H∞ Loop Shaping Robust Control for Body Roll of Tractor-semitrailer on Ice-Snow Road

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Abstract. In view of the problems that the poor driving stability and the increase body rolling even instability of the tractor-semitrailer in turns with a middle-speed on the ice-snow road, a robust stably controller that uses a combination method of $H_\infty$ and loop shaping is designed. The tractor-semitrailer dynamics model with the body roll degree of freedom is been established, and the influence of different ice-snow road adhesion coefficients on the dynamic characteristics of body rolling angle is analyzed. Finally, the simulation verification carries out that the controller which is used $H_\infty$ loop shaping can make the body roll of tractor-semitrailer stable, and the controller has a good robust stability.

1. Preface
Under the conditions of ice-snow road, the road adhesion coefficient is small. When the tractor-semitrailer runs especially turns on this road, the driving stability becomes extremely poor. If the speed is too high, even a small front wheel angle may cause the entire tractor-semitrailer to appear problems of lateral shimmy increasing and rolling motion, which is not easy to stabilize. Therefore, in order to analyze the roll stability of tractor-semitrailer, it is necessary to establish a dynamic model including the body roll degree of freedom, that model can be used to analyze the influences of different road adhesion coefficients on the dynamic characteristics of the vehicle’s body rolling angle.

Based on a combination method of $H_\infty$ and loop shaping, in view of the poor handling stability of tractor-semitrailer, an effective controller is designed to make the body-rolling angle reach the stability requirement.

2. Six-degree-of-freedom model in vehicle reference coordinate system
When analyzing the roll stability of a tractor-semitrailer under ice-snow road conditions, the road surface adhesion coefficient $\mu$ needs to be considered, and the road adhesion coefficient $\mu=0.2$$-0.6$ under ice-snow road conditions, the cornering stiffness of each axle acting on the tractor-semitrailer needs to be multiplied by $\mu$.

2.1 Equation of motion
The model parameters are described in [1], and the equations of motion of the tractor, semitrailer and steering system are as follows
The vehicle velocity is 75km/h, the system of the semitrailer when the longitudinal velocity are

$$I_{21} \dot{r}_1 + I_{21} \dot{\phi}_1 = a_2 C_f \left( \frac{v_1 + a_1 r_1}{u_1} - \delta - E_f, \varphi_1 \right) \cos \delta - b_2 C_i \left( \frac{v_1 + a_1 r_1}{u_1} - E_i, \varphi_1 \right) - F_{yb} \varepsilon$$

Simultaneous formulae (1), (2) and (3) form a tractor-semitrailer dynamic model including body roll and considering the degrees of freedom of the steering system [2] [3].

2.2 State space representation

The state space equations of formulas (1), (2), and (3) can be expressed as

$$\begin{cases}
\dot{x}(t) = Ax(t) + Bu(t) \\
y(t) = Cx(t) + Du(t)
\end{cases}$$

\(\delta_{in}\) represents the input variable \(u(t)\), the state vector is

$$x(t) = \begin{bmatrix} v_1 & r_1 & \psi & p_1 & p_2 & \varphi_1 & \varphi_2 & \dot{\delta} & \delta \end{bmatrix}^T$$

3. Dynamic characteristics analysis of tractor-semitrailer

Suppose the tractor-semitrailer is turning at a small angle, the steering angle step input of the tractor is 25°, the road adhesion coefficient on ice-snow road is \(\mu = 0.3\), and other initial conditions are 0, and the dynamic characteristics of the vehicle system are simulated and analyzed.

Figures 1 is the curves of body rolling angle of the semitrailer when the longitudinal velocity are 30km/h (8.3m/s), 60km/h (16.7m/s), and 75km/h (20.8m/s).

![Figure 1. \(\mu = 0.3\), body rolling angle](image1.png)

![Figure 2. \(\mu = 0.2-0.6\), \(u_1 = 60\)km/h.](image2.png)

As can be seen from Figures 1, when the forward velocity increases, the driving stability of the vehicle becomes worse during cornering, and when the vehicle velocity is 60 km/h, the response curves of the body rolling angle characteristics of the tractor and semitrailer oscillate significantly, adjust the time to grow. When the vehicle velocity is 75km/h, the system cannot be stabilized, which indicates that the conditions of the ice-snow road have a significant adverse effect on the stability of the tractor-semitrailer, which seriously threatens the driving safety of the vehicle.

In order to find out the influence of different road adhesion coefficients on the dynamic characteristics of vehicle body rolling angle under the conditions of ice-snow road, a vehicle velocity...
of 60km/h is taken as an example to analyze the response characteristics of the body roll angle of the semitrailer with the main load.

At this time, the road adhesion coefficient $\mu$ is 0.2~0.6, and the step length is 0.1. In order to compare the steady state value, the simulation time increases to 50s, and the simulation result is shown in figure 2. It shows that under conditions of ice-snow road, when the road adhesion coefficient increases, the body roll angle of the semitrailer can stabilize at a smaller value, and the dynamic characteristics become better more. That is, the larger the road adhesion coefficient is, the better the adhesion performance changes and the more stable the vehicle drives.

However, in general, the dynamic characteristics of the vehicle are not ideal within the current velocity and ice-snow road conditions.

4. Roll control for tractor-semitrailer

The above analysis shows that as the driving velocity of vehicle increases, dynamic characteristic is more sensitive to changes in road conditions, and poor road conditions can easily lead to poor vehicle driving conditions. Therefore, a combination method of $H_\infty$ and loop shaping proposed by scholars such as McFarlane, D.C. and K. Glover is used to design an effective controller [4]-[6] to improve the vehicle's dynamic response characteristics under various road conditions. When the road adhesion coefficient and driving velocity change within a certain range, the controller can achieve the goals of reducing the number of rolls of the vehicle body and the steady state value.

4.1 Control for body Roll of semitrailer

4.1.1 Control result analysis

The setting conditions are $u_1=60$km/h, $\mu=0.2$, the steering angle step input and other conditions of the tractor remain unchanged. The semitrailer body rolling angle $\phi_2$ is used as the control target requires $\phi_2$ to achieve stable performance in a short time under the action of the controller. Through debugging, take $W_1=870/(s+0.1)$, $W_2=1$, and use the loop shaping to find the index $\gamma=3.1652$ (which satisfies $1<\gamma<10$) [7]. The singular value curve is shown in Figure 3.

The singular value curve shown in Figure 3 shows that under the action of the controller, the feedback loop has reached a high loop gain and possible controller gain in the required frequency band. Each time the curve is increased by $\gamma$ times, its corresponding decibel number is increased by $20\log\gamma$, and the open-loop transfer function $GK$ singular value bode curve (solid line) is between the $W_2GW_1$ curve (ie, $G_1$) $\pm 20\log\gamma$ decibels, which meets the eclectic requirements of good performance and robustness and strong anti-noise.

Figure 4 is a simulation result of using the controller to control the body rolling angle $\phi_2$ of the semitrailer. It shows that under the action of the designed controller the oscillation reduces significantly, the stabilization time is short, and the steady state value reduces greatly.

4.1.2 Comparison of control results after changing parameters

Still take $u_1=60$km/h, the road adhesion coefficient is $\mu=0.6$, and the control analysis of the semitrailer body rolling angle $\phi_2$ is performed. The control result is shown in figure 5. Compare and analyze the control effect of the controller when the vehicle velocity increases, take $u_1=75$km/h, $\mu=0.3$, and
perform control simulation on the semitrailer body rolling angle $\phi_2$. The control result is shown in figure 6.

![Figure 5. $u_1=60$km/h, $\mu=0.6$.](image)

![Figure 6. $u_1=75$km/h, $\mu=0.3$.](image)

The body rolling angle $\phi_2$ of the semitrailer in figure 6 uses the controller calculated by $\gamma=3.5653$ to stabilize the originally unstable output and improve the performance significantly, indicating that the controller also has strong adaptability when the vehicle velocity becomes larger.

5. Conclusion

(1) According to the dynamic model, the simulation analyzes the dynamic characteristic curve of the rolling angle of the tractor-semitrailer when turning on ice-snow road at medium and low velocity. The results show that under ice-snow road conditions, the dynamic characteristics of body rolling angle at medium velocity are difficult to stably output, which indicates that road conditions have a great influence on vehicle handling stability.

(2) The controller was designed using a combination method of $H_\infty$ and loop shaping, and the control effect of a tractor-semitrailer running at different velocity on various ice-snow road with various adhesion coefficients was compared and analyzed. The results show that when the weighting function of the controller is unchanged, under different conditions of vehicle velocity and different adhesion coefficients, the control algorithm can calculate different indicators $\gamma$ according to changes in input parameters. It can effectively control the body rolling angle of the vehicle, obtain stable performance, and the controller itself has strong robustness.

Acknowledgments

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