while the fuzzy control would maintain the insensitivity to parameter variation and disturbances. The MFLVSC strategy is simulated and applied to a ship handling, namely course keeping, course changing and course tracking are given to demonstrated of the proposed control scheme. Simulation results indicated that MFLVSC system performance with respect to the sensitivity to parameter variations is greatly reduced. Also, its can achieve a rather accurate course tracking and avoids the chattering phenomenon.

Keywords: Ship Maneuvering: Uncertain Dynamics: Variable Structure Control: Fuzzy Logic

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1. Introduction

A ship maneuvering is critical for marine safety. In the part, several design methods, e.g., classical controller, adaptive control and other modern control technique [1, 2], for autopilots and ship have been proposed. The nonlinear ship dynamic model is shown in Fig. 1. The maneuvering problem including course keeping, course tracking, berthing and anti-collision were considered in those papers. As the nonlinear behavior involved in ship maneuvering is very complicated, characterization of ship maneuvering behavior by a pure mathematical model is usually difficult. In real case of ship maneuvering, the parameter uncertainties and external load disturbances should be considered. Consequently, the robustness of controlled system is one of the important factors in controller design. A conventional linear controller may not assure satisfactory requirements.

It has been a subject of active research to design control systems which are insensitive to plant uncertainties and external disturbances. Many researchers have devoted themselves into this subject by utilizing different design methodology. One of the most attractive approaches to deal with this problem is the so called Variable Structure Control (VSC) or Sliding Mode Control (SMC). The important feature in VSC is what is termed sliding mode. The VSC approach possesses other salient advantages such as high speed of response, good transient performance and no need for precise knowledge of the controlled plant. Although the conventional VSC approach has been applied successfully in many applications [3, 4], it cannot perform well in servo applications where the system is designed to track a command input. In order to improve tracking performance, the Integral Variable Structure Control or IVSC approach, presented in [5-7], combines an integral controller with the conventional VSC. The IVSC approach can eliminate the steady tracking error due to a step command input. However, IVSC yields the error when the system has to follow a changing command input, e.g., a ramp input. Note that, this kind of input is generally encountered in servo control applications. The Modified Integral Variable Structure Control or MIVSC approach, proposed in [8, 9], uses a double integral action to solve this problem. Although, the MIVSC method can give a better tracking performance than the IVSC method does at steady state, its performance during transient period needs to be improved. However, the main problem of VSC, IVSC and MIVSC is the chattering phenomenon restricts its application.

Fuzzy control is a practical control method which imitates human being fuzzy reasoning and decision making processes. Fuzzy logic control is derived from the fuzzy logic and fuzzy set theory that were introduced in 1965 by Professor Lotfi A. Zadeh of the University of California at Berkeley. Fuzzy logic control can be applied in many disciplines such as economics, data analysis, engineering and other areas that involve a high level of uncertainty, complexity or nonlinearity. In engineering, engineers can use the fundamentals of fuzzy logic and fuzzy set theory to create the pattern and the rules, then design the fuzzy controllers, Finally, the output response of many systems can be improved by using a fuzzy controller [10]. The method is applicable to conduct robustness control over target for which a mode is hard to be established. The final program form of the method is simple and easy to achieve. Therefore, combining fuzzy control with the VSC would maintain the insensitivity of sliding mode control to parameter perturbation and external disturbances while in the mean time effectively eliminate the chattering phenomenon.

This paper presents the design and simulation of ship maneuvering tracking control systems using the Modified Fuzzy Logic Variable Structure Control with an integral compensator or MFLVSC approach. This approach, which is the extension of IVSC approach, incorporates a feedforward path and fuzzy control to improved the dynamics response for command tracking and strong robustness. Also, it can achieve a rather accurate servo tracking and is fairly robust to plant parameter variations and external load disturbances. Simulation results are presented for demonstrating the potential of the proposed scheme and the tracking performance can be remarkably improved.

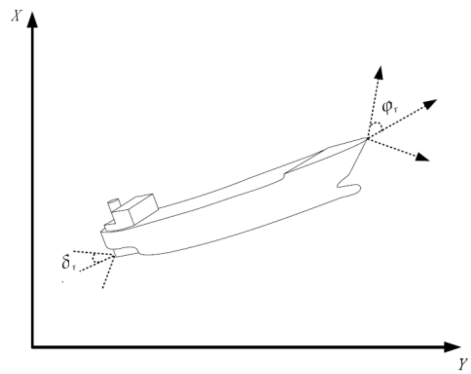

Figure 1 The nonlinear ship dynamic model.

2. Design of MFLVSC System

The structure of MFLVSC is shown in Fig. 2 can be described by the following equation of state

$$\dot{x}_i = x_{i+1}\ ,i=1,\ldots,n\text{-}1 \quad (1a)$$

$$\dot{x}_n = -\sum_{i=1}^{n} a_i x_i + bU - f(t) \quad (1b)$$

$$y = x_1 \quad (1c)$$

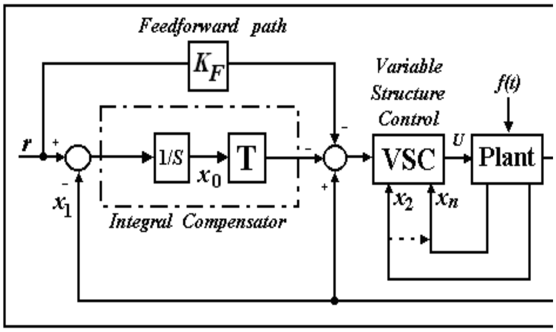

Figure 2 The structure of FLVSC system.

The switching function, σ is given by

$$\sigma = -K_F r - rTK_I + \sum_{i=1}^{n} c_i x_i \qquad (2)$$

where $C_i > 0$=constant, C_n=1 and T=integral time.

The control signal, U can be determined as follows, from (1) and (2), we have

$$\dot{\sigma} = -K_F g - TK_I(r - x_1) + \sum_{i=2}^{n} c_{i-1} x_i - \sum_{i=1}^{n} a_i x_i + bU - f(t) \cdot \qquad (3)$$

where $g = \dot{r}$.

In the defining equation for the switching function r is the desired tracking command, $x_1 - r$ is the tracking error, Z is the integral of the tracking error satisfying $\dot{z} = r - x_1$, K_F and K_I are the defined as the gain of feedforward and integral controllers, respectively.

Let $a_i = a_i^0 + \Delta a_i$;$i = 1, \ldots, n$ and $b = b^0 + \Delta b$, where a_i^0 and b are nominal values, and Δa_i, Δb are the variations of a_i and b. Without loss of generality, we assume that $b^0 > 0$ and $\Delta b > - b^0$.

The control signal can be separated into

$$U = U_{eq} + U_{swF} + U_{swI}. \qquad (4)$$

This condition results in

$$U_{eq} = \{K_F g - c_1 TK_I(r - x_1) - \sum_{i-2}^{n-1} c_{i-1} x_i + \sum_{i=1}^{n-1} a_i^0 x_i\} / b^0 \cdot \qquad (5)$$

The transfer function when the system is on the sliding surface can be shown as

$$H(s) = \frac{X_1(s)}{R(s)} = \frac{\alpha_n}{s^n + \alpha_1 s^{n-1} + \ldots + \alpha_{n-1} s + \alpha_n} \cdot \qquad (6)$$

The transient response of the system can be determined by suitably selecting the poles of the transfer function.

Let $\quad s^n + \alpha_1 s^{n-1} + \ldots + \alpha_{n-1} s + \alpha_n = 0 \qquad (7)$

be the desired characteristic equation(closed-loop poles), the coefficient C_1 and T can be obtained by

$$C_{n-1} = \alpha_1,\ C_1 = \alpha_{n-1} \text{ and } T = \frac{\alpha_n}{\alpha_{n-1}}.$$

3. Synthesis of Fuzzy Logic Controller

The component U_{swF}, the feedforward-type control, and U_{swI}, the integral-type control, are used to eliminate the influence due to the plant parameter variations Δa_i, Δb and disturbances $f(t)$ in order to guarantee the existence of a sliding mode control. They are given by

$$U_{swF} = k_{1F}(r - x_1) + \sum_{i=2}^{n} k_{iF} x_i \tag{8}$$

and

$$U_{swI} = k_{1I}(x_1 - Tx_0 - rK_I) + \sum_{i=2}^{n} k_{iI} x_i + k_{n0} \tag{9}$$

where

$$k_1 = \begin{cases} \alpha_1 & \text{if } (x_1 - Tx_0 - rK_F)\sigma > 0 \\ \beta_1 & \text{if } (x_1 - Tx_0 - rK_F)\sigma < 0 \end{cases},$$

$$k_i = \begin{cases} \alpha_i & \text{if } x_i\sigma > 0 \\ \beta_i & \text{if } x_i\sigma < 0 \end{cases}, i = 2,\ldots,n$$

and $$k_{n+1} = \begin{cases} \alpha_{n+1} & \text{if } \sigma > 0 \\ \beta_{n+1} & \text{if } \sigma < 0 \end{cases}.$$

The condition for the existence of a sliding mode is known to be

$$\sigma\dot{\sigma} < 0 . \tag{10}$$

In order for (10) to be satisfied, the following conditions must be met,

$$k_i = \begin{cases} \alpha_i < \text{Inf } [\Delta a_i - a_i^0 \Delta b / b^0 + c_{i-1}\Delta b / b^0 \\ - c_i(c_{n-1} - a_n^0)(1 + \Delta b / b^0)] / b \\ \beta_i > \text{Sup } [\Delta a_i - a_i^0 \Delta b / b^0 + c_{i-1}\Delta b / b^0 \\ - c_i(c_{n-1} - a_n^0)(1 + \Delta b / b^0)] / b \end{cases} \tag{11a}$$

where $i = 1,\ldots,n\text{-}1$, $c_0 = 0$

$$k_n = \begin{cases} \alpha_n < \text{Inf } [\Delta a_n + a_n^0 - c_{n-1}] / b \\ \beta_n > \text{Sup } [\Delta a_n + a_n^0 - c_{n-1}] / b \end{cases}$$

and where $$k_{n+1} = \begin{cases} \alpha_{n+1} < \text{Inf } [-N] / b \\ \beta_{n+1} > \text{Sup } [-N] / b \end{cases}. \tag{11b}$$

Now we consider the effect of $\Delta k_i (i=1,\ldots n)$, Δk_i is the function is to eliminate the chattering phenomenon of the control system and find out Δk_i by making use of fuzzy set theory. Firstly take positive constants α and β, normalize switching function σ and its rate of change against time.

Suppose $$\sigma_n = \alpha.\sigma, \tag{12}$$

$$\sigma_n = \beta.\sigma \tag{13}$$

The input variable of the fuzzy controller is

$$\sigma_n sign(x_1 - Tx_0 - rK_F),$$

$$\dot{\sigma}_n sign(x_1 - Tx_0 - rK_F),$$

$$\sigma_n sign(x_i)$$

and $\dot{\sigma}_n sign(x_i)$ $(i=2,\ldots n)$, the output of the controller is Δk_i.

Secondly, define the language value of σ_n and $\dot{\sigma}_n$ as P, Z, N: Δk_i is language value as PB, PM, PS, ZE, NS, NM, NB; as well as their subordinate functions as in Figs. 3~5:

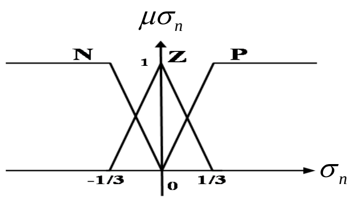

Figure 3 The subordinate function of σ_n .

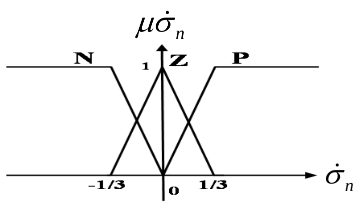

Figure 4 The subordinate function of $\dot{\sigma}_n$.

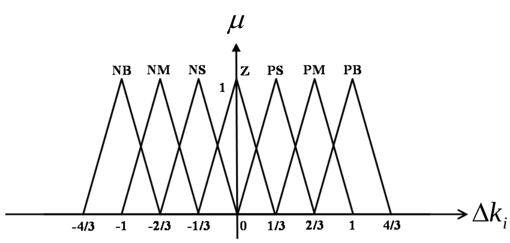

Figure 5 The subordinate function of Δk_i.

Define the following fuzzy control regularity Table 1.

Table 1. Fuzzy control regularity

	N	Z	P
N	PB	PM	PS
Z	PS	ZE	NS
P	NS	NM	NB

According to the above form, use the fuzzy calculation method introduced in [11] and gravity method to turn fuzzy output into precise control quantity

$$\Delta k_i = \left(\int \Delta k_i \tilde{\mu}_{\Delta k_i} d\Delta k_i\right) / \left(\int \tilde{\mu}_{\Delta k_i} d\Delta k_i\right) \quad (14)$$

When

(1) $\sigma_n \le -\frac{1}{3}, \dot{\sigma}_n \le -\frac{1}{3}$; it is easy to get $\Delta k_i = 1$,

and when

(2) $\sigma_n \le -\frac{1}{3}, -\frac{1}{3} \langle \dot{\sigma}_n \le 0$; σ_n (N), $\dot{\sigma}_n$ (N,Z).

The subordinate function of Δk_i(PB, PM) corresponding to is shown in [12].

Thus, points P_1 and P_2's abscissa are $\dot{\sigma}_n + \frac{2}{3}, \dot{\sigma}_n + 1$;

P_3 and P_4's abscissas are $-\dot{\sigma}_n + \frac{2}{3}, \dot{\sigma}_n + \frac{4}{3}$; then

$$\Delta k_i = \frac{-\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n + \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}}$$

Using the same method we get the precise output Δk_i under other circumstances to be

for $i=1$, σ_n is $\sigma_n sign(x_1 - Tx_0 - rK_F)$ and $\dot{\sigma}_n$ is $\dot{\sigma}_n sign(x_1 - Tx_0 - rK_F)$; for $i=1$, σ_n is $\sigma_n sign(x_i)$ and $\dot{\sigma}_n$ is $\dot{\sigma}_n sign(x_i)$.

Finally, the control function of MFLVSC approach for simulate is obtained as

$$U = U_{eq} + k_I(x_1 - Tx_0 - rK_F) + \sum_{i=2}^{n} k_i x_i + K\left[\Delta k_i(x_1 - Tx_0 - rK_F) + \sum_{i=2}^{n} \Delta k_i x_i\right]. \quad (16)$$

Among them, U_{eq} is given by (5), k_i is given by inequality (11), Δk_i is given by (15), therefore U is a continuous function.

The above equations represent the process of designing a standard slide mode control method step by step as well as the application of fuzzy control methods for more efficient process control applications depend on both the time domain and the frequency domain. The following sections describe the process control equation model.

$$\Delta k_i = \begin{cases}
1 & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n + \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & -\frac{1}{3}\langle \dot{\sigma}_n \le 0 \\
\dfrac{-\frac{3}{2}\dot{\sigma}_n^2 + \frac{1}{6}\dot{\sigma}_n + \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & 0\langle \dot{\sigma}_n \le \frac{1}{3} \\
\frac{1}{3} & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \rangle \frac{1}{3} \\
\dfrac{-4\dot{\sigma}_n^2 - 2\dot{\sigma}_n + \frac{1}{9}}{-6\dot{\sigma}_n^2 - 2\dot{\sigma}_n + \frac{1}{3}} & -\frac{1}{3}\langle \sigma_n \le 0 & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-3\dot{\sigma}_n^2 - 2\sigma_n - \frac{1}{2}\dot{\sigma}_n^2 - \frac{1}{2}\dot{\sigma}_n}{-3\dot{\sigma}_n^2 - 2\sigma_n - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & -\frac{1}{3}\langle \sigma_n \le 0 & -\frac{1}{3}\langle \dot{\sigma}_n \le 0 \\
\dfrac{-2\dot{\sigma}_n^2 - \frac{4}{3}\sigma_n + \frac{1}{2}\dot{\sigma}_n^2 - \frac{1}{2}\dot{\sigma}_n}{-3\dot{\sigma}_n^2 - 2\sigma_n - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & -\frac{1}{3}\langle \sigma_n \le 0 & 0\langle \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-\frac{2}{3}\sigma_n - \frac{1}{9}}{-6\dot{\sigma}_n^2 - 2\sigma_n + \frac{1}{3}} & -\frac{1}{3}\langle \sigma_n \le 0 & \dot{\sigma}_n \rangle \frac{1}{3} \\
\dfrac{-\frac{2}{3}\sigma_n - \frac{1}{9}}{-6\dot{\sigma}_n^2 + 2\sigma_n + \frac{1}{3}} & 0\langle \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{-\dot{\sigma}_n^2 + \frac{3}{2}\dot{\sigma}_n^2 + \frac{1}{6}\dot{\sigma}_n - \frac{1}{9}}{-3\sigma_n^2 - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{2}{3}} & 0\langle \sigma_n \le \frac{1}{3} & -\frac{1}{3}\langle \dot{\sigma}_n \le 0 \\
\dfrac{\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n - \frac{2}{9}}{-3\sigma_n^2 - 3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{2}{3}} & 0\langle \sigma_n \le \frac{1}{3} & 0\langle \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{4\dot{\sigma}_n^2 - 2\dot{\sigma}_n - \frac{1}{9}}{-6\sigma_n^2 + 2\sigma_n + \frac{1}{3}} & 0\langle \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \rangle \frac{1}{3} \\
-\frac{1}{3} & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3} \\
\dfrac{\frac{3}{2}\dot{\sigma}_n^2 + \frac{1}{6}\dot{\sigma}_n - \frac{2}{9}}{-3\dot{\sigma}_n^2 - \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & -\frac{1}{3}\langle \dot{\sigma}_n \le 0 \\
\dfrac{\frac{5}{2}\dot{\sigma}_n^2 - \frac{7}{6}\dot{\sigma}_n - \frac{2}{9}}{-3\dot{\sigma}_n^2 + \dot{\sigma}_n + \frac{1}{3}} & \sigma_n \le \frac{1}{3} & 0\langle \dot{\sigma}_n \le \frac{1}{3} \\
-1 & \sigma_n \le \frac{1}{3} & \dot{\sigma}_n \le \frac{1}{3}
\end{cases} \quad (15)$$

4. Dynamics modeling of the ship

The nonlinear ship model [1] relates the yaw angle φ_r to the rudder angle δ_r, as shown in Fig. 1, according to

$$\ddot{\varphi}_r + \frac{K}{T} H(\dot{\varphi}_r) = \frac{K}{T}\delta_r \tag{17}$$

The linearized model of system (17) is shown as follows:

$$x_1 = x_2\,,\ \dot{x}_2 = -\frac{K}{T}\alpha x_2 + \frac{K}{T}\delta_r\,, \tag{18}$$

where K is the gain, T is a time constant and $H(\dot{\varphi}_r) = \alpha\dot{\varphi}_r + \beta\dot{\varphi}_r{}^3$ (α and β are constants) is a nonlinear function in φ_r determined experimentally from the standard spiral test. The original nonlinear system can be piecewisely linearized under some cruise conditions. In this research, the nominal cruise speed is set to be 30 knots. The nominal rudder angle, heading angle and the change rate of heading angle are set to zero degree in this simulation. Moreover, for a more complete description of the ship model, the rudder servomechanism has to be taken into account. For instance, a natural constraint of the steering machine is given by

$$-\delta_{\max} \le \delta \le \delta_{\max} \tag{19}$$

where $\delta_{\max} = 35$ degree is the maximum rudder angle.

In general, the environment disturbance of the ship steering should be considered, especially the wave, which can affect the yaw angle of ship heading. For simplicity of illustration, the disturbance $f(t)$ in (1b) is generated by

$$f(s) = h(s)\omega(s) \tag{20}$$

where $\omega(\bullet)$ is a zero-mean Gaussian white noise and the transfer function $h(s)$ is given by

$$h(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{21}$$

In (19), ζ is the damping coefficient, ω_0 is the dominating wave frequency, and $K_\omega = 2\zeta\omega_0\delta_\omega$ is the gain constant with representing the wave intensity. We then take $F(t)$ in (3) as $F(t) = |f(t)|$.

5. MFLVSC for the ship system

The conventional maneuvering problems can be classified into four types, namely course keeping handling, course changing handling, course tracking handling, and special motion handling (for instance, marine search handling, rescue handing). In this section, the handling problems of course keeping, course changing, and course tracking, will be investigated by using the proposed integral and feedforward controller [13-14].

The reference model is chosen as

$$\dot{x}_{m1} = x_{m2},\ \dot{x}_{m2} = x_{m3} \qquad (22a)$$

$$\dot{x}_{m3} = -a_{m1}x_{m1} - a_{m2}x_{m2} - a_{m3}x_{m3} + b_m U_m . \qquad (22b)$$

Defining $e_i = x_{pi} - x_{mi}$;(i= 1,2,3), the FLVSC system can be represented as $\dot{e}_1 = e_2$, $\dot{e}_2 = e_3$ and

$$\begin{aligned}\dot{e}_3 = &-a_{p1}e_1 - a_{p2}e_2 - a_{p3}e_3 + (a_{m1} - a_{p1})x_{m1} \\ &+ (a_{m2} - a_{p2})x_{m2} + (a_{m3} - a_{p3})x_{m1} - b_m U_m + b_p U_p - f(t).\end{aligned} \qquad (23)$$

The objective of the control is to keep the course position of the ship to follow the desired trajectory as closely as possible. The nominal values of the MFLVSC controller are listed in Table 2.

Table 2. Parameters of the MFLVSC controller

Parameter	Value
λ_1, λ_2	-13.126±28.463i
λ_3, λ_4	-23.234, -11.109
C_1, C_2, K_I, K_F	837, 41.25, 20.22, 11.06
$\varphi_1, \varphi_2, \varphi_3, \varphi_4$	-1, -0.05, -0.0005, -0.005
$a_{m1}, a_{m2}, a_{m3}, b_m$	8,000, 335, 23, 7,500
$a_{p2}^0, a_{p3}^0, b_p^0$	2,446.47, 875, 34,926.65
δ_0, δ_1	0.05, 0.5

Following the design procedure we have the control law to simulate as:

$$\begin{aligned}U_P = \{&c_1(K_I\dot{z}) + a_{p1}^0 e_1 + a_{p2}^0 e_2 - [(a_{m1} - a_{p1}^0)x_{m1} \\ &+ (a_{m2} - a_{p2}^0)x_{m2} + (a_{m3} - a_{p3}^0)x_{m3} + b_m U_m)] \\ &+ (c_2 - a_3^0)[c_1(e_1 - K_I z - rK_F) + c_2 e_2]\}/b^0 \\ &+ (\varphi_1|e_1 - K_I z - rK_F| + \varphi_2|e_2| + \varphi_3|e_3| + \varphi_4)M_\delta(\sigma)\end{aligned} \qquad (24)$$

The switching function, σ from (5), is

$$\sigma = c_1(e_1 - K_I z - rK_F) + c_2 e_2 + e_3 \ ;r = U_m. \qquad (25)$$

In the simulation, the course keeping problem is considered. The main goal of course keeping handling is to keep the handling angle of vessel on the fixed direction. The desired output is set to be nine degree. The problem of the ship maneuvering in restricted water, such as harbors, canals, river inlets, etc., is of major concern from the viewpoint of marine safety. It is very important for a shipmaster to make a ship-handling plan before approaching such maritime space just mentioned. The vessel must navigate in the desired course tracking problems. The next section presents a plant control simulation using MATLAB software package to show the response to input track and testing of plant parameter variations and external load disturbances.

6. Simulation results and discussion

In order to evaluate the tracking performance of the MFLVSC approach for both steady and transient periods, a ramp command is first introduced for certain period of time before it is changed abruptly to a constant value. In the simulation of course tracking handling, the desired heading angle φ_d is 10sin(0.2πt/180). In addition the results are compared with those obtained from MIVSC and IVSC approaches under the same testing conditions, as shown in Fig. 6 and Fig. 7. It is clear from the figures that the MFLVSC can follow the course command input extremely well during steady state as well as transient periods. That is, it converges very fast to zero but the other give rise to steady state errors. It is apparent that the performance of the MFLVSC is quite good. Although MIVSC seems to track well during the steady state of the ramp command input, it gives a noticeable overshoot and tracking error during the input change. Among them, IVSC performs poorly, it gives a substantially sustained course tracking error.

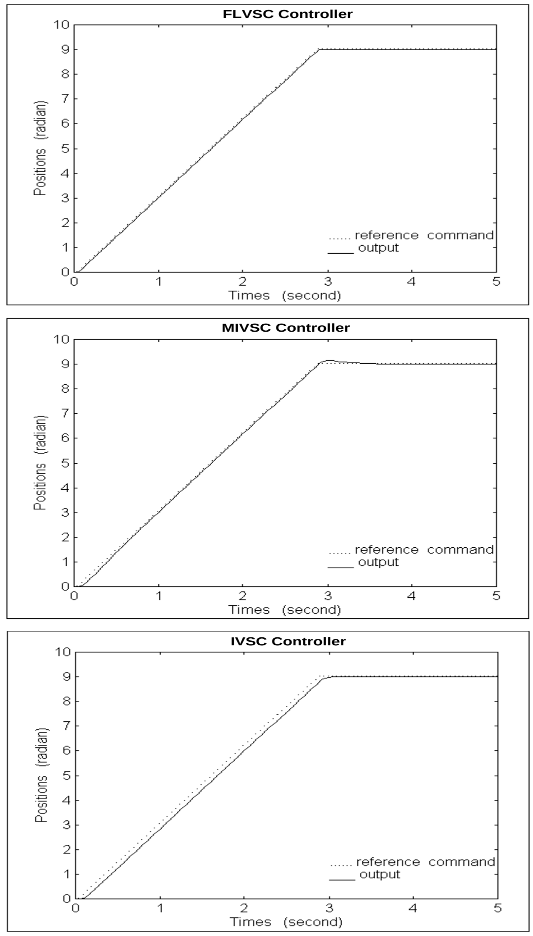

Figure 6 Comparison of ramp course tracking.

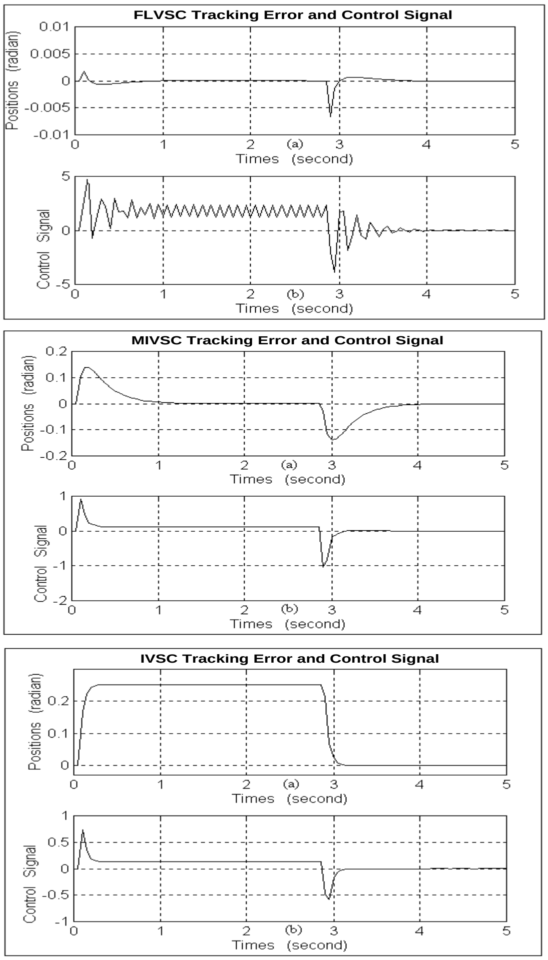

Figure 7 Comparison of course tracking error and control signal.

7. Conclusions

In this paper, the MFLVSC approach for a ship maneuvering is presented. The marine vessel maneuvering problems have been solved by using the MFLVSC strategy. It exhibits good feature of the conventional IVSC with proportional and integral controller, such as robustness in the face of model error and parameter variations. The application of FLVSC to a ship tracking control system has illustrated that the MFLVSC method can improve the course tracking performance by 52% and 68% when compared to the MIVSC and IVSC approaches, respectively. Moreover, we firmly believe that the MFLVSC is useful for solved the problems, also for the maritime search and rescue problems. In further research, it can be applied in this controller for the design of other process control methods requiring tolerance of internal plant parameter deviations and external load disturbances, as well as stability testing in both the time and frequency domains.

8. Acknowledgements

Authors of the paper would like to acknowledge the support of Rattanakosin International College of Creative Entrepreneurship, Rajamangala University of Technology Rattanakosin, Thailand.

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