Electro-hydraulic Two-Axle Steering System for City Crane

Koichi SHIMOMURA[*1], Takashi MORITA[*2]
[*1] Engineering & Development Div. System & Component Development Dept., KOBELCO CRANES CO., LTD.
[*2] Electronics Research Laboratory, Technical Development Group

This paper describes a new steering system for a city crane, the RKE450. Unlike conventional fully-hydraulic steering, the new system adapts a mechanical steering system for the front axle and an electro-hydraulic steering system for the rear axles, where the latter system is automatically controlled in accordance with the movement of the front axle. In addition to the safety feature carefully built into the control system, the new steering system also achieves low tire wear, better driving stability, and a smaller turning radius. As a result, the crane complies with the European regulations for driving on public roads at speeds as high as 80km/h and has several auxiliary functions for crane actions in the off-road mode at speeds below 25km/h, as required by the regulations.

Introduction

A new city crane, the RKE450 (**Fig. 1**), is now on the European market. When the machine was being developed, it was essential to make the steering mechanism comply with European regulations. The model that is the Japanese counterpart of this new crane has conventionally employed a hydraulic steering mechanism that does not comply with the European regulations. Therefore, a new system has been developed, comprising front and rear axles, in which the front axle is mechanically steered and the rear axles are automatically steered electro-hydraulically in accordance with the amount of steering done by the front axle.

This has led to the establishment of a new steering system that has been proven to be safe and that can be driven on European motorways, with its features of minimal tire wear, high running stability and a small turning radius. The following describes the details.

Fig. 1 Photograph of RKE450

1. Conventional steering mechanism for Japanese models

A standard city crane, which is classified as a large-sized special motor vehicle in Japan, is equipped with two steering modes: i.e., a normal mode that is used for driving on public roads, during which time the steering is performed only by the front axle, and a special mode (including "clamp", "crab" and "rear", as shown in **Fig. 2**), which decreases the turning radius when driving on non-public roads and on work sites. The cab, from which the steering is directed, is located on the crane's upper slewing body, while the mechanism that actually steers the axles is located in the lower traveling body. This steering configuration makes city cranes different from ordinary automobiles. We have adopted hydraulic steering systems (**Fig. 3**) along this line for over 30 years. Each hydraulic steering system comprises an all-hydraulic power-steering control unit, rather than using mechanically linked steering systems. The hydraulic control unit converts the driver's steering operation

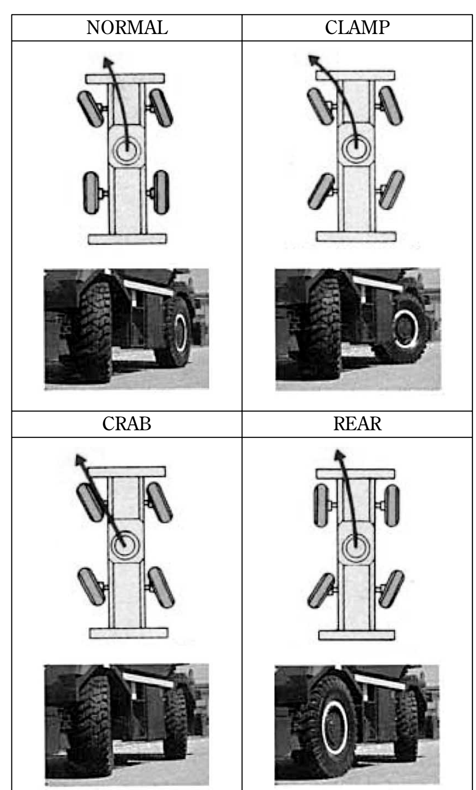

Fig. 2 Steering mode

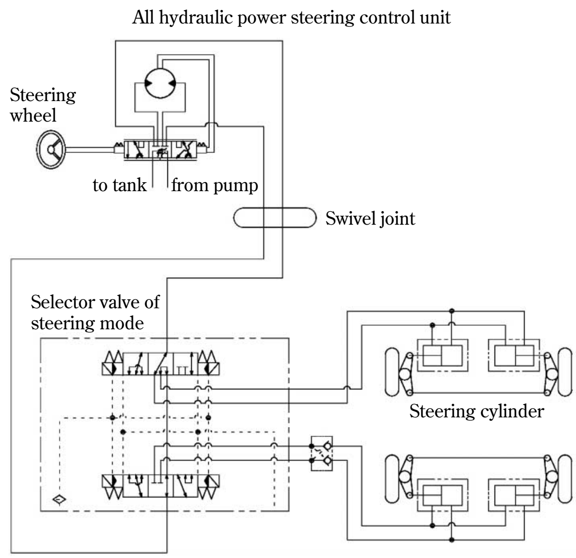

Fig. 3 Hydraulic Steerage mechanism

into oil pressure, transmits the pressure from the upper slewing body to the lower traveling body via a swivel joint, and, thus, hydraulically actuates steering cylinders to complete the steering. Switching between the normal mode and special mode is accomplished by an electromagnetic switching valve that changes the hydraulic circuit as the controller detects the driver's actions and makes a judgment in accordance with various switching conditions.

In the normal mode, the hydraulic circuit actuates only the front axle (while the rear axles are in a hold state). In the special mode, the hydraulic circuit actuates both the front and rear axles such that they cooperate in steering the vehicle. However, not having a mechanically-linked steering mechanism for driving on highways, this construction is deemed not strong enough to satisfy the requirements of European regulations for driving on public roads.

2. Steering mechanism for the newly developed RKE450

2.1 Construction of the steering mechanism

In the newly developed RKE450 (hereinafter referred to as the "present machine"), the front axle is mechanically linked, through a lower steering mechanism, with the steering wheel in the cab such that the driver's steering operation is directly transmitted through the link mechanism. The rear axles (i.e., second and third axles), on the other hand, are controlled and driven electro-hydraulically. Electromagnetic switching valves (hereinafter referred to as "check valves") are used to allow steering and related operations, while electromagnetic proportional valves are used to adjust the amount of steering based on the command from an electrical controller (**Fig. 4**). Steering angle sensors detect the angle to which the driver moves the front axle in steering. The controller automatically calculates the degree of steering for the rear axle(s) in accordance with each steering mode. The degree of steering applied to each rear axle is also detected by steering angle sensors, and the result is used to determine the command.

In the above construction, the front and rear axles are not linked, either mechanically or hydraulically; this increases the degree of freedom in rear-axle steering. Therefore, an adequate control can decrease tire wear and the turning radius, increasing the appeal of the product. This structure, however, is quite different from that of the conventional domestic model, whose front and rear axles are hydraulically linked and always have a synchronized relationship. In the new construction, a failure of the electronic control (due to some anomaly, or to component

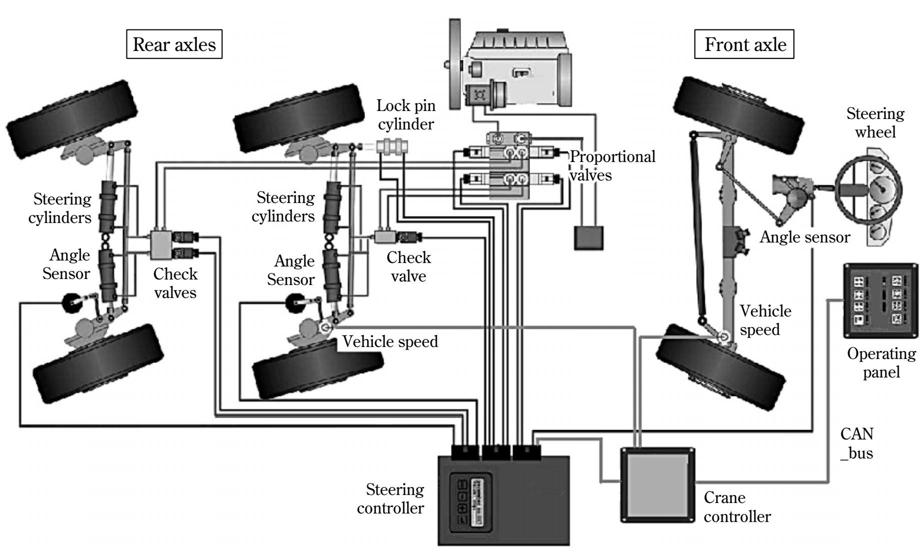

Fig. 4 Diagram of steering system of RKE450

failure) may cause an unsafe event, in which the rear axle steering does not cooperate with the front axle steering. Therefore, as described later, safety was given prime consideration in developing the present machine, resulting in the further enhancement of its safety over that of the conventional machine.

2.2 Steering modes

The present machine comprises a "highway mode" for running on public roads and an "off-road mode" for running on non-public roads.

The highway mode ensures the running stability required for high-speed driving of up to 80km/h and controls the steering of each axle independently to reduce wear on the tires on the rear axles. (The model that is its domestic counterpart does not have this independent steering control.) The second axle is kept in a neutral state, while the third axle is automatically steered in accordance with the steering angle of the first axle (**Fig. 5**).

In the low-speed range where the vehicle is moving at no more than 10km/h, steering is controlled such that the center of the turning circle always falls on the line that extends the axis of the second axle. This minimizes tire wear during steering and decreases the turning radius. The center of this turning circle is uniquely determined from the steering angles of the first and third axles and from the axial distance, pre-stored in the controller, of the actual machine. The controller calculates the steering angle of the third axle for the automatic steering control on the basis of the steering angle of the first axle, an angle that is constantly being changed by the driver's operation.

In the high-speed range where the speed of the vehicle is greater than 30km/h, running stability is ensured by keeping both the third and second axles in the neutral state, regardless of the steering angle of the first axle. This steering is specified on the basis of two aspects: The effect on tire wear is negligible in the high-speed range, and a small change in the steering angle significantly affects the direction (directional stability) of the vehicle body and its safety. In order to suppress tire wear, the speed control is more advantageously switched at a higher threshold. The threshold speed of 30km/h, thus determined, is higher than that of the other vehicles already in the European market (25km/h), and its safety has been well established by demonstrations using actual machines.

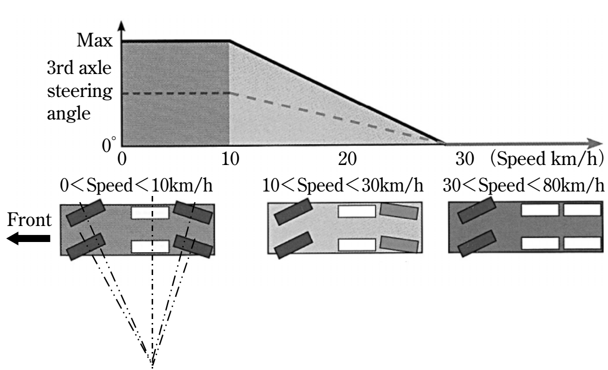

Fig. 5 Steering system in on-highway mode

In the mid-speed range above 10km/h and no higher than 30km/h, the steering angle of the third axle changes, proportionately to the speed, from the angle that has been set for the low-speed range, until it reaches the angle for the high-speed range. This change is made in such a way that the driver does not feel any difficulty in steering the rear axle.

The off-road mode, rather than limiting the vehicle speed to a maximum of 25km/h to comply with the European regulations, serves for special steering, including all-wheel steering, crab steering, and manual steering, thus ensuring mobility under the various limiting conditions of the work sites. This mode enables the second axle, which is kept in neutral when in highway mode, to steer the vehicle, thus taking full advantage of the steering performed by all the axles.

The all-wheel steering minimizes the turning radius. The steering angles of the second and third axles are automatically controlled such that the center of the turning circle always falls on a line extending from the center axis of the vehicle body. Crab steering optimizes the pull-over operation by automatically controlling the steering angles of the second and third axles so that they are equal on the basis of the steering angle of the first axle. Manual steering uses a switch that is separate from the steering wheel to steer the rear axle. The switch makes it possible to steer the second and third axles independently of the first axle such that the phases of the front and rear axles can be determined independently according to various limiting conditions (**Fig. 6**).

2.3 Safety considerations

2.3.1 State detection

Detecting the steering angle of each axle is extremely important in maintaining the accuracy, safety and reliability of the system. The detection of steering angles is particularly important from the aspect of safety. A mismatch between the detected and actual steering states can cause a steering operation that is totally unexpected and can immediately lead to a serious accident.

With this in mind, the detection of the steering

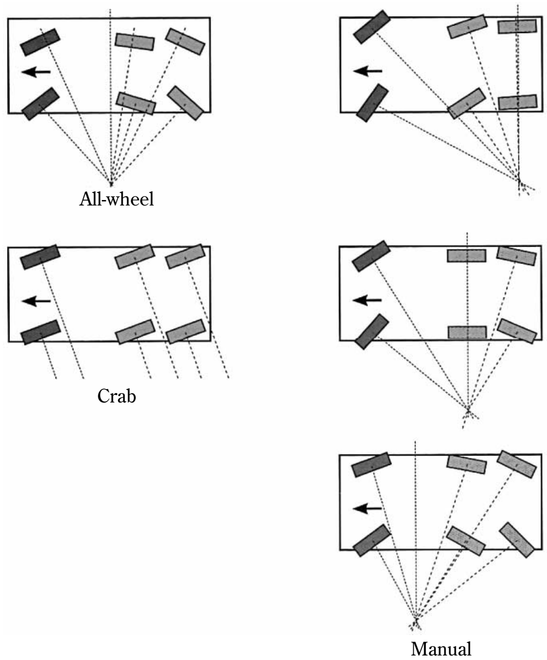

Fig. 6 Steering system in off-road mode

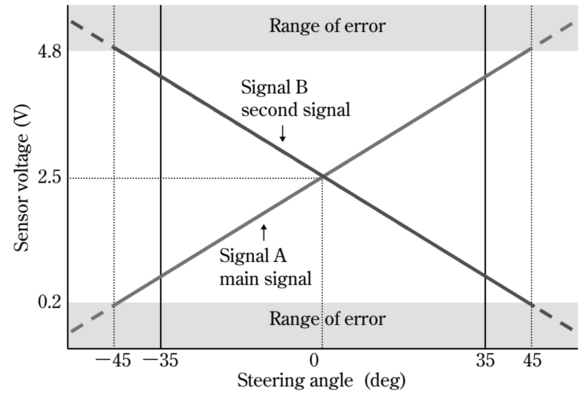

Fig. 7 Signal of steering angle sensor

angle has been devised with special care and taken to a higher level than that of the state detection in the conventional domestic model. As a natural procedure, a duplexed system is employed for signal detection in a manner similar to that of other critical state detections, such as the detection of accelerator operation. The duplexed signals, however, may both be distorted in the same manner by a disturbing factor. Redundancy by cross-sensing is adapted to prevent this problem from happening and to further improve reliability (**Fig.7**). There is a risk that one or both of the duplexed signals may not reflect the actual value even when the signals are in the normal range (or in a range that is beyond the upper or lower limit of the sensor voltage, but does not reach the failure range). This happens when, for example, something causes the supply voltage for the sensor and/or the electrical potential level of the grounding to deviate from the normal range. This problem happens also when unintended powering or a ground fault occurs on the signal line. The above configuration makes it possible to judge anomalies even when such problems occur. In the newly developed system, one of the duplexed signals is taken as a base. An anomaly is judged to have taken place when the other signal is converted into an angle that exceeds ±10% of the range of the base value. If this happens, the values are not used for the control, and the system is shifted to a failure procedure.

Vehicle speed signals from the speed detection sensors are also critical because they are used for calculating the steering angle and mode switching conditions when in highway mode. Vehicle speed signals are used not only for the steering control, but also for other controls. In a conventional machine, two sensors are provided, i.e., a main sensor on the rear axle and a sub-sensor on the front axle. The steering controller receives input via dual channels, i.e., a direct input of pulse signals from the rear axle and an indirect input via a Controller Area Network (CAN) from the front axle, in which the signal passes through other controllers. Unlike ordinary anomaly detection, the signals from the dual channels are compared and an anomaly is judged to exist when the difference exceeds a predetermined value. The signals are not used by the control and are shifted over to a failure procedure.

2.3.2 Steering operation

Even if the above described state detection returns a normal result, a steering operation that is totally unmatched with the driver's steering actions may occur when there is an anomaly in the electrical output from the steering controller or in the hydraulic actuators receiving the electrical output. Therefore, special care has been taken to devise duplex channels, not only for the electrical system, but also for the hydraulic system (Fig.4).

The system is configured around the basic concept that the rear axle must never act on its own when in highway mode. (In particular, it must remain in neutral in the high-speed range.) This basic concept takes precedence over everything else. For each of the rear axles, i.e., the second and third axles, the steering operation is determined by the strokes of two cylinders whose movement is governed by the output from the steering control valve (proportional valve), which is actuated on the basis of commands from the steering controller. The proportional valves are disposed facing each other on both sides of each control valve and are constructed so as to maintain the steering state unless there is an electrical output. In other words, when the outputs from the proportional valves are equal (including zero outputs), the control valve enters the neutral state and the steering cylinders are kept in the hold state.

Due to sticking (e.g., by seizure of the spools), or due to electrical anomalies, the hydraulic output of a steering control valve (proportional valve) may work on the unsafe side. In case of such an emergency, the steering state is maintained by the hydraulic circuit configured in a duplex manner. This enables the steering controller to detect an anomaly, and the check valves that are provided in front of the steering cylinders are actuated to shut down the circuit in order to maintain the state of the steering cylinders. These check valves themselves are configured to open the hydraulic circuit and to make the steering cylinders operable when an electrical signal is output. It should be noted that a check valve is provided for each steering cylinder of the third axle so that the steering cylinders are not actuated if one of the check valves fails to operate. For the second axle, only one check valve, common to both of the steering cylinders, is provided. Instead, to ensure a neutral state when in highway mode, a mechanical locking mechanism (including lock pins) conventionally used in the domestic model is provided, in addition to the hydraulic holding mechanism. A pneumatic lock cylinder actuates a pin to lock the steering cylinder.

As for the electrical aspect, the feedback from the proportional valve output is monitored as in the case of the domestic model, and the operation shifts to a failure procedure as soon as an anomaly is detected. The electrical output to each check valve is configured such that the outputs of both the high side (power supply side) and the low side (grounding side) come from the steering controller. As a result, there is only a negligibly small possibility of a check valve's failing to hold the steering cylinder due to an electrical problem.

2.3.3 Fail-safe procedure

A fail-safe procedure has been devised to prevent an unsafe event from happening in the event that an anomaly should occur in the state detection, steering controller, or output system. Anomalies are categorized in four levels, according to their importance, from Level 0 (minor) to Level 3 (major). The steering controls on the second and third axles are limited in certain ways, depending on the level, to prevent major unsafe events, while, as far as possible, keeping the steering function effective (**Table 1**).

In Level 0, the normal control is continued. In Level 1, an axle affected by an anomaly is steered by the driver until the axle goes into neutral and, thereafter, is held in neutral. In Level 2, only the axle affected by the anomaly is forcibly steered into the neutral state and, thereafter, held in neutral. In Level 3, the axle affected by the anomaly is immediately shifted to a hold state, while the axles that are not directly affected are steered by the driver until they enter the neutral state and, thereafter, are held in neutral.

Table 1 Definition of fail-safe

Error level	Axle2				Axle3			
	No effect	Lock next center	Move to center	Lock actual	No effect	Lock next center	Move to center	Lock actual
System level0	○				○			
System level1		○				○		
System level2			○				○	
System level3				○				○
Axle2 level0	○				○			
Axle2 level1		○			○			
Axle2 level2			○		○			
Axle2 level3				○		○		
Axle3 level0	○				○			
Axle3 level1	○					○		
Axle3 level2	○						○	
Axle3 level3		○						○

2.3.4 Verification of safety

Just as in the case of conventional development, the new control system was established after the verification of control specifications by testing on bench and actual machines, as well as by a thorough confirmation of their behavior under each failure mode as defined by Failure Mode and Effects Analysis (FMEA). The typical verification items are as follows.

The steering mode performance for the operation of a normal system is verified. Above all, straight-line stability is regarded as an important factor. The specifications require that the rear axle in the neutral state must be aligned within +/- 0.3 degree. Testing on an actual machine under various conditions has proved that the actual alignment falls within +/- 0.15 degree.

It is most critical to verify the behavior under failure. Verification based on FMEA, including the effective use of accumulated data, was performed with the cooperation of a steering system manufacturer.

For the sake of safety and for compliance with European regulations, a swing-out test is a particularly important part of the verification process. The test includes checking the amount of swing-out when the rear part of the vehicle body sways from side to side due to an abrupt change in the steering angle of the third axle. This behavior of the third axle is regarded as the worst case in the

FMEA (unintended powering of the steering control proportional valve line). European regulations require the amount of lateral sway to be less than 10% of the vehicle width (or about 255mm for the present vehicle). On the other hand, the amount measured in the early stage of development was about 300mm, which was not acceptable. It took about 220ms from point at which the fail state of the proportional valve output was detected until the check valve was actuated to cease the steering operation of the third axle. During this period, the steering angle changed by about 5.4 degrees. A study of the response time revealed that the hydraulic response was dominant. Therefore, the specifications of the check valve and proportional valve were revised to improve the hydraulic response while maintaining steering accuracy under normal operation. In the resultant final product, the steering angle during the swing-out test has been held to 1 degree, with a thoroughly acceptable swaying amounting to several tens of millimeters.

Another test that is important from the aspect of safety and compliance with European regulations is the verification of the evacuation operation if the third axle should become locked at the maximum steering angle while in highway mode. This test verifies whether or not the vehicle can be driven for a certain distance for the sake of evacuation in the event that the third axle has been steered to the maximum angle and is locked there due to an anomaly. The present vehicle was set to the highway mode with its third axle fixed at its maximum steering angle of 19 degrees. In this state, the vehicle was driven straight, using only the steering operation of the first axle. Even though this was not easy, the evacuation of the vehicle was deemed to be possible (**Fig.8**).

Fig. 8 Fail test

Conclusions

Electronic controls will be increasingly used, not only for city cranes, but also for other mobile cranes, including crawler cranes, to improve their product competitiveness by providing high-function, high-performance features. Special care was taken during this development to assure fail-safety and reliability when constructing and implementing such a system, and such care will be essential in future development as well. We will continue to provide products having balanced features of function, performance, safety and reliability.