

The Decoupling Control of ARS and DYC Based on the Neutral Network Inverse System Method

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Abstract. According to the interference and coupling characteristics among sub-systems of the chassis of the forklift truck, the the neutral network inverse system method of the non-linear system is applied for the decoupling control of the active rear steering (ARS) and the direct yaw moment control (DYC) of the forklift truck. Based on the analysis of the reversibility of the chassis system, a back propagation neutral network reverse system model is set to decouple the chassis system into two independent pseudo-linear system; A PD closed loop controller is designed to comprise a composite controller with the neutral network reverse system and the simulation is performed for verification. The simulation result shows that the decoupling control strategy with the neutral network reverse system can eliminate the interference and coupling among sub-systems of the chassis and thus enhances the status tracking and operating stability of forklift trucks.

1. Introduction

Recent years, the application of integrated control over the sub-systems of the chassis of vehicles to exploit the functional potentials of sub-systems has become a hotspot in the study of the vehicle dynamics[1-3]. The sub-systems of the chassis of vehicle are designed to realize certain functions. The active rear steering (ARS) and the direct yaw moment control (DYC) can both enhance the lateral stability[4-5]; therefore, the cross-interference of the control function occurs, and, inevitably, the interfering coupling occurs, debasing the performance of the vehicle system and the reliability. If decoupling is performed for the integrated chassis system whose channels are inter-coupled to eliminate the interactions among dynamic sub-systems during the design of the control system, additional functions that independent sub-systems cannot be provided may be realized and therefore the comprehensive performance of the vehicle is enhanced.

References [6-7] study the decoupling control of the sub-systems of the chassis. This paper mainly discusses the decoupling control on the ARS and the DYC of forklift trucks with the neutral network reverse system method of the non-linear system based on the non-linear dynamic characteristics of vehicles caused by non-linearity of tires, and uses Matlab/Simulink to perform simulation analysis on the control system to verify the effects of the decoupling control on the control system.

2. Reference model of the control system



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The reference model of the control system is a 2-DOF dynamic model. The ARS and the DYC respectively control the yaw and steering stability laterally and vertically and applies a 2-DOF vehicle model of lateral and yaw as the common control reference model, as shown in Figure 1.

In Figure 1, v , β and ω_r are respectively the vertical velocity, slidslip angle and yaw velocity of the vehicle; m is the mass of the forklift truck; a , b are respectively the front and rear wheel bases; I_z is the moment of inertia; C_{af} and C_{ar} are respectively cornering stiffness of the front and rear wheels; δ_r , δ_c and T are the turning angle of the rear wheels applied by the driver, the turning compensation angle of the rear wheels and the yaw control torque.

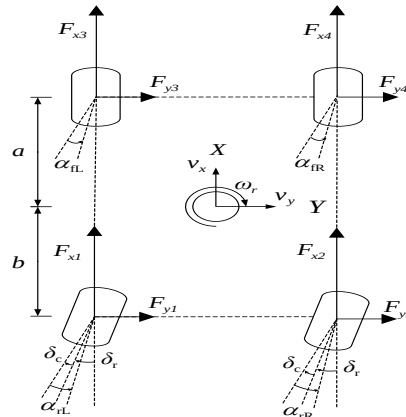


Figure 1. Reference model of the control system

The status variable of the system is defined as $x = (\beta \ \omega_r)^T$, the control input variable as $u = (\delta_c \ T)^T$ and the control output variable as $y = (\beta \ \omega_r)^T$, then the state equation of the vehicle can be described as follows:

$$\begin{cases} \mathbf{M}\dot{\mathbf{x}} = \mathbf{K}\mathbf{x} + \mathbf{N}\mathbf{u} + \mathbf{Q}\delta_r \\ \mathbf{y} = \mathbf{C}\mathbf{x} \end{cases} \quad (1)$$

wherein:

$$\mathbf{M} = \begin{pmatrix} m\nu & 0 \\ 0 & I_z \end{pmatrix}, \quad \mathbf{K} = \begin{pmatrix} -2(C_{af} + C_{ar}) & -mv + \frac{2(aC_{af} - bC_{ar})}{v} \\ 2(aC_{af} - bC_{ar}) & -2\frac{a^2C_{af} + b^2C_{ar}}{v} \end{pmatrix}, \quad \mathbf{N} = \begin{pmatrix} 2C_{ar} & 0 \\ 2C_{ar} & 1 \end{pmatrix}, \quad \mathbf{Q} = \begin{pmatrix} 2C_{ar} \\ 2bC_{ar} \end{pmatrix}, \quad \mathbf{C} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

Obviously as shown above, the reference model (1) of the vehicle system is a typical 2-input and 2-output multi-variable system.

3. Design of the decoupling control system

3.1. Reversibility analysis

For the multi-input and multi-output integrated chassis control system (1) described by the above state equation, the Interactor algorithm is usually used to verify the system reversibility: calculate the derivative of each order of output variable y relative to time until the derivative equation of the output explicitly contains the input variable u , according to (1), the following can be obtained:

$$\begin{aligned} \dot{y}_1 = \dot{\beta} &= -2(C_{af} + C_{ar})\beta / mv \\ &+ 2\omega_r(aC_{af} - bC_{ar}) / mv^2 - \omega_r + 2C_{ar}(\delta_r + \delta_c) / mv \end{aligned} \quad (2)$$

Recorded as $\mathbf{Y}_1 = \dot{y}_1$, its rank of the Jacobian matrix relative to the input variable u is:

$$t_1 = \text{rank}\left(\frac{\partial \mathbf{Y}_1}{\partial \mathbf{u}^T}\right) = \text{rank}\left(\begin{array}{cc} \frac{\partial \dot{y}_1}{\partial \delta_c} & \frac{\partial \dot{y}_1}{\partial T} \end{array}\right) = 1 \quad (3)$$

$$\begin{aligned} \dot{y}_2 = \dot{\omega}_r &= 2(aC_{af} - bC_{ar})\beta / I_z - 2(a^2C_{af} + b^2C_{ar})\omega_r / I_z v \\ &+ 2bC_{ar}(\delta_r + \delta_c) / I_z + T / I_z \end{aligned} \quad (4)$$

Recorded as $\mathbf{Y}_2 = (\dot{y}_1 \quad \dot{y}_2)^T$, its rank of the Jacobian matrix relative to the input variable $\mathbf{u}$ is:

$$t_2 = \text{rank}\left(\frac{\partial \mathbf{Y}_2}{\partial \mathbf{u}^T}\right) = \text{rank}\left(\begin{array}{cc} \frac{\partial \dot{y}_1}{\partial \delta_c} & \frac{\partial \dot{y}_1}{\partial T} \\ \frac{\partial \dot{y}_2}{\partial \delta_c} & \frac{\partial \dot{y}_2}{\partial T} \end{array}\right) = 2 \quad (5)$$

Due to nonnegative integer $\alpha_1 = 1$, $\alpha_2 = 1$ makes t_2 the number of the outputs of system (1), then the vector relative degree of the system is:

$\alpha = (\alpha_1 \quad \alpha_2)^T = (1 \quad 1)^T$; meanwhile, $\sum_{i=1}^2 \alpha_i = n = 2$ (n is the degree of the system). According to the implicit function theorem, the reverse system of the integrated system (1) does exist and the output $\mathbf{u}$ (the input of the original system) of the reverse system can be described as follows:

$$\mathbf{u} = \varphi(\mathbf{x}, \dot{\mathbf{y}}_1, \dot{\mathbf{y}}_2) = \varphi(\mathbf{x}, \mathbf{v}) \quad (6)$$

wherein $\mathbf{v} = (v_1 \quad v_2)^T = (\dot{y}_1 \quad \dot{y}_2)^T$, $\varphi(\cdot)$ is the nonlinear mapping relation between the output and the input of the reverse system. Set $z_1 = y_1$ and $z_2 = y_2$, and $v_1 = \dot{y}_1$ and $v_2 = \dot{y}_2$ as the inputs of the reverse system, then the standard form of the reverse system of the integrated system (1) can be described as:

$$\begin{cases} \dot{z}_1 = v_1 \\ \dot{z}_2 = v_2 \\ \mathbf{u} = \varphi(z_1 \quad z_2 \quad v_1 \quad v_2) \end{cases} \quad (7)$$

According to (7), the pseudo-linear system comprised by connecting the reverse system (7) in series before the original system (1) is equivalent to two first order integral linear sub-systems. Therefore, the control of the close coupling multi-variable system (1) with the ARS and the DYC can be transformed into the control on the two first order integral linear sub-systems, then the decoupling of the system is realized, as shown in Figure 2.

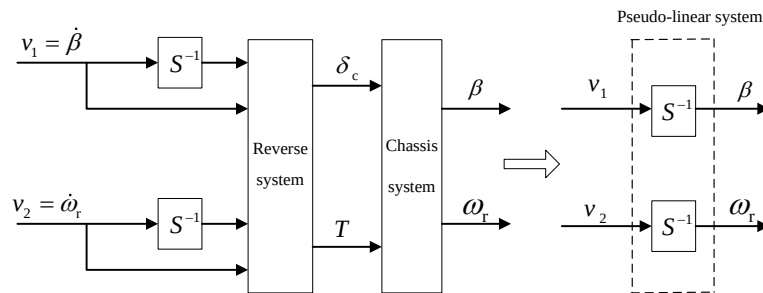


Figure 2. Equivalent structural diagram after decoupling

3.2. Construction and training of the neural network reverse system

The static neural network and the integrator are used to construct the system (7) and the structure of the neural network reverse system of the integrated chassis system is obtained as 4-10-2, as shown in Figure 3.

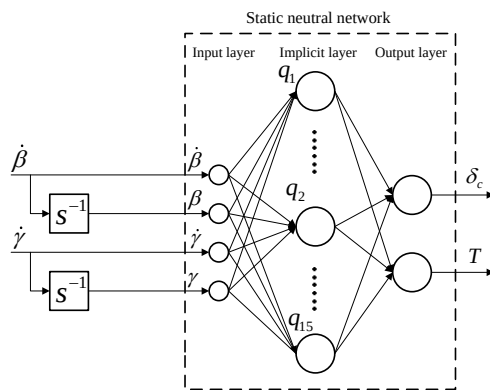


Figure 3. Structure of the BP neural network reverse system

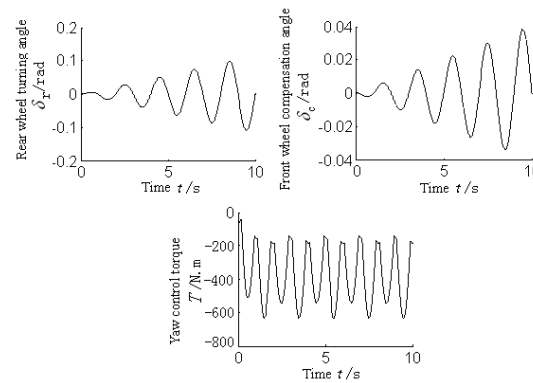


Figure 4. Excitation signal for training of the neural network reverse system

Supposed that the velocity of the vehicle is 10 km/h and the turning angle of the rear wheels applied by the driver is variable-amplitude sine curve, the turning compensation angle δ_c of the rear wheels and the excitation signal input by the yaw control torque T are as shown in Figure 4. Set the times of training to 500, the learning efficiency to 0.05 and the network target error to 10^{-4} , the precision required is obtained after 61 times of training.

3.3. Design of the closed loop controller

To improve the response quality of the integrated system, a composite controller comprised of a closed loop controller and a neutral network reverse system is designed to control the integrated system, as shown in Figure 5.

The PD closed loop controller:

$$\mathbf{v} = \mathbf{K}_p \text{diag}\{\mathbf{e}\} + \mathbf{K}_d \text{diag}\{\mathbf{de}\} \quad (8)$$

wherein:

$\mathbf{e}$, $\mathbf{de}$ - Deviation and deviation change rate of the system output signals

$\mathbf{K}_p$, $\mathbf{K}_d$ - Proportional and differential coefficients

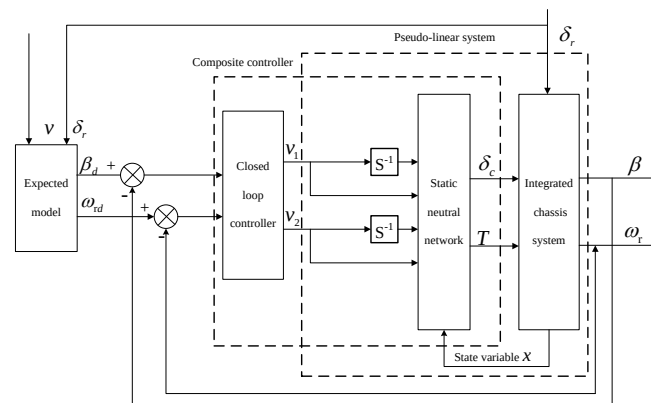


Figure 5. Structural diagram of the decoupling control on the integrated chassis system

4. Simulation and Result Analysis

The simulation to the designed decoupling control system of the chassis and relevant analysis are performed based on Matlab/Simulink. The simulation parameters are: $m=4639\text{kg}$, $a=1.00\text{m}$, $b=0.97\text{m}$, $I_z=8428\text{kg}\cdot\text{m}^2$, $C_{af}=154.86\text{kN}\cdot\text{rad}^{-1}$, and $C_{ar}=150.45\text{kN}\cdot\text{rad}^{-1}$. The initial velocity is set to $v=10\text{m/h}$ and the factor of adhesion is $\mu=0.85$.

The simulation to the single lane change is performed for the PD control without system decoupling (PD control for short) and the decoupling PD control based on the neutral network reverse system

method (decoupling PD control for short), and the simulation results are compared with the expected values. The amplitude of the turning angle of rear wheels applied by the driver is set to 0.08rad and the frequency is set to 0.5Hz for the simulation; then the yaw velocity and slidslip angle response curves are obtained under the condition of single lane change, as shown in Figures 6 and 7.

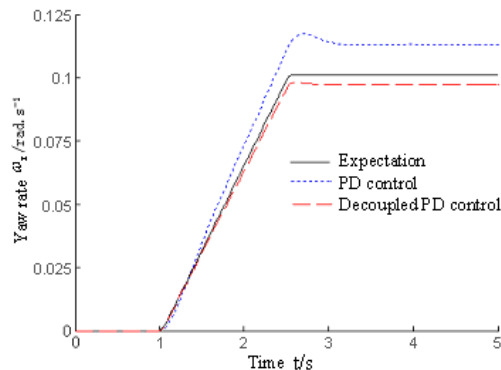


Figure 6. Yaw velocity response curve

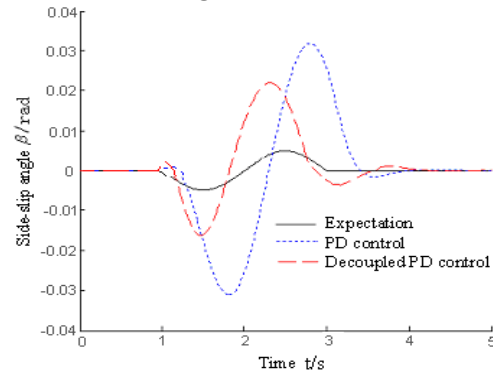


Figure 7. Slidslip angle response curve

According to Figures 6 and 7, compared with pure PD control, the yaw velocity under decoupling PD control can better follow up the expected values, the overshoot is small and the slidslip angle is controlled within a small range for stable driving.

Conclusion

This paper discusses the decoupling control on the ARS and the DYC of forklift trucks with the neutral network reverse system method, analyzes the reversibility of the integrated system of the chassis, and constructs a BP neutral network reverse system. Then a pseudo- linear system corresponding to the inputs and outputs of the original system is obtained by connecting the reverse system in series with the integrated system to realize the decoupling among control loops, thus effectively enhancing the state tracking and stability of forklift trucks and improving the steering stability of forklift trucks under extreme working conditions.

Acknowledgements

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