Study and application of finite time convergence ADRC with dead zone and anti-saturation disturbance compensation

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Abstract. For the problem of frequency operation and the saturation of control input of the controller which caused by the unpredictable load disturbance of propulsion system, the active disturbance rejection control (ADRC) with dead zone and saturation disturbance compensation is designed. The dead zone and anti-saturation disturbance compensation module are introduced into the observer to reduce the operating frequency of the propulsion control system under load disturbance and to improve the control performance when the control input is saturated. However, the error feedback part of ADRC uses the finite-time sliding mode feedback. Simulation results show that the proposed algorithm reduces the operating frequency of the control system and improves the control performance when the control input is saturated.

1. Introduction
The load disturbance often results in frequent fluctuation of ship propulsion system, which not only increases the wear of the actuator of the control system, but also results in the vibration of diesel engine speed. In addition, the oscillation of diesel speed makes the fuel injection fluctuate sharply, and the supercharger pressure lags behind the change of fuel injection, which will worsen the Combustion performance of diesel engine and increase the emission of pollutants. If there is extreme load disturbance, even the control input saturation phenomenon will occur, which will cause overshoot increase, control lag, adjustment time become longer, and make the system unstable when serious (Guo et al., 2015).

At present, the main control law of the diesel engine adopts PID control, but the PID control parameter needs to change with the working condition change, otherwise the control effect is limited. Therefore, some scholars combine fuzzy control and neural network to improve the adaptive performance of PID control (Sun and Chen, 2015; Huang, 2007; Shi et al., 2012; Arnold et al., 2009); Some scholars jumped out of the PID control framework and adopted modern control theory, such as synovial control, model-free control, optimal control and other design control methods to improve the control effect (Utkin et al., 2017; Liu et al., 2017; Abomasa et al., 2017; Zhang et al., 2017; Betsch, 2017). None of the above documents has studied the phenomenon that the control system moves frequently or even controls the input saturation caused by the load disturbance. For the problem of frequent operation of control system, Zhao (Zhao, 2015) introduces dead-time control into the control input, and the control effect is good. The simplest way to deal with the saturation phenomenon of control input is to reduce the gain of the control system and avoid the saturation phenomenon. However, because the capacity of the control system is not fully utilized, the practical performance of the actuator is reduced. Ultimately,
the performance of the control system is degraded (Lin et al., 2017; Li and Xin 2017; Sun et al., 2017; Sheng et al., 2017). Therefore, it is of great theoretical and practical significance to study and design a method of restraining the control system from frequent actions and controlling the input saturation. ADRC is a model-free control algorithm proposed by Han Jingqing of the Chinese Academy of Sciences. Because of its simple structure and active anti-interference capability, ADRC has attracted wide attention in recent years (Xia et al., 2018; Fu and Tan, 2017). Professor GAO Zhiqiang reduces the difficulty of theoretical analysis of ADRC through linearization and parameterized bandwidth, and expands the range of practical applications (Zhao and GAO, 2014).

In order to effectively suppress the effects of load disturbance, this paper presents an ADRC with dead time and anti-saturation disturbance compensation (DSFT-SADRC). The dead-band and anti-saturation components are firstly introduced into the design of control law, and the error disturbance is compensated by the observer to achieve the purpose of suppressing the load disturbance. Secondly, the feedback control law of DSFT-SADRC based on finite time convergence is designed, and the finite-time convergence analysis is carried out. Finally, the effectiveness of the proposed method is verified by the comparison of simulation experiments between DSFT-SADRC and ADRC.

2. Problem Formulation

In this paper, the electric controlled diesel engine 7RT-Flex60C is studied. The maximum sustained power is 16520kW, and the rated speed is 114rpm. Using the mean value model method, the speed control equation is established for the propulsion system of an electrically controlled diesel engine.

\[
\frac{dh_e}{dt} = -\frac{10^3 V_o (k_1 n_e + k_2 n_e^2)}{N_{st} I} 30 - \frac{K_o \rho n_e^2 D^5}{I} \left(\frac{30}{\pi}\right)^2 \frac{10^4 \eta H_f \dot{m}_f}{n_e I}
\]

Where \( V_o \) is the volume of air cylinder per cycle, \( k_1, k_2 \) is the coefficient of fitting function, \( N_{st} \) is the number of strokes, \( K_o \) is the torque coefficient, \( \rho \) is sea water density, \( D \) is the diameter of the propeller., \( \eta \) is indicating thermal efficiency., \( I \) is the total moment of inertia of diesel engine, shaft system and propeller, \( H_f \) is the low heat value of the fuel., \( \dot{m}_f \) is the average mass of fuel flowing into the cylinder per cycle, \( n_e(t) \) is the diesel engine speed. Suppose \( u = \dot{m}_f \),

\[
f(n_e(t)) = -\frac{10^3 V_o (k_1 n_e(t) + k_2 n_e(t)^2)}{N_{st} I} \left(\frac{30}{\pi}\right)^2 \frac{K_o \rho n_e(t)^2 D^5}{I} \frac{30}{\pi} \frac{10^4 \eta H_f}{n_e(t) I}, \quad \text{then the formula (1) can be expressed as:}
\]

\[
\frac{dn_e}{dt} = f(n_e) + g(n_e)u.
\]

Assume the state of the Marine electric control diesel engine system is: \( x_1(t) = \int n_e(t) dt \), \( x_2(t) = n_e(t) \), then the formula (1) can be expressed as:
Where \( b_0 > 0 \); suppose \( f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))u(t) - b_0u(t) \) is the sum of system disturbances, and bounded; \( u(t) \) is the control input for the system; \( y(t) \) is the system output.

Figure 1. The propulsion control system with load disturbances

The load perturbation of diesel engine is the disturbance caused by complex sea conditions. The ADRC system with load disturbance characteristics is shown in Fig. 1.

According to the working principle of Figure 1, the marine diesel engine propulsion control system with load disturbance can be expressed as follows:

\[
\begin{align*}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))u(t) - b_0u(t) + l(t) \\
y(t) &= x_2(t)
\end{align*}
\]  

(3)

Where \( l(t) \) is the system load disturbance, \(|l(t)|<L\), \( L \) is a constant. Let \( x_3 = f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))u(t) - b_0u(t) + l(t) \) be the expansion state amount, and suppose \( \dot{x}_3 = o(t) \), the original system (3) expands to:

\[
\begin{align*}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= x_3(t) + b_0u(t) \\
\dot{x}_3(t) &= o(t) \\
y(t) &= x_2(t)
\end{align*}
\]  

(4)
3. Controller design with dead zone and anti-saturation disturbance compensation

In this paper an inverse hyperbolic sine function is used to establish the differentiator (TD).

\[
\begin{align*}
\dot{v}_1(t) &= v_2(t) \\
\dot{v}_2(t) &= R^2 \left\{-a_1 \left| e_1 \right|^b \arsh(e_1) - a_2 \left| e_2 \right|^b \arsh(e_2 / R) \right\}
\end{align*}
\]

(5)

Where \( e_i(t) = \int e_i(t) dt \), \( e_2(t) = v_2(t) - r(t) \); \( r(t) \) System reference signal; \( R > 0, a_1 > 0, a_2 > 0, 0 < b < 1 \).

Then for any bounded integrable function \( r(t) \), the tracking value of \( r(t) \) is \( v_2(t) \) which satisfies the formula (6):

\[
\lim_{T \to \infty} \int_0^T \left| v_2(t) - r(t) \right| dt = 0
\]

(6)

Where \( T > 0 \).

The principle of anti-saturation disturbance compensation based on the observer (ESO), as shown in Figure 2. We use the inverse hyperbolic sine function to establish TD and ESO, and then establish the error feedback control law by finite time nonlinear feedback.

![Figure 2. Anti-windup control principle](image)

Assuming that the control input of the system is \( u \), and \( u_{\text{max}} \) is the actuator saturation value. And hence, the saturation function can be expressed as,

\[
N(u) = \begin{cases} 
    u & \left| u \right| \leq u_{\text{max}} \\
    u_{\text{max}} & \left| u \right| > u_{\text{max}}
\end{cases}
\]

(7)

Assume that \( u_a \) is the set value of saturation; \( K \) is anti-saturation compensation coefficient, the greater the value, the more obvious the role of compensation, but too large easily lead to system instability. \( \dot{u}(t) \) Is the actuator output, we define \( \dot{u}(t) = N(u) \).
where $u_a = \begin{cases} u & |u| \leq u_{\text{max}} \\ \frac{u_{\text{max}}}{\tau} & |u| > u_{\text{max}} \end{cases}$, we define $\tau = 1.1$.

Figure 2 shows that when the system is saturated, the saturation disturbance is compensated by the observer.

According to the advanced anti-saturation design method (Wang et al., 2016), the observer is designed as follows

$$
\begin{align*}
e_1(t) &= z_1(t) - \int_0^t y(t)dt \\
\dot{z}_1(t) &= z_2(t) - \beta_1 e_1(t) \\
\dot{z}_2(t) &= z_3(t) - \beta_2 \cdot \text{arsh}(e_2(t)) + b_0 u(t) - K(u(t) - u_o) \\
\dot{z}_3(t) &= -\beta_3 \cdot \text{arsh}(e_3(t))
\end{align*}
$$

(8)

where $\beta_1 > 0, \beta_2 > 0, \beta_3 > 0, K > 0$. If we take the appropriate value for $\beta_1, \beta_2, \beta_3, K$, the observer (8) can predict all state variables $x_1(t), x_2(t)$ and $x_3(t)$ of system (4), also known as $z_1(t) \rightarrow x_1(t), z_2(t) \rightarrow x_2(t), z_3(t) \rightarrow x_3(t)$. Here, we define $K = 0.4$.

For the observer ESO the method of parameter tuning is used and described as follows:

$$
\beta_1 = 9v_{\text{eso}}, \beta_2 = 27v_{\text{eso}}^2, \beta_3 = 27v_{\text{eso}}^3
$$

(9)

Where $v_{\text{eso}}$ Observer observation speed, we define $v_{\text{eso}} = 1.5w_c$. Because of $\beta_1\beta_2 - \beta_3 = 243v_{\text{eso}}^3 - 27v_{\text{eso}}^3$, and $w_c > 0$, the stability condition of observer in can be satisfied (Xue and Huang, 2014): $\beta_1\beta_2 - \beta_3 > 0$.

In order to improve the control performance we apply the sliding mode error feedback control law based on finite time convergence to the ADRC. The state error of propulsion control system of marine electronic control diesel engine is assumed to be: $\epsilon(t) = \int e(t)dt, e(t) = y(t) - r = x_2(t) - r$. Here, we define that $r$ is the system reference signal, and $e(t) = \begin{cases} 0 & |e(t)| \leq \zeta \\
|e(t)| & |e(t)| > \zeta \end{cases}$, $\zeta$ is the dead zone threshold, $\zeta = 0.05$. And hence, the error system corresponding to system (3) is

$$
\begin{align*}
\dot{e}_6(t) &= e_1(t) \\
\dot{e}_7(t) &= f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))u(t) \\
&\quad - b_0 u(t) + b_0 u(t) + l(t)
\end{align*}
$$

(10)

Because of $u(t) = (u_0(t) - z_1(t))/b_0$, the system (10) can be rewritten as

$$
\begin{align*}
\dot{e}_6(t) &= e_1(t) \\
\dot{e}_7(t) &= f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))\left(\frac{u_0(t) - z_1(t)}{b_0}\right) \\
&\quad - b_0 \frac{u(t)}{b_0} + b_0 u(t) + l(t)
\end{align*}
$$
Due to the expansion of the observer (8) convergence, that is: $z_1(t) \rightarrow x_1(t)$, $z_2(t) \rightarrow x_2(t)$, $z_3(t) \rightarrow x_3(t) = f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))u(t) - b_0u(t) + l(t)$. The system (11) can be rewritten as

$$
\begin{align*}
\dot{e}_6(t) &= e_7(t) \\
\dot{e}_7(t) &= f(x_1(t), x_2(t)) + g(x_1(t), x_2(t))u(t) - b_0u(t) + l(t) + u_0(t) - z_3(t)
\end{align*}
$$

(11)

For system 12, the sliding surface is designed as

$$
S = e_7(t) + k_1\left|e_6(t)\right|^\gamma \text{sgn}(e_6(t))
$$

(13)

Where $0 < \gamma < 1$, $k_1 > 0$.

According to the sliding mode control theory, in order to make the system state approach the sliding mode surface and move along the sliding mode surface, the approach law is selected as follows

$$
\dot{S} = -\frac{\alpha \text{sgn}(S)}{R} |S|^{\eta}, \alpha > 0, \eta > 0
$$

(14)

Where $R = |e_6|$, $0 < R < R_0$, $R_0 = r$.

From (13) and (14) shows

$$
SS = -\frac{\alpha}{R} |S|^{\eta+1} < 0
$$

(15)

Thus, the sliding mode arrival condition is satisfied, that is, the system state can reach the sliding mode surface.

We take the derivative of formula (13), and then connect the formula (11) and formula (14), the can be rewritten as

$$
u(t) = \frac{1}{b_0} (-f(x_1(t), x_2(t)) - g(x_1(t), x_2(t))u(t) + b_0u(t) - l(t) - k_1\gamma|e_6(t)|^{\gamma-1}e_7(t) - \frac{\alpha}{R} \text{sgn}(s)|s|^\eta)
$$

$$=
\frac{1}{b_0} (-z_3(t) - k_1\gamma|e_6(t)|^{\gamma-1}e_7(t) - \frac{\alpha}{R} \text{sgn}(s)|s|^\eta)
$$

(16)
We take the nonlinear control law as

$$ u_0 = -k_1 \gamma [e_6(t)]^{\gamma-1} e_7(t) - \frac{\alpha}{R} \text{sgn}(s)|s|^{\eta} $$

(17)

Therefore, control input can be obtained as:

$$ u(t) = \frac{1}{b_0} (-z_3(t) + u_0(t)) $$

(18)

In the case of dead-zone and anti-saturation compensation, the formula (18) can be written as

$$ \begin{cases} 
  u(t) = \frac{1}{b_0} (-z_3(t) + u_0(t)) \\
  \hat{u}(t) = N(u(t)) 
\end{cases} $$

(19)

4. Simulation Study

In this section, we will compare the FT-SADRC with ADRC by Matlab/Simulink.

The observer parameters of the ADRC algorithm are $\beta_1, \beta_2, \beta_3$, the error feedback parameter is $\beta_{01}$ and $\beta_{02}$, the simulation step of the differentiator is $T_0$, the velocity factor is $r_0$, the filter factor is $h$, $b_0$ is an estimate. ADRC parameter is set as follow: $T_0 = 0.01$, $r_0 = 10$, $h = 0.2$, $b_0 = 1000$, $\beta_1 = 15$, $\beta_2 = 200$, $\beta_3 = 80$, $\beta_{01} = 120$, $\beta_{02} = 21$.

DSFT-SADRC parameter is set as follow: $R=10$, $a_1=1$, $a_2=1$, $b=0.3$, $b_0=1000$, $t_s = 3$, $K = 0.4$, $k_1 = 0.6$, $\gamma = 0.8$, $\alpha = 0.4$, $\eta = 0.5$. Load disturbance is $l(t) = 25 \times 10^5 \sin(t \cdot 20\pi)$, and unknown in the control process.

We simulates the conditions of maneuvering sailing in and out of port, overtaking and avoiding ships irrespective of factors such as storms and ships inertia. The simulation time is set to 100 s, the initial speed of diesel engine is rated speed 114r/min, At 50s, and the bridge sets the speed of the diesel engine to 90.5r/min. In the process, the load torque of propeller is 1390kN.m and constant. Where the dead zone threshold $\zeta = 0.35$, Control input saturation $\hat{u}(t) = [0 \ 0.07]$.

Under the influence of the load disturbance and the control input is not limited, Fig. 3 is a comparative diagram of the speed response curves of marine electronically controlled diesel engines for DSFT-SADRC and ADRC. Fig. 4 is marine electronic diesel engine speed error curve comparison chart for DSFT-SADRC and ADRC.
From figs. 3 and 4, we can see that the speed fluctuation of DSFT-SADRC control algorithm is small, however the control method of ADRC fluctuates greatly which proves that DSFT-SADRC algorithm is better.

5. Conclusion
In order to overcome the problem of frequent operation and even control input saturation caused by load disturbance, an expansion observer with dead-time and saturation compensation module is designed in this paper. In order to improve the control effect, the sliding mode error feedback control law with finite time convergence is designed, the mathematical form of the convergence time is given, and the finite time convergence characteristic of the improved control law is proved theoretically. The simulation results show that the dead-time and saturation compensation control proposed in this paper can reduce the frequency of the control system and improve the control effect when the control input is limited.

Acknowledgements
This work was supported by the National Natural Science Foundation of China under Grant 51479017.

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