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Design of γ-Suboptimal H_∞ Speed Controller for Diesel Engine

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Abstract. Diesel engine is a complex nonlinear system. In view of the uncertainty of the model in the process of linearization of diesel engine model and the insufficient robustness of the existing PID controller, the robust control theory is applied to the speed control of diesel engine. Firstly, the quasi-steady state model of diesel engine is locally linearized to establish its state space model. Then, by analyzing the robust stability under friction torque uncertainty, the diesel engine speed H_∞ controller is established, and the control law is finally obtained by solving the LMI method. Finally, a simulation experiment is designed in the MATLAB/Simulink environment. The simulation results show that the designed speed controller has strong model fault tolerance, good resistance to external disturbance, and the speed regulation is obviously better than the traditional PID speed controller.

Keywords. Desel engine, H_∞ controller, simulation

1. Introduction

Diesel engine is widely used as the main power unit of ships, and its speed regulation performance determines the maneuverability and stability of ships [1]. Traditional control algorithms can no longer meet the needs of equipment development. In terms of traditional control algorithm improvement, the reference [2] studied the fuzzy adaptive PID control algorithm to adjust the speed of diesel engine, which improved the real-time performance of speed regulation. The reference [3] optimized the PID controller based on the improved particle swarm algorithm, which reduced the overshoot and the adjustment time. The reference [4] established a radial basis neural network PID (RBF-PID) speed control system to improve the diesel engine speed control system, and the overshoot and fluctuation ratio have been greatly improved. Reference [5] introduced a robust control algorithm for the single-axis turntable control problem in the aerospace inertial guidance test process. The anti-interference performance was better than the traditional PID controller, and the system stability is significantly improved. Reference [6] used robust control algorithm for quadrotor aircraft attitude control, and the response speed and attitude accuracy have been improved. Reference [7] applied robust control theory to the control field of flexible robotic arms, and achieved significant improvements in control accuracy, especially resistance to external disturbances. Reference [8] applied the robust control theory to the automatic tracking control of

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heavy commercial vehicles, which significantly improved the trajectory tracking accuracy.

In summary, the current mainstream research direction of diesel engine speed regulation is the optimization and improvement of the control performance of the PID controller, and less research has been done on the uncertainty of the model and the anti-interference of the control process. In this paper, the model-based design (MBD) method is studied to design the PA-6 diesel engine ECU. Through the establishment of a fast model, the development of the H_∞ control law, and the design of the governor circuit, the intelligent control of the diesel engine speed is realized.

2. System Modeling and Uncertainty Analysis

The PA-6 diesel engine is a four-stroke medium and high-speed diesel engine, and its effective torque is,

$$M_e = M_i \eta_m = \frac{H_u g_c \eta_i \eta_m}{\tau \pi} \tag{1}$$

where, g_c is circulating fuel injection quantity, M_i is indicated torque, H_u is low calorific value of fuel, η_i is indicative efficiency.

The dynamic equation of diesel engine is,

$$N_d = \frac{30}{\pi I_e} \int \left(M_e - M_B - M_{f1}\right) d_t \tag{2}$$

where, I_e is moment of inertia, M_B is load torque, M_{f1} is friction torque, N_d is diesel engine speed. When the diesel engine model runs stably, the steady-state operating point of the system is selected to locally linearize it to establish a model. The system state space expression can be obtained,

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{3}$$

where, x is state variable, u is control variable.

$$A = \begin{bmatrix} -0.0093 & 0.0102 & 0 & 0 \\ 0 & -2 & 0 & 100 \\ 0 & 0 & -10 & -100 \\ 0 & 0 & 1 & 0 \end{bmatrix}、 B = \begin{bmatrix} 0 & -0.0011 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \end{bmatrix}、 C = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

In order to ensure that the stability of the system will not be affected by the uncertainty of the model, a robust stability analysis of the uncertain system is required before designing the controller. Considering the uncertainty caused by the friction torque, there is an approximate linear relationship between the friction torque and the speed of the diesel engine.

$$M_f = k_f N_d \tag{4}$$

where, k_f is scale factor. The uncertain system can be described as the structure shown in figure 1.

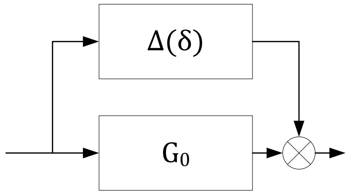

Figure 1. System structure diagram with uncertain parameters.

The uncertainty system can be expressed as,

$$\tilde{G} = G_0 + \Delta(\delta) \tag{5}$$

where, $\tilde{G}$ is the actual uncertain system. G_0 is the nominal system. $\Delta(\delta)$ is the system uncertainty.

The system state space expression can be rewritten as:

$$\begin{cases} \dot{x} = A(\delta)x + Bu \\ y = Cx \end{cases} \tag{6}$$

$A(\delta)$ can be written as: $A(\delta) = A_0 + \Delta(\delta)$. The error matrix $\Delta(\delta)$ can be obtained by linearizing all steady-state operating points at rated speed. Where, $\Delta(\delta)_{12} = 1.4e - 0.4$.

According to the definition of quadratic stability, if there is a symmetric positive definite matrix P such that all uncertain parameters δ belong to Δ, then there is a matrix inequality:

$$A^T(\delta)P + PA(\delta) < 0 \tag{7}$$

If equation (7) holds, the system is quadratic stable. The quadstab function of the LMI toolbox in MATLAB is used for analysis, and the symmetric positive definite matrix P and the minimum coefficient t that make the inequality (7) hold are obtained. The result is:

$$P = \begin{bmatrix} 0.0779 & -0.0001 & -0.0001 & 0.0013 \\ -0.0001 & 0.4456 & 0.5825 & 1.8752 \\ -0.0001 & 0.5825 & 2.3692 & 11.2293 \\ 0.0013 & 1.8752 & 11.2293 & 120.6625 \end{bmatrix}$$

At this time, t=-0.0053<0 .The results show that the system $\widetilde{G}$ is quadratic stable, while satisfying the robust stability conditions.

3. Construction of a State Observer

The internal state variables of the diesel engine are only the speed parameters that can be obtained by direct measurement, and other state variables cannot be directly observed. When designing a state feedback controller, it is necessary to construct a state observer to reconstruct the state vector. The structure of the diesel engine state feedback control system with state observer is shown in figure 2.

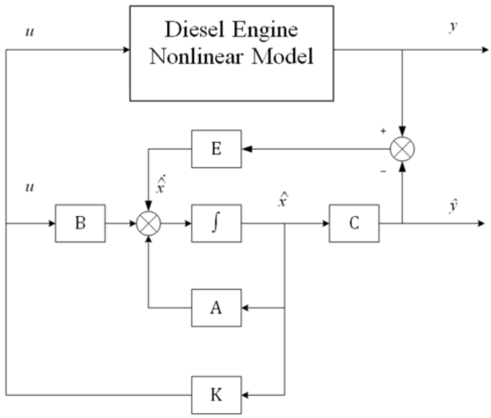

Figure 2. Structure diagram of diesel engine state feedback control system with state observer.

From the structure diagram, we can get:

$$\dot{\hat{x}} = A\hat{x} + Bu + E(y - \hat{y}) \tag{8}$$

where, $\hat{x}$ is the refactoring state quantity, $\hat{y}$ is estimated output.

Therefore, after adding the state observer, system (4) can be rewritten as:

$$\begin{cases} \dot{\hat{x}} = (A - EC)\hat{x} + Bu + Ey \\ \hat{y} = C\hat{x} \end{cases} \tag{9}$$

At this point, the control input is $u = K\hat{x}$. Diesel engine speed control is a typical system tracking control. Let the error e between the system output y and the set speed r,

$$e(t) = r - y(t) \tag{10}$$

Integrating Equation (10) can get

$$q(t) = \int e(\tau)d\tau = \int [r - y(\tau)]d\tau \tag{11}$$

Combining the reconstructed state vector with the error integral forms a new state vector. The reconstructed system expression is:

$$\begin{cases} \dot{\hat{x}} = (A - EC)\hat{x} + Bu + Ey \\ \dot{q} = -Cx + r \approx -C\hat{x} + r \\ \hat{y} = C\hat{x} \end{cases} \tag{12}$$

4. Design of *r*-Suboptimal H_∞ Controller

The system structure is adjusted to the generalized two-terminal model of the system as shown in figure 3. *P* represents the controlled system, and *K* is the feedback control law. *w* is the external disturbance input, the external disturbance is often uncertain but the energy is limited. In the diesel engine speed control system, the external disturbance is set as the strong uncertain disturbance from the load during the operation of the main engine. *z* is the controlled output, which is the output condition of the system in the ideal state.

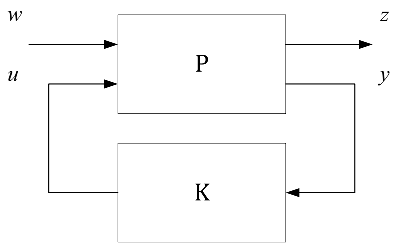

Figure 3. Two terminal graph of singular system.

The generalized two-terminal system state space is thus described as:

$$\begin{cases} \dot{x} = Ax + B_1 w + B_1 u \\ z = C_1 x + D_{11} w + D_{12} u \\ y = C_2 x + D_{21} w + D_{22} u \end{cases} \tag{13}$$

Design the controller u=Kx so that the closed-loop system is internally stable, and the H_∞ norm of the closed-loop transfer function T_{zw} from the disturbance input w to the controlled output z is less than 1, namely:

$$\|T_{zw}(s)\| < 1 \tag{14}$$

Bringing the control input u=Kx into system (14) results in a closed loop system:

$$\begin{cases} \dot{x} = (A + B_2K)x + B_1w \\ z = (C_1 + D_{12}K)x + D_{11}w \end{cases} \tag{15}$$

At the same time, the norm of the closed-loop transfer function is limited to be less than a certain constant, that is,

$$\|T_{zw}(s)\|_\infty < \gamma \tag{16}$$

Simplified to:

$$\|T_{zw}(s)\|_\infty = \left\|(C_1 + D_{12}K)[sI - (A + B_2K)]^{-1}B_1 + D_{11}\right\| < \gamma \tag{17}$$

Solving equation (17), the γ -suboptimal u=Kx controller K of system is obtained.

5. Simulation

The set speed is 400rpm, and the speed regulation process is shown in figure 4. The continuous speed regulation curve under load conditions is shown in figure 5.

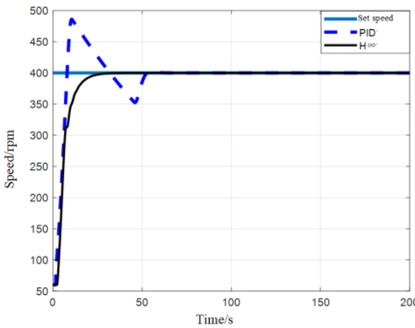

Figure 4. The curve of step response.

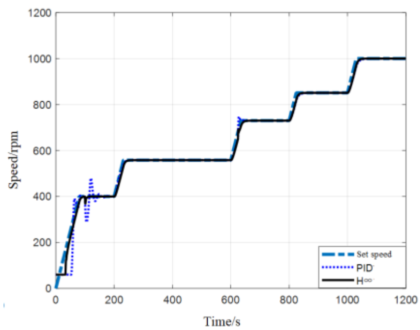

Figure 5. Diagram of diesel engine operation curve with load.

The response curve reveals that both governors can stabilize the diesel engine speed near the set speed. But the PID controller not only has a large overshoot, but also has a long adjustment time. It can be seen from the speed regulation curve that when the system is under load, the PID speed controller fluctuates significantly, and stabilizes after a long adjustment time. The H_∞ controller always runs smoothly, with small fluctuations at the moment of load, and quickly restores the set speed. The subsequent speed regulation process has a strong inhibitory effect on the load disturbance.

6. Conclusion

The H_∞ control theory takes into account the uncertainty of the model and the external disturbance, which not only makes up for the performance impact caused by the insufficient accuracy of the control object model, but also effectively suppresses the disturbance from the outside of the system. It can be seen from the simulation that the H_∞ controller can effectively enhance the robustness of the system, and the speed regulation performance of the system has also been greatly improved.

Acknowledgments

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