Modeling and co-simulation based on Adams and AMESim of pivot steering system

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Abstract: The pivotal steering ability of vehicles is important in the case of narrow steering space. In this study, a pivot steering system for the rescue vehicle is designed, and the 1D + 3D co-simulation model is established based on dynamic analysis of mechanical systems (Adams) and advanced modelling environment for performing simulation of engineering systems (AMESim). The dynamic analysis of the pivot steering system has been compared with the theoretical calculations, which proved the correctness of the model. In addition, through the simulation, the authors can hold the conclusion that the tyre cornering stiffness has a great influence on the pivot steering system.

1 Introduction

Steering system is essential for vehicles, and the steering radius is the important data in evaluating the steering performance of wheeled vehicles [1, 2]. There are a lot of steering modes applied in four-wheel vehicles in the last few years, such as Ackerman steering (including four-wheel steering and two-wheel steering) and articulated steering [3]. However, all of the steering radius of the modes mentioned above cannot be zero, which means that the space bigger than itself is needed once the steering is desired. In this context, a pivot steering system with four wheel independent steering mechanism is designed in this paper.

In some cases, the space is narrow for many vehicles to steer to perform a task, such as ambulance and other rescue vehicles, which will lose time and threaten to cause major disruption. To overcome the limitations of space due to the steering modes, a pivot steering system is required in this study. The pivot steering system of an individual wheel drive vehicle is an effective steering maneuver in the limited space. Meanwhile, the researches related on the pivot steering system are very much limited. Chi-Ung et al. studied the pivot steering control of an in-wheel drive vehicle with trailing arm [4]. The model Kim suited is an individual wheel motor drive, which is difficult to arrange. Xiaodong and Xiuhua proposed a small agricultural chassis of self-moving greenhouse based on linkage control mechanism, whose steering mechanism enables the chassis to turn in situ, making it more flexible when operating in a narrow space [5].

The rest of this paper is organised as follows: Section 2 presents a pivot steering system, and introduces detailed principle; Section 3 establishes the co-simulation model of the pivot steering system based on advanced modelling environment for performing simulation of engineering systems (AMESim) and automatic dynamic analysis of mechanical systems (ADAMS) software. Co-simulation method is used to evaluate the effectiveness of the validated steering model; Section 4 focuses on the analysis validation of the simulation data through mathematical derivation; Section 5 discusses the effects of tyre cornering stiffness on pivot steering system; and finally is the conclusion.

2 Fundamentals of pivot steering system

The steering system is a coupled closed-loop system composed of electro-hydraulic control system and steering mechanism parts, which are shown in Fig. 1. On one hand, the hydraulic section is a closed system, including hydraulic pump, proportional electromagnetic valve, swing hydraulic cylinder etc. On the other hand, the mechanical drive part is composed of gear cases, wheel rims and tyres etc.

The whole process of the pivot steering system is divided into two steps. Firstly, the four tyres rotate to a same degree, and the speed of the vehicle is 0 km/h at the moment. Then the whole vehicle rotates in place, and the speed of the vehicle is not 0 km/h until it turns the direction needed.

In order to achieve the zero steering radius, the position of instantaneous centre of rotation can only locate in the centre of the vehicle frame [6]. That means the pivot steering system has a certain steering angle with one frame of the vehicle. Due to a certain steering angle, the steering mode is conducted by a switch in the cab rather than the steering wheel for the other steering mode (such as front wheel steering, four-wheel steering). In this paper, we take a rescue vehicle as the example. The parameters of the rescue vehicle are listed in Table 1.

According to Table 1, the steering angle for the pivot steering system of the rescue vehicle can be obtained by means of computational geometry. As shown in Fig. 2, ‘O’ is the instantaneous centre of rotation, AB is the wheel-base, EF is the tread of the rescue vehicle, and \( \alpha \) is the steering angle of the vehicle.

Table 1 Parameters of the rescue vehicle

| No | Parameters | Value |
|----|------------|-------|
| 1  | tread      | 1868 mm|
| 2  | wheel-base | 3000 mm|
| 3  | tyre radius| 209.5 mm|
| 4  | vehicle weight | 7 t |
The hydraulic schematic of the pivot steering system is shown in Fig. 3. It can be seen that the four proportional electromagnetic valves are independently controlled in order to achieve the independent control of four-wheel steering angles. Once the pivot steering mode is activated through pressing the switch inside the cab, the electric signal will be sent to the proportional electromagnetic valve, after that, the valve is opened according to the corresponding current. Also then the hydraulic fluid will enter into the swing hydraulic cylinders arranged on the vehicle frame, thereby driving the steering of wheels through the gear cases attached to the cylinders.

3 Design and modelling

3.1 Mechanical model

Considering the weak modelling capability of Adams and the advantage of powerful modelling of Pro/Engineer, the three-dimensional modelling should be established in Pro/Engineer, firstly, the main part of which is shown in Fig. 4 [7]. Then the model is further simplified and imported into the Adams with the ‘.x_t’ format. Thirdly, the hard ground should be built in Adams. Finally, the constraints and parameters should be set accurately in Adams, as shown in Fig. 5. In order to consider fully the force between the tyres and the ground, the contact forces are added to the model. The parameters of the constraints and tyres are listed in Tables 2 and 3, respectively.

Heterogeneous components (such as engine, rear cowling and cab) can be equivalent to lumped mass block. As shown in Fig. 6, three mass blocks are built and assembled in the Adams to ensure the vehicle centre of gravity position and the total weight of the vehicle, which ensures the authenticity of the tyre load [8].

3.2 Hydraulic model

In AMESim, hydraulic modelling of the rescue vehicle is carried out, which is shown in Fig. 7.

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The system pressure is designed to 22 Mpa, and the flow rate of the pump is set to 4 L/min. In order to reach the angle in formula (1) in Section 2, the displacement of the swing hydraulic cylinders can be obtained according to the following formula [9]:

\[
\alpha = \alpha_{OAE} = \tan^{-1}\frac{OE}{AE} = \tan^{-1}\frac{3000}{1868} = 58.09°
\]

(1)

\[
\left(\frac{\Delta t}{360°} \times q\right)\text{ml} = \left(\frac{Q \times 10^3}{60}\text{ml/s}\right) \times \Delta t
\]

(2)

\[
q = \frac{4 \times 10^3}{60} \times \Delta t \times \frac{360°}{58.09°} = 413.15\Delta t
\]

\[
\Delta t \leq 2
\]

(3)

\[
q \leq 826.3
\]

(4)

where \(q\) is the displacement of the swing hydraulic cylinder; \(Q\) is the flow rate of the pump; \(\Delta t\) is the time to complete the pivot steering, as shown in formula (3). As a result, the displacements of the swing hydraulic cylinders are set to 800 ml/r. The model parameters in AMESim are set as shown in Table 4.

4 Co-simulation based on adams and AMESim

It is important to check that the proposed pivot steering system can realise precise steering performance. Before manufacturing an actual prototype, simulation is an effective means to research probable performance and investigate potential options, accelerating design and reducing cost [10]. A separate analysis of the coupled closed-loop system composed of electro-hydraulic control system and steering mechanism is inaccurate, so the co-simulation method is a better choice [11–13]. A co-simulation model for the system is built based on Adams and AMESim due to the advantages of Adams for mechanism dynamics and AMESim for hydraulic system simulation.

Since Adams and AMESim are separate software modules, an interactive interface should be used in co-simulation. AMESim provides a mode to realise co-simulation, as shown in Fig. 8. Also the final co-simulation model in AMESim is shown in Fig. 9.

Fig. 2 Schematic diagram of the pivot steering geometry

Fig. 3 Hydraulic schematic of the pivot steering system (1 – hydraulic pump; 2 – relief valve; 3 – proportional electromagnetic valve; 4 – hydraulic lock; 5 – left front swing hydraulic cylinder; 6 – left rear swing hydraulic cylinder; 7 – right front swing hydraulic cylinder; 8 – right rear swing hydraulic cylinder; 9 – hydraulic tank)

Fig. 4 Main mechanism part of the rescue vehicle pivot steering system

Fig. 5 Dynamic model of the rescue vehicle in ADSMS

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As a result of the certain steering angle of the four tyres, a switch instead of steering wheel is needed to turn on this mode. Also the input signal of the pivot steering mode is the step signal. Once the feedback signal of angle from tyres reached the valve set by controller, the flow area will close instantly.

| Table 2 Constraints relationships |
|-----------------------------------|
| No | Mechanism 1 | Mechanism 2 | Motion pair | Quantity | Remark |
|----|-------------|-------------|-------------|----------|--------|
| 1  | frame       | swing hydraulic cylinders | fixed       | 4        | every cylinder |
| 2  | swing hydraulic cylinder body | swing hydraulic cylinder rod | revolute | 4 | every cylinder |
| 3  | swing hydraulic cylinder body | gear cases | fixed | 4 | every gear cases |
| 4  | wheel rim   | gear cases | fixed | 4 | every wheel rim |
| 5  | tyre        | ground     | contact-force | 4 | every tyre |

Table 3 Parameters setting of tyres

| Name  | Mass, kg | Tyre cornering stiffness | Radius, mm | Tyre pressure, MPa |
|-------|----------|--------------------------|------------|-------------------|
| tire  | 38       | 56,800                   | 209.5      | 1.1               |

Fig. 6 Dynamic model with mass blocks in ADSMS

Fig. 7 Hydraulic modelling of the rescue vehicle pivot steering system

Table 4 Main parameters setting in AMESim

| No | Name                  | Parameters explanation                      |
|----|-----------------------|---------------------------------------------|
| 1  | pump                  | flow rate: 16 L/min, speed of pump: 1000 rev/min |
| 2  | motor                 | shaft speed: 1000 rev/min                   |
| 3  | relief valve          | cracking pressure: 22 Mpa                   |
| 4  | hydraulic lock        | cracking pressure: 3 bar, Flow rate: 4 L/min normal pressure drop: 0.5 bar |
| 5  | swing hydraulic cylinders | displacement: 800 ml/rev, angle stroke: 90° |
The whole simulation time is 8 s, and the simulation step size is 0.01 s.

5 Analysis validation of simulation results

The co-simulation is dominated in AMESim by controlling the opening of proportional electromagnetic valve to realise the corresponding angle of the swing hydraulic cylinder. The function of the switch of pivot steering mode is simulated by controlling the input signal of the proportional electromagnetic valve. The results of the co-simulation are shown in Figs. 10–14.

In Fig. 10, the control signal from the controller and the feedback signal from the tyre are displayed. The steering angles of four tyres are shown in Fig. 11, and the four tyres take 1.9 s finishing the same steering angle (2–3.9 s). The structure after steering is shown in Fig. 12.

The flow area of the proportional electromagnetic valves and swing hydraulic cylinders are shown in Figs. 13 and 14, respectively. It can be seen that the valve is opened to the maximum at about 2.15 s, and the flow area is proportional to the flow rate after 2.15 s. As a result, the speed control of independent rotation of four cylinders is realised.

In the process of co-simulation, the tyre cornering stiffness is set to 56,800 and 66,800 (see Fig. 15). It can be seen that the difference of this parameter of tyres has an impact on the steering resisting torque, ultimately, on the outlet pressure of the proportional electromagnetic valves.

6 Conclusion

(1) A pivot steering system for the rescue vehicle is designed, and the 1D + 3D co-simulation model is established based on Adams and AMESim.

(2) Comparing the simulation results and the theoretical calculation, the validity of the pivot steering system is demonstrated in this paper.
Combining the theory principle with simulation model, it is concluded that the tyre cornering stiffness has an impact on the steering torque.

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