Reliability Analysis of Synchronous Steering Control for Multi-vehicle Formation

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Abstract. The transportation of large engineering equipment or engineering modules usually adopts multi-vehicle formation cooperative transportation, and multiple vehicles form a fixed shape formation. In order to ensure the safety of transportation, the formation control must be reliable. Multi-vehicle formation can realize multiple steering modes. The reliability of coordinated control of synchronous steering hydraulic system group of multi-vehicle formation is studied. Firstly, the steering mechanism and steering hydraulic system of the transport vehicle are analyzed, and the reliability model and mathematical model of single steering hydraulic system are established. The reliability of a single steering system is calculated by MATLAB. On this basis, the reliability of the hydraulic system group of multiple steering units is analyzed and obtained. Based on the poor steering simultaneity of multi vehicle steering in the practical engineering, the fault tree model is established, and the weak links leading to the fault are analyzed. On this basis, the reliability measures to improve the coordinated control of multi vehicle formation steering hydraulic system group are put forward.

Keywords: multi-vehicle formation · combined transportation · hydraulic system group · coordinated steering

1 Background Introduction

The size and weight of super large engineering modules, equipment and goods are very large, such as large ship sections, large launch vehicles and large bridge structures. It is difficult for traditional railway and road vehicles to complete the transportation task [1]. Multiple large hydraulic vehicles can be used for combined transportation. Multi-vehicle collaborative transportation is easier to complete the work than using a single super large transport vehicle, and has the advantages of high efficiency and low cost [2]. Large hydraulic transport vehicle is a complex electro-hydraulic system. The combination of multiple vehicles will form a huge hydraulic system group [3]. Multi-vehicle combined transportation can realize straight, oblique and multiple steering modes through coordinated control. The coordinated control of the hydraulic system group is the key to safe and stable transportation [4].

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Multi-vehicle formation coordinated transportation has strong bearing capacity and flexible formation scheme, which has a very large application prospect in the large-scale engineering transportation. When the formation is driving, the distance and angle of all vehicles must be unchanged, that is, the formation shape must remain unchanged. When the formation needs to turn, all wheel sets need coordinated control. The turning radius and driving speed of each wheel set are different, and a certain relationship should be maintained. Therefor, in order to transport safety, the reliability of steering coordinated control must be improved.

Because the factors such as unbalanced load, unequal friction resistance, different leakage of hydraulic cylinder, compressibility of hydraulic oil and manufacturing error will affect the control accuracy, it is necessary to study the high-precision coordinated control [5].

2 Steering System Analysis

The steering mechanisms commonly used in large hydraulic vehicles mainly include rack and pinion type, worm and worm type, hydraulic cylinder connecting rod type, etc. [6]. In this paper, the hydraulic connecting rod steering mechanism used in the transport vehicle. The the hydraulic cylinder connecting rod steering mechanism is shown in Fig. 1. The rotary support is mainly driven by the hydraulic cylinder to realize the rotation of the wheel set. The advantages of hydraulic cylinder connecting rod steering mechanism are simple and reliable structure, low cost, and high steering accuracy can be achieved through electro-hydraulic closed-loop control. The disadvantage is that the size of the mechanism is large and the range of steering angle is limited, which is not suitable for small tonnage vehicle.

One transport vehicle has four steering wheel sets. The load sensitive variable pump and proportional valve are used in the steering hydraulic system to control the hydraulic cylinder. The hydraulic cylinder drives the wheel set steering. The hydraulic system is shown in Fig. 2. The steering system can meet the steering mode of the transport

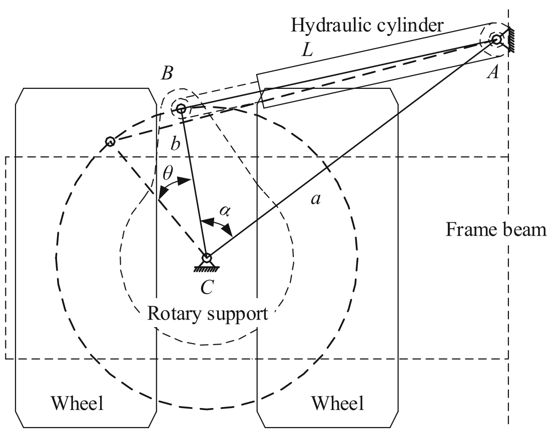

Fig. 1. Hydraulic cylinder connecting rod steering mechanism.

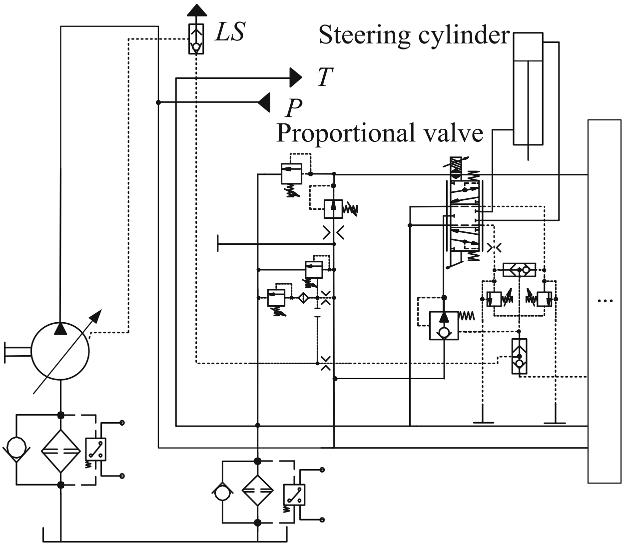

Fig. 2. Steering hydraulic system.

vehicle, and the steering angle can be accurate through control according to the feedback comparison of the actual angle.

3 Steering Control

The research object of this paper is a four-vehicle formation, which has 16 steering hydraulic cylinders, that is, the 16 wheel sets that can realize independent steering. Theoretically, the coordinated control of these hydraulic cylinders can make the formation realize straight, oblique and multiple steering modes. However, due to manufacturing errors and leaks, the desired steering angle and steering simultaneity of the wheel set may deviate. When the situation is serious, if the formation continues to drive, the frame mechanism may be damaged or even a major overturning accident may occur. Therefore, the reliability and coordinated control of steering system must be analyzed.

In the actual formation transportation, oblique walking is a common mode, that is, all vehicles in the formation turn at the same angle before driving. As shown in Fig. 3, the steering angle of all vehicles in the formation is the same. When the multi vehicle formation moves obliquely, each wheel set has a sensor, which can measure the actual steering angle of the wheel set, and make the actual steering angle approach the theoretical steering angle through the closed-loop control system.

However, according to the actual application of this steering control, it is found that this control method has shortcomings, which is due to the influence of external factors such as road parameters, mechanical friction resistance and load offset. The speed consistency of steering hydraulic cylinder is poor, and even with the same control signal, the steering synchronization of wheel set is also poor.

Therefore, according to the fuzzy PID control principle and the motion characteristics of multi vehicle formation steering, fuzzy PID control can be used to improve the

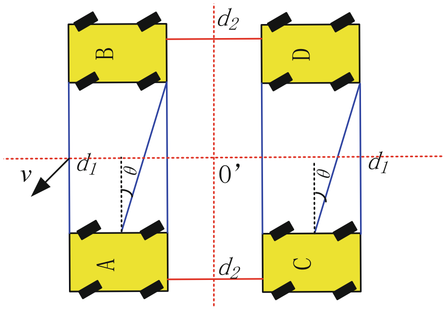

Fig. 3. Formation running obliquely.

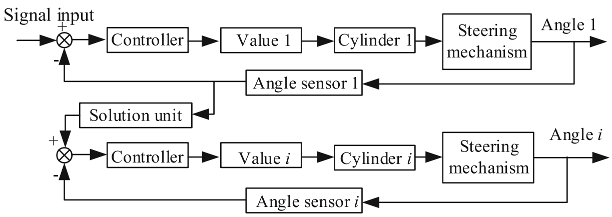

Fig. 4. Diagram of steering hydraulic system.

simultaneity and stability of multiple wheel sets steering control [7]. The principle of the control scheme is shown in Fig. 4. The function of the solution unit is to calculate the steering angle 2 according to the steering mode mathematical model and the steering angle 1. If it is synchronous steering, the two angles are the same.

When the multi-vehicle formation moves obliquely, the control of the whole formation needs to connect the CAN steering control module of each vehicle to realize the data transmission between vehicles. For the steering of the formation, all wheel groups need to achieve the same steering angle at the same time, otherwise the formation cannot drive normally.

4 Reliability Model

4.1 Reliability Measurement Index

Reliability is a very key index to measure the reliability of the system. It is defined as the probability that the product will complete the specified function under the specified conditions and within the specified time [8]. If there are N elements in the system, after time t, $n(t)$ of the elements fail. Reliability can expressed as follows.

$$R(t) \approx \frac{N - n(t)}{N} \tag{1}$$

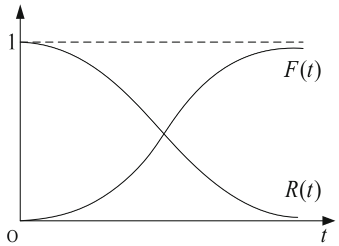

Fig. 5. Relationship of unreliability and reliability.

Unreliability, that is, when a product fails, is also known as the life distribution function. Unreliability is an indicator completely opposite to reliability, and it can expressed as follows.

$$F(t) = 1 - R(t) \tag{2}$$

The curve of the relationship between unreliability and reliability is shown in Fig. 5.

Fault density function is the probability of product fault at a certain time, also known as fault density function, is also a parameter that changes with time, it is obtained as follows.

$$f(t) = \frac{dF(t)}{dt} \tag{3}$$

The relationship between the above three indexes is as follows.

$$R(t) = 1 - F(t) = \int_t^{\infty} f(t)\mathrm{d}t \tag{4}$$

Fault rate, also known as fault efficiency, refers to the probability of fault of a product in the next time period Δt after a period of normal working time t. It is a conditional probability density function, and its mathematical expression can be described by the limit method.

$$\lambda(t) = \lim_{N\to\infty} \frac{n(t + \Delta t) - n(t)}{[N - n(t)]\Delta t} = \frac{f(t)}{R(t)} \tag{5}$$

The definition of average life is the average value of working time before product fault, that is, mean time between faults (MTTF).

$$MTTF = \frac{1}{N}\sum_{i=1}^{N} t_i \tag{6}$$

4.2 Steering System Reliability Model

The first step in the reliability analysis of hydraulic system is to establish the reliability model. Generally, when studying and analyzing the reliability of construction machinery, the main reliability models are series system model and parallel system model [9].

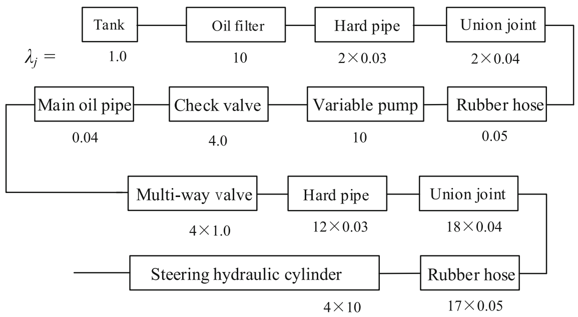

Fig. 6. Reliability block diagram of steering hydraulic system.

According to the working principle of the steering hydraulic system schematic diagram of the hydraulic vehicle, the structure of the steering system is a series structure because the components are connected in series. The reliability block diagram of the steering system is shown in Fig. 6. The number below the square is the reliability (10^{-6}/hour) of the corresponding element. Because one vehicle has four steering wheel sets, and which are connected in parallel, the reliability of steering hydraulic cylinder and proportional multi-way directional valve is four times.

The fault rate of one vehicle steering system is as follows.

$$\lambda_i = \pi_E \pi_D \pi_R \sum_{j=1}^{n} \lambda_j = \pi_E \pi_D \pi_R \left(\lambda_1 + \lambda_2 + \cdots + \lambda_j\right) \tag{7}$$

where λ_i is the fault rate of one vehicle steering system, π_E is the environmental factor, π_D is the derating factor, π_R is the correction factor, λ_j is the fault rate of hydraulic component j.

The reliability of the single vehicle steering system can be obtained as follows.

$$R_i(t) = e^{-\lambda_i t} = e^{-\pi_E \pi_D \pi_R \sum_{j=1}^{n} \lambda_j t} \tag{8}$$

The transport vehicle belongs to the ground equipment, so in this case π_E is set to 10, and π_D is set to 0.85. The high precision filter is used in steering hydraulic system, so the correction factor π_R is set to 0.935. According to the reliability block diagram of the steering system and Eq. (8), the reliability simulation of the steering hydraulic system of the engineering vehicle is carried out by using the software MATLAB, and the reliability curve of steering hydraulic system is obtained, as shown in Fig. 7.

It can be seen that the reliability of hydraulic steering system is relatively low. That is mainly caused by the large number of components connected in series in the system. The best way to improve the reliability of hydraulic system is to adopt the method of reliability simplified design to reduce the weak links of the system.

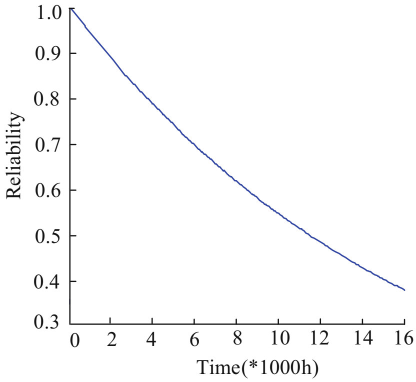

Fig. 7. Reliability of the vehicle steering hydraulic system.

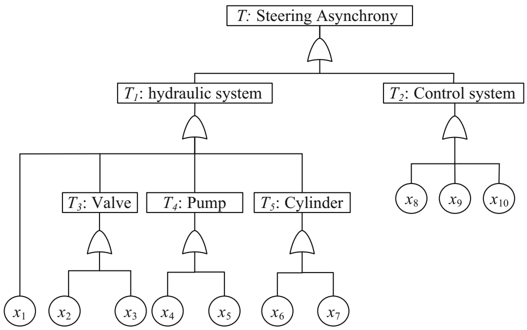

Fig. 8. Fault Tree of the formation steering.

5 Fault Tree Model and Analysis

The whole formation steering group contains four hydraulic steering system, in case of any system fault, the steering cannot be completed. In the hydraulic system, the fault often occurs, and it is difficult to predict when the fault occurs. Therefore, if you want to analyze the component fault tree, you must first set the fault type of the component. The fault tree of the formation steering asynchrony can be established as shown in Fig. 8.

There are only logic OR gates in the fault tree, the top event is T, the next fault number events are T_1, T_2, T_3, T_4, T_5, according to the Boolean algebra representation of the OR gate, Eq. (9) can be obtained as follows by the Boolean algebra. It means that the top event will occur if any bottom event fails, the bottom events' name is shown in Table 1.

$$T = x_1 + x_2 + \cdots + x_{10} \tag{9}$$

Each bottom event is a minimum cut set of the top event, so the fault of each bottom event has a great impact on the top event. To improve the reliability of steering control, we need to improve the reliability of each bottom event as much as possible. According to the reliability theorem, the structural importance of each event is $1/2^{10}$.

Table 1. The event name of the fault tree.

No.	Event Name
T	Steering asynchrony
T_1	Hydraulic system fault
T_2	Control system fault
T_3	Hydraulic valve fault
T_4	Hydraulic pump fault
T_5	Steering hydraulic cylinder fault
x_1	Hydraulic pipeline leakage
x_2	Valve core stuck
x_3	Electromagnet fault
x_4	Hydraulic pump serious internal leakage
x_5	Pump variable mechanism fault
x_6	Hydraulic cylinder serious stuck
x_7	Hydraulic cylinder serious internal leakage
x_8	Sensor fault
x_9	Feedback loss
x_{10}	CAN bus fault

After the fault tree analysis of the formation steering asynchrony, Quantitative analysis should be carried out on the steering control system according to the minimum cut set. The lethal degree of the j fault mode of the i component in the steering hydraulic system is as follows.

$$C_{ij} = \alpha_{ij}\beta_{ij}\lambda_i \mathrm{t} \tag{10}$$

where C_{ij} is the lethal degree, a_{ij} is the frequency ratio, correction factor, β_{ij} is the Fault impact factor, λ_i is the fault rate of hydraulic components.

According to the fault mode and fault rate of the components, combined with relevant data and specific working conditions, the parameters such as and are effectively estimated, and the working time is set to 2000 h, the lethal degree of each component to the hydraulic system is obtained as shown in Table 2.

Therefor, the staff can well grasp the fault state and fault mode of the whole system, avoid these faults as much as possible in the design, reduce and increase the reliability of the system in terms of manufacturing and maintenance, reduce the occurrence of faults, and focus on monitoring the faults with high lethal degree.

Table 2. Quantitative analysis data of the fault tree.

No.	$\lambda_i(\times 10^{-6}/\text{h})$	a_{ij}	β_{ij}	$C_{ij}(\times 10^{-6})$
x_1	0.20	1.00	1.00	40000
x_2	5.06	0.25	0.10	253
x_3	7.10	0.75	0.10	1065
x_4	5.00	0.75	0.20	1500
x_5	8.00	0.25	1.00	4000
x_6	0.10	0.20	1.00	40
x_7	5.00	0.80	1.00	8000
x_8	0.10	0.30	1.00	60
x_9	2.00	0.30	1.00	1200
x_{10}	0.20	0.40	1.00	160

6 Conclusion

The reliability of steering synchronization control in multi-vehicle formation is studied. The reliability analysis and calculation of the steering hydraulic system of the transport vehicle are carried out, and finally the reliability curve of the steering hydraulic system is obtained. The reliability of steering hydraulic system in the transportation can be observed from the reliability curve. And the fault tree of the formation steering asynchrony, From the fault tree, the weak links of the steering hydraulic system and control system of the combined transportation are obtained. At the same time, the lethal degree of the bottom event are obtained. The reliability should be improved from the bottom event with high probability importance. These results can provide reference for the steering system maintenance, design and manufacture.

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Authors' Contributions. Jingyi Zhao proposed the research method. The model establishment and calculation were performed by Wenlei Li and Rui Guo, and the manuscript was written by Jianjun Wang.

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