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Research Article

Innovative Design of Compact Heavy-Load Independent Transfer Device for Nuclear Engineering System

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The transportation of heavy equipment in nuclear engineering has always been the focus of engineers, especially those transfer devices with the characteristics of small geometric size and heavy load. According to this kind of compact heavy-load transfer device and its engineering tasks, the core problems caused by excessive vertical and horizontal forces in the design process were analyzed. By introducing the theory of inventive problem solving (TRIZ) design method, these problems were creatively solved by the contradiction theory and substance-field model in TRIZ, and an innovative design scheme of the compact heavy load-independent transfer device was obtained. Through the analysis of the design scheme and the stability and rapidity of its hydraulic system, some key parameters were determined. The power of the transfer device was all from the hydraulic system, and it can carry up to 300 t weight of reactor equipment, while its geometric size was only 1600 × 400 × 500 mm. It was of great significance to improve the efficiency of the nuclear engineering system.

1. Introduction

Traditionally, when heavy equipment such as reactor pressure vessel, steam generator, or pressurizer enters the nuclear island plant, it first needs to be lifted by a special transfer device, and then pulled to the designated position by the towing mechanism in front of the device [1]. Such devices are usually similar to flatcar with rails [2]. Its width size cannot be changed, so the same large operation space is required for the different types of heavy equipment. Moreover, the devices cannot run independently and need many construction personnel of auxiliary operation in the transportation process. These factors lead to large site conditions and labor cost investment. In recent years, in the construction of some third-generation nuclear power plants, such as AP1000, the heavy equipment placed outside can be lifted from the top of the reactor building to the installation position by a large crane before the reactor building is capped (This is called the open-top construction method) [3]. The method has strict requirements on weather and wind speed due to the safety of lifting operations, so the time cost and potential risk are uncontrollable [4]. Since the additional time cost is unacceptable to any nuclear power plant, the ground transportation mode of reactor heavy equipment is more valuable from the perspective of avoiding project delay, but the transfer device needs to be further improved.

In order to improve the efficiency of reactor construction and adapt to the narrow operation space of new compact reactor construction in the future, the transfer device has to be developed in the direction of miniaturization, heavy load, and automation.

In some pieces of literature, engineering researchers have developed transfer devices according to the development trend. For example, Wan et al. [5] designed a device for transporting electron guns, which was characterized by gear guide tracks, strong electrical motor, and power loss protection in a radiation environment. Although the design is novel, it cannot yet complete the heavy-duty work. Usually, the wheeled hydraulic flatbed trucks can bear heavyweight, but it is mainly used for offsite transportation of nuclear engineering equipment because of their large body.

Therefore, rail vehicles are a commonly used method of heavy-load transportation. Ding et al. [6] realized the transportation of containment vessel assembly through multiple rail vehicles, but the horizontal driving force of each vehicle needs to be provided by external traction, which puts forward higher requirements on the process. In some patents [2, 7] or related products [8], it is rare to take into account the transfer device with a small geometric size and heavy load at the same time. Heavy-load transfer devices in nuclear engineering involve consideration of various factors such as hydraulic system [9], control [10], and component fatigue [11]. The coupling of these factors forms various design problems in the development of transfer devices.

To innovatively solve these design problems, some scholars have introduced innovative design methods and ideas into the field of nuclear engineering design [12, 13]. The theory of inventive problem solving (TRIZ) is a set of theoretical and methodological systems proposed by the famous inventor Altshuller and his team after analyzing nearly 2.5 million high-level patents around the world and integrating principles from multiple disciplines [14]. After dozens of years of development, TRIZ has formed a matured theoretical system for solving product design problems. The steps of solving the TRIZ problem are shown in Figure 1. Designers abstract a specific nonroutine engineering problem into a generic problem, including contradictory problems and substance-field problems. According to the mapping rules in TRIZ, they find some abstract conceptual solutions, such as invention principles and standard solutions. Finally, combined with engineering experience, they analogize conceptual solutions to specific creative solutions. TRIZ stimulates designers to think about various possibilities of solving problems from different directions, and provides conceptual knowledge and method tools for designers to discover and solve problems in the process of creative design [15].

To address the design difficulties caused by the complex and narrow working conditions, this paper uses TRIZ to help solve the key problems in the design of the heavy load transfer device. The process demonstrates TRIZ's ability to improve work efficiency and design creativity, and at the same time, an innovative transfer device scheme is achieved.

2. Design Task and Conceptual Scheme

2.1. Description of Design Task. The function of the transfer system is to transport hundreds of tons of reactor equipment to the designated location inside the nuclear power plant. Due to the limitation of some narrow transportation operation space, the transfer system must be miniaturized and compacted. In this narrow heavy-duty transportation situation, in engineering, the double guide rails are usually used as the uniform stress structure and guide the path of the transfer system, and two or more (generally even) transfer devices can be arranged on the guide rail, which works synchronously to complete the transportation task.

The design task is to develop these transfer devices. According to the reactor equipment weight and space layout, the main design parameters of a single device (mainly designed for a single device in this paper) include: (1) the rated load is 300 t; (2) the lifting distance of equipment is 50 mm; (3) the overall dimension is less than 420×500 mm (width × height), the length should not be too long; and (4) the traveling speed is greater than 0.2 m/min. Others are related to motion accuracy, reliability, power loss protection measures, as well as control parameters when multiple devices work synchronously.

2.2. Description of Conceptual Scheme. According to the above task description, the basic functions of the transfer device include horizontal transportation function, lifting function, regulating balance function, locating function, power failure locking function, and working synchronization. As pointed out in *engineering design: a systematic approach* [16], when analyzing functions, designers will use "temporary work structure or solution" to establish the functional structure of products. Therefore, under such a large load condition, the hydraulic system will first be selected as the mechanical structure of lifting and regulating balance function. The horizontal transportation function can be realized by electrical motor driving. Range sensors, such as laser sensors and travel switches, can realize locating. In the hydraulic system, a protection mechanism is set to ensure that the device remains in a normal lifting state after power failure. The servo system is used to support synchronous working.

At the same time, the device also needs to have the function to meet the constraint requirements, including high strength and small deformation (met through high-quality material and structural design), miniaturization (met by the compact arrangement of components), and reliability (enough safety margin shall be reserved in mechanical calculation and hydraulic system design).

According to the functional analysis, the conceptual scheme of the transfer device can be roughly described, as shown in Figure 2.

3. Problem Analysis

3.1. Problem Comes from Vertical Stress Condition. If the weight of 300 t is applied to two pairs of wheels, the radial force of the selected bearing will reach 750 kN (g value is 10 N/m^2). Considering the overall dimensions of the device, a suitable bearing cannot be found. Therefore, in order to distribute the force, a very simple method is to use multiple pairs of wheels. For example, six pairs of wheels can be designed with two bearings for each wheel, and the radial force of a single bearing is 125 kN, which will enable the selection of standard bearings that meet the dimensional requirements. However, when multiple groups of wheels walk on the same rails at the same time, due to synchronization and assembly errors, it is very easy to cause uneven force on the wheels, affect the service life of the wheels and their transmission components, and even cause structural damage. This is a contradictory problem, which is hereinafter referred to as the load problem.

3.2. Problem Comes from Horizontal Stress Condition. The force required to overcome friction during horizontal transportation of the device can usually be considered to be

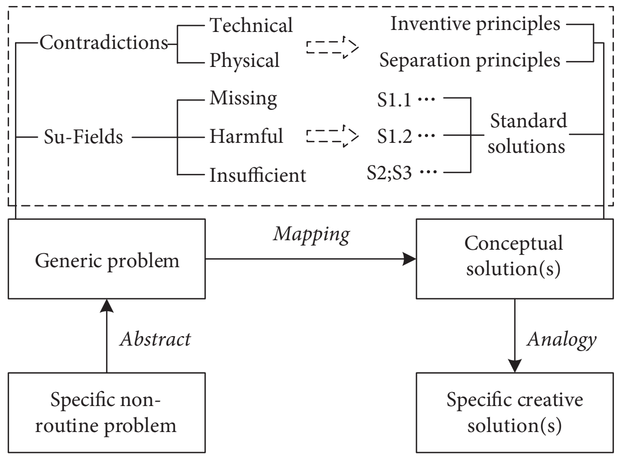


Figure 1: TRIZ problem-solving methods.

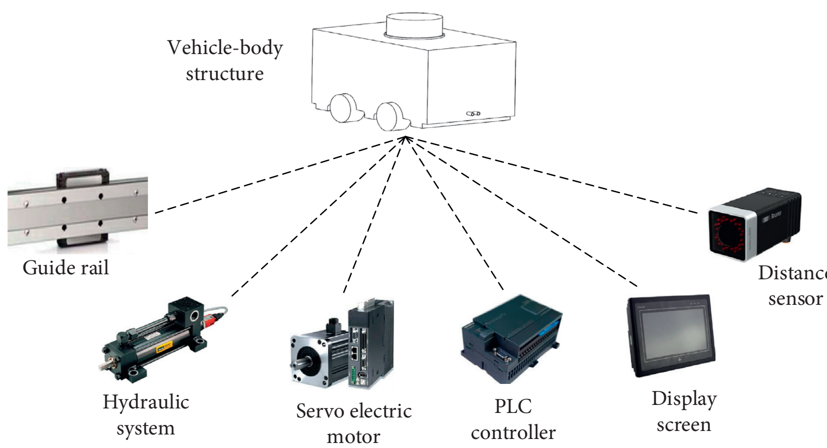


Figure 2: The conceptual scheme of the transfer device.

provided by the electrical motor. The wheel and guide rail of the device is made of steel, and the rolling friction coefficient between them is estimated to be 0.05. Assuming that the wheel diameter of the device is 80 mm, the servo electrical motor (servo system is selected to maintain synchronization accuracy while excluding the hydraulic motor whose transmission ratio cannot be strictly controlled) needs to provide 6000 Nm torque to overcome the friction caused by 300 t weight. In order to provide enough torque, the usual way is to use the reducer to amplify the output torque of the servo electrical motor. However, within the interface range of 420×500 mm, it is still difficult to meet the torque demand by the torque magnification from the reducer. This problem is called the torque problem.

4. Problem-Solving Based on TRIZ

4.1. Solving Load Problem. The point of contradiction of the load problem is that the number of pairs of wheels should be as more as possible and while as few as possible. This is the same technical parameter with mutually exclusive requirements. Therefore, it can be attributed to the physical contradiction of TRIZ. According to the four separation principles under the TRIZ analysis framework, the load problem can be described based on the condition separation principle.

4.1.1. First Step. Define physical contradiction. Parameter: number of wheels; Requirement 1: more; Requirement 2: less.

4.1.2. Second Step. What conditions need to be met. Condition 1: the number of wheels is more under the condition of small bearing force; Condition 2: the number of wheels is less under the condition of reducing errors and uneven force.

4.1.3. Third Step. Whether the above two conditions intersect. No: condition separation can be applied; Yes: try other separation methods.

Since the two conditions do not intersect, it can use the condition separation method. According to the corresponding relationship between TRIZ physical contradiction and invention principle, the invention principle corresponding to the potential solution of condition separation principle is shown in Table 1.

Scheme one: according to the No. 1 *segmentation principle* "divide an object into independent parts," the scheme uses multiple pairs of wheels, and not each pair of wheels is used as the torque output end but adopts the arrangement structure of the driving wheel and driven wheel. There is only one pair of driving wheels on the guide rail, and the rest are driven wheels, as shown in Figure 3. Therefore, as long as the vertical force points of the device are reasonably arranged to ensure that the load is evenly distributed to each pair of wheels, the structural damage caused by wheel transmission can be avoided.

Scheme two: according to the No. 5 *merging principl*e "merge identical or similar objects to perform parallel operations," the main idea is to ensure the synchronization of multiple pairs of wheels from the mechanical structure. Instead of providing torque to a single pair of wheels, the torque output by the motor is evenly transmitted to each pair of wheels through the same drive shaft by the transmission mechanism, that is, multiwheels driving, as shown in Figure 4. The structure can improve the force uniformity of the wheels.

Compared with scheme one, the transmission system in scheme two is longer, resulting in the disadvantages of complex structure, high manufacturing cost, and low transmission efficiency of multiwheel driving. Therefore, scheme one is considered a better solution.

4.2. Solving Torque Problem. The key of the torque problem can be described as the deficiency of output torque in finite space. The problem is analyzed by TRIZ substance-field model and expressed structurally under the guidance of TRIZ.

4.2.1. First Step. Relevant elements should be identified. According to the characteristics of horizontal motion, the device needs to output torque. Related elements are S1 electrical motor, S2 wheels, and F mechanical field (torque force).

4.2.2. Second Step. A substance-field model should be established. This problem belongs to the third type model, which is an insufficient complete model. The corresponding model is shown in Figure 5.

4.2.3. Third Step. The general solution of the substance-field model should be selected. There are many standard solutions for insufficient complete models, as shown in Table 2.

According to the standard solution provided in Table 2, the model needs to be transformed into a complex substance-field model empirically. Through the idea of S2.1.1 Chain Su-field, S2 is transformed into an independent control complete model. As described in Section 3.2, the reducer is added to amplify the output torque of the motor, but the desired torque is still not obtained on this occasion. Considering that the hydraulic cylinder has the characteristics of small volume and large step-less speed regulation range, the reducer is replaced by a hydraulic cylinder. However, the hydraulic cylinder can only move in a straight line, and the obtained substance-field model is still not sufficient, as shown in Figure 6.

The torque provided by linear motion in the hydraulic cylinder is related to the length of its piston rod, so the torque cannot be output continuously. The key to whether the non-sufficient model in Figure 6 can become a sufficient model is to solve the problem of resetting the piston rod of the hydraulic cylinder, that is, to change the relative position of the piston rod relative to the wheel transmission shaft. According to S2.1.2 Double Su-field, add another controllable field to form a dual-field model to solve the problem, as shown in Figure 7. The field *F*3 realizes that the piston rod is separated from the transmission shaft, then the piston rod is reset, and then the piston rod meshes with the transmission shaft again. After meshing, the hydraulic cylinder will continue to output torque. This is a step-by-step walk. Therefore, it is necessary to design a reciprocating mechanism to realize the separation and meshing between the piston rod and the transmission shaft. At this time, because it does not need a lot of force, the general electrical motor or hydraulic cylinder can drive such a mechanism to realize this function.

Considering that the lifting function and torque output function of the transfer device adopts the hydraulic system, the actuator of the reciprocating mechanism still selects the hydraulic cylinder to make full use of the existing oil circuit. Figure 8 shows in detail the structure diagram of the horizontal movement of the hydraulic drive system, which is characterized in that the force output by the horizontal hydraulic cylinder is transmitted to the gear through the rack so as to drive the horizontal movement of the transfer device. After each step movement of the horizontal hydraulic cylinder, the hoisting hydraulic cylinders hoist the horizontal hydraulic cylinder, then complete the action of separation-reset-meshing according to the logical relationship to realize the step-by-step walk. The displacement sensor realizes the detection and displacement feedback of walking.

5. Design Scheme Analysis

5.1. Key Parameters and Control Logic

5.1.1. Key Parameters of Vertical Hydraulic Cylinder. According to the characteristics of the oil source device, pipeline, and servo electrical motor, the standard working pressure of the hydraulic system is 21 MPa. According to the load of 300 t, it can be calculated that the piston rod diameter of the hydraulic cylinder needs to be greater than 426 mm (excluding the cylinder size). This completely does not meet the width (420 mm) requirement in the task description. Through calculation, three vertical hydraulic cylinders with a piston rod diameter of 250 mm can be arranged in the rail direction for a single transfer device, and each vertical hydraulic cylinder can uniformly load the weight of 100 t so as to meet the total load requirements.

Table 1: Correspondence between condition separation principle and invention principle.

	Inventive principles
Separation upon condition	1-segmentation; 5-merging; 6-universality; 7-nested structures; 8-anti-weight; 13-reverse; 14-curved; 22-convert harm into benefit; 23-feedback; 25-self-service; 27-inexpensive short-lived objects; 33-homogeneity; and 35-parameters and properties changes

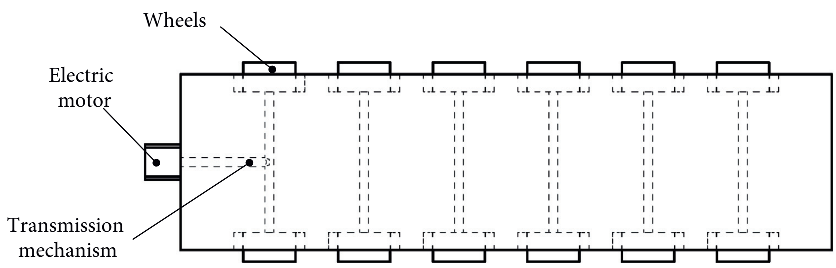


Figure 3: The layout diagram of driving and driven wheels.

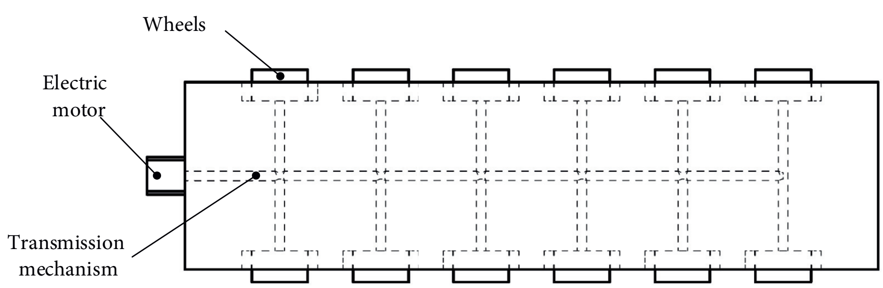


Figure 4: The layout diagram of multiwheels driving.

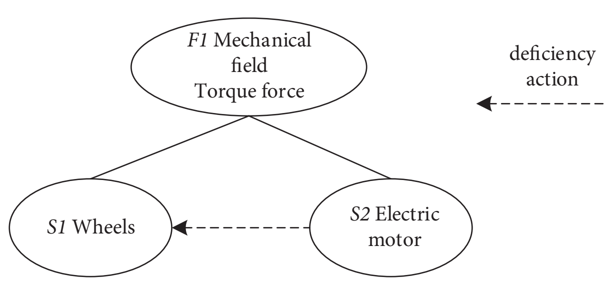


Figure 5: The substance-field model of the torque problem.

Table 2: Standard solutions for insufficient complete model.

	Classifications	Standard solutions
Insufficient complete model	S2.1 Transition to complex Su-fields S2.2 Forcing of Su-fields …… S3.1 Transition to bi-systems and polysystems ……	S2.1.1 Chain Su-field S2.1.2 Double Su-field S2.2.1 Increasing of field’s controllability ……

5.1.2. Key Parameters of Horizontal Hydraulic Cylinder. The rolling friction coefficient between the wheels of the transfer device and guide rails is 0.05, and the working pressure of the hydraulic system is 21 MPa. Similarly, it can be calculated that the diameter of the piston rod of the horizontal hydraulic cylinder needs to be greater than 95.4 mm to meet the driving force requirements of the load of 300 t.

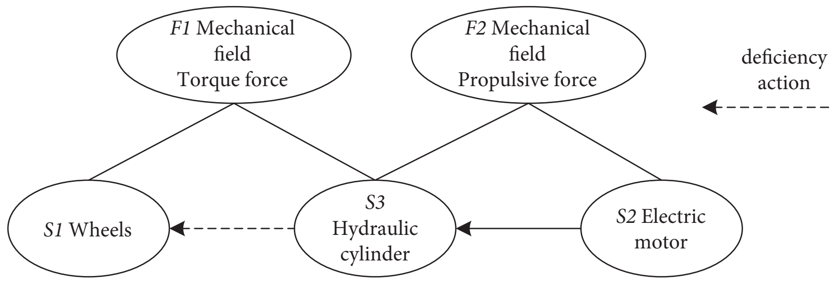


Figure 6: The substance-field model including hydraulic cylinder.

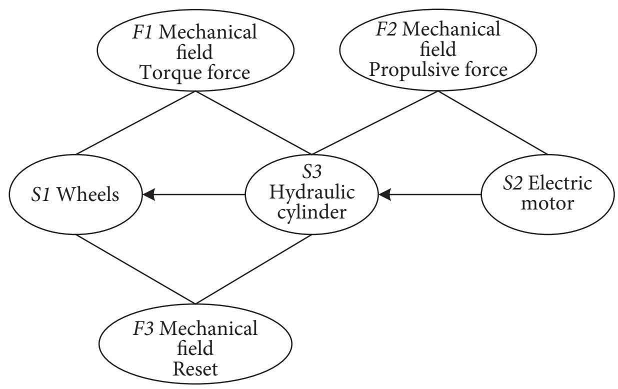


Figure 7: The substance-field model of hydraulic driving.

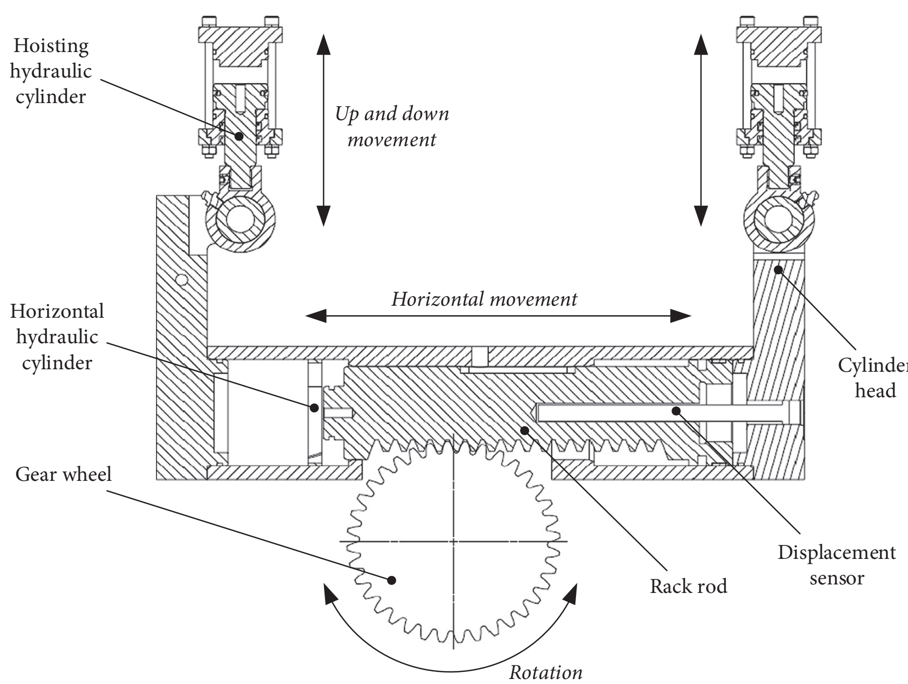
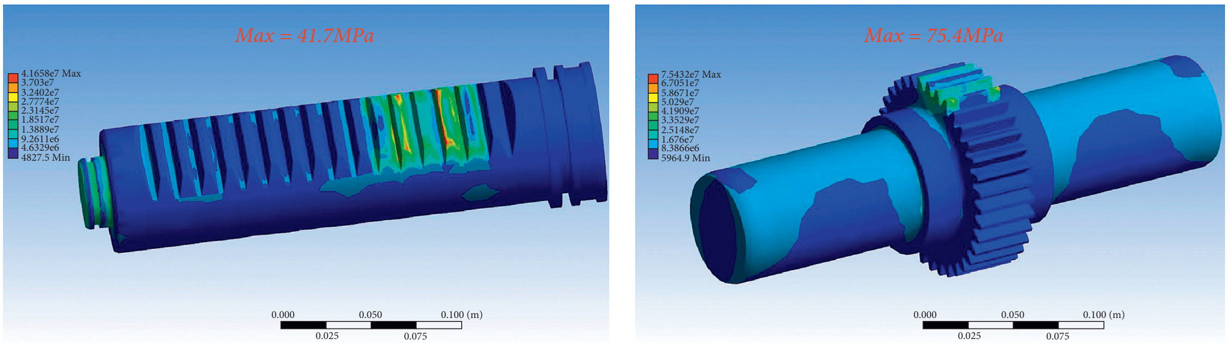


Figure 8: The structure diagram of horizontal movement mechanism.

5.1.3. Key Mechanical Strength Analysis. The stress conditions of key components in the structure of the transfer device are the bending stress on the shaft where the gear is located and the comprehensive stress on the teeth of the rack rod and gear wheel. According to the load and mechanical formula [17], each shaft ($\Phi 80 \times 400$ mm) is subjected to bending stress of approximately 331.7 MPa. Therefore, the material of the shaft can be ASTM 4135 (the yield strength is 835 MPa). According to the selected material ASTM 4135 and the horizontal friction force, the Mises stress



(a) (b)

FIGURE 9: The Mises stress distribution on the teeth of the rack rod and gear wheel. (a) The rack rod in the piston. (b) The gear wheel in the shaft.

distribution on the teeth of the rack rod and gear wheel can be calculated by ANSYS Workbench finite element simulation, as shown in Figure 9.

At the same time, the lifting distance of the vertical hydraulic cylinder is only 50 mm, and its piston diameter is 250 mm. The length/diameter ratio is small, so buckling will not occur.

Based on the above analysis of the key parameters, an innovative design of a compact heavy load-independent transfer device is completed, as shown in Figure 10. The overall dimension of the scheme is about $1600 \times 400 \times 500$ mm (length × width × height) to meet the requirements of a narrow workspace.

5.1.4. Control Logic of Hydraulic System. The power for horizontal transportation, lifting, and regulating the balance of the transfer device comes from the same set of hydraulic system. The executive ends of horizontal, vertical, and hoisting hydraulic cylinders can act independently but are limited by the control and protection of corresponding sensors. When the process path parameters are set, the transfer device can execute an automatic mode of the complete transfer process, as shown in Figure 11.

5.2. Stability and Rapidity Characteristics of Hydraulic Control System. According to reference [18], the open-loop transfer function mathematical model of the servo-hydraulic control system adopted in this design scheme is as follows:

$$W_k(s) = \frac{K_v}{S\left(\left(1/\omega_h^2\right)S^2 + \left(2\zeta_h/\omega_h\right)S + 1\right)}, \quad (1)$$

where ω_h is the natural frequency, $\omega_h = A_1[2\beta_e(1+\lambda^3)/mV]^{1/2}$. ζ_h is the damping ratio, $\zeta_h = C[2\beta_e(1+\lambda^3)/mV]^{1/2}/2A + B_p[V/2\beta_e m(1+\lambda^3)]^{1/2}$. ζ_h will change greatly with the change of working conditions, which is difficult to determine accurately. The calculated value is very different from the actual value. The measured value is generally 0.2~0.7, which is taken here as $\zeta_h = 0.2$. K_v is the gain of the open-loop transfer function, $K_v = K_{sv}D_pK_f/A_1$. A_1 is the area of the rodless cavity of the hydraulic cylinder. A_2 is the area of the rod cavity of the hydraulic cylinder. λ is the area ratio, $\lambda = A_2/A_1$. β_e is the oil elastic modulus. m is the piston weight. V is the total compressed volume of hydraulic cylinder. C is the pressure coefficient. B_p is the viscous damping coefficient. K_{sv} is the gain of hydraulic system control. K_f is the gain of displacement sensor. D_p is the pump delivery.

Relevant parameters of the hydraulic system (the vertical hydraulic cylinder as an example) are shown in Table 3.

By calculation, $\omega_h = 170$, the open-loop transfer function of the hydraulic system is

$$W_k(s) = \frac{K_v}{S\left(\left(1/\omega_h^2\right)S^2 + \left(2\zeta_h/\omega_h\right)S + 1\right)} = \frac{K_v}{S\left(\left(1/170^2\right)S^2 + (2 \times 0.2/170)S + 1\right)}. \quad (2)$$

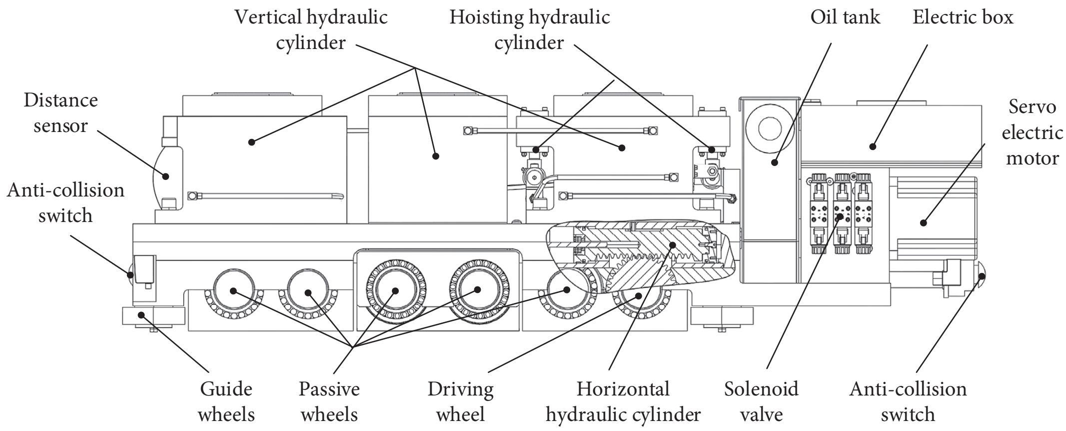


FIGURE 10: The design scheme of the transfer device.

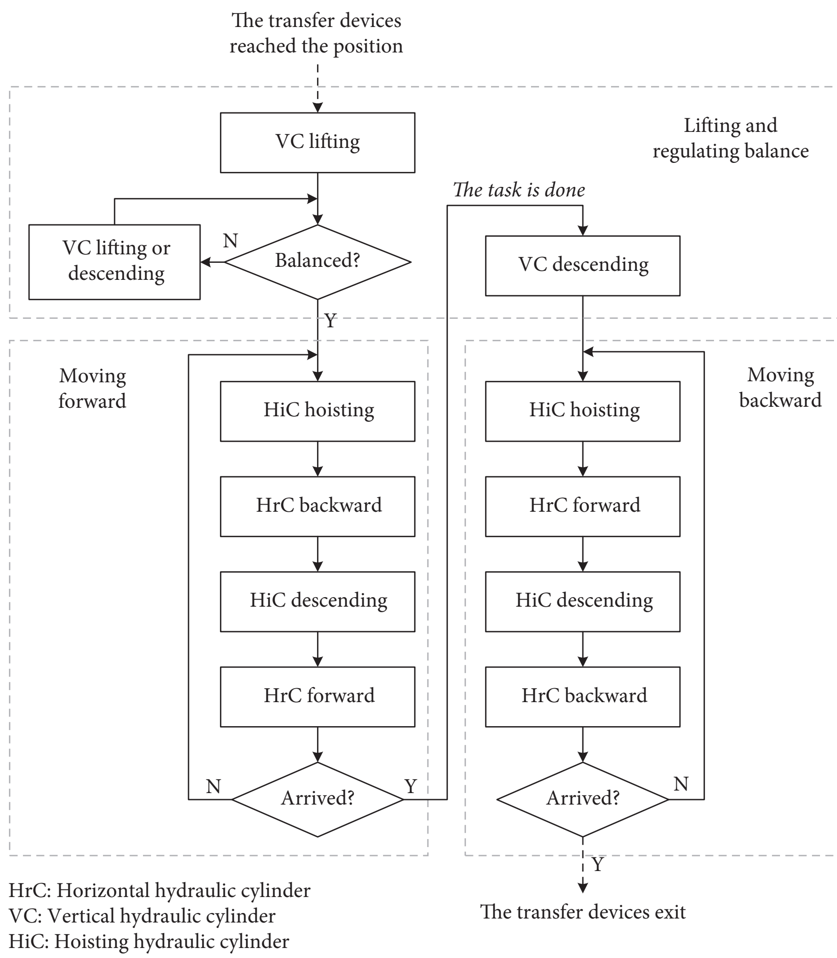
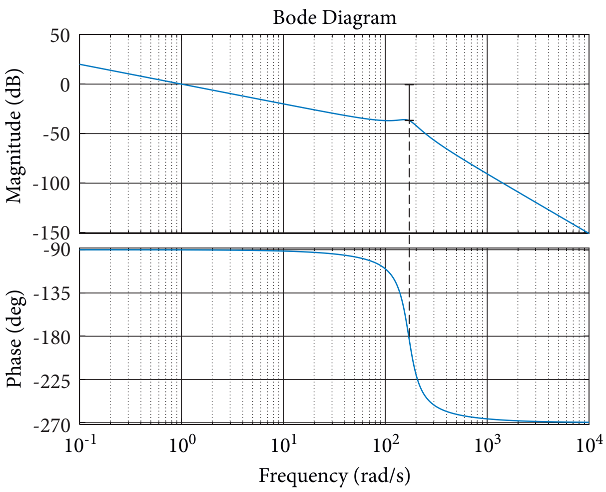


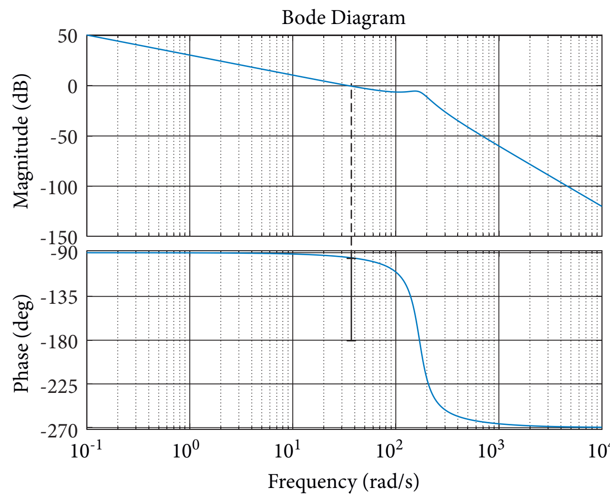
FIGURE 11: The control logic of the transfer device in automatic mode.

TABLE 3: Some parameters of vertical hydraulic cylinder system.

A_1 cm^2	A_2 cm^2	λ	β_e N/cm^2	m N·s^2/cm	V cm^3	C cm^5/(N·s)	K_f	D_p mL/r
490.6	236.3	0.48	70000	1000	1300	0.039	1	100



(a)



(b)

FIGURE 12: The open-loop Bode plot of the system. (a)$K_v = 1$, (b)$K_v = 33.9$.

The log magnitude-frequency characteristics and log phase-frequency characteristics of the open-loop transfer function are, respectively

$$L(\omega) = 20\lg K_v - 20\lg\omega - 20\lg\sqrt{\left(1-\frac{\omega^2}{170^2}\right)^2+\left(\frac{0.4\omega}{170}\right)^2}, \tag{3}$$

$$\varphi(\omega) = -\frac{\pi}{2} - \arctan\frac{0.4\omega/170}{1-(\omega/170)^2}. \tag{4}$$

Referring to the log magnitude-frequency characteristics plot of the hydraulic system when $K_v = 1$, the open-loop Bode plot of the system is drawn according to equation (2), as shown in Figure 12(a). When $\varphi(\omega) = 180^\circ$, the phase crossover frequency of the open-loop system $\omega_g = 170$ rad/s, magnitude margin $L(\omega_g) = 36.6$ dB.

The larger the K_v value, the smaller the steady-state error of the system. Therefore, under the condition that the relative stability of the system is satisfied (i.e. $L(\omega) \geq 6$ dB), the log magnitude-frequency characteristics plot is moved up by 30.6 dB, as shown in figure 12(b). At this time, the break frequency $\omega_c = 35.4$ rad/s, $K_v = 33.9$, that is, under the condition of satisfying the relative stability of the system, the maximum value of K_v is 33.9. From figure 12(b) or equation (4), it can be seen that the open-loop phase margin $\gamma = 85^\circ$, and γ is greater than 30°, therefore, the system satisfies the relative stability.

For high-order (above third-order) open-loop systems, the rapidity performance index of closed-loop systems can be estimated based on engineering experience. The approximate equations are [19]

$$\sigma\% = \left[0.16 + 0.4\left(\frac{1}{\sin\gamma} - 1\right)\right] \times 100\% \quad (35^\circ \leq \gamma \leq 90^\circ), \tag{5}$$

$$t_s = \frac{\pi}{\omega_c}\left[2 + 1.5\left(\frac{1}{\sin\gamma} - 1\right) + 2.5\left(\frac{1}{\sin\gamma} - 1\right)^2\right] \quad (35^\circ \leq \gamma \leq 90^\circ). \tag{6}$$

According to $\gamma = 85^\circ$, the percent overshoot $\sigma\% = 0.16\%$, and the settling time $t_s = 0.177$ s. Therefore, the vertical hydraulic cylinder system has a good transient response to the input signal. Similarly, it can be calculated and concluded that the horizontal and hoisting hydraulic cylinder system also has good stability and transient.

6. Conclusion

In this paper, a horizontal stepping hydraulic drive transfer device for nuclear engineering system is completed through TRIZ and computing analysis. It has the characteristics of compact structure, heavy load, and independent operation. In the ongoing physical prototype test, various design indexes have reached the expectation.

According to the specific load conditions, a certain number (even number) of transfer devices will be selected for combination and synchronous operation in future nuclear engineering construction, which can transport all kinds of heavy equipment to the nuclear island. This will evidently improve the efficiency of existing engineering construction. Besides, the application fields of this device can be further expanded, such as engineering buildings, heavy machinery assembly, and heavy equipment installation.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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