Technology Explanation

Semi-Absolute-Type Stroke Sensing Cylinder

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Abstract

In recent years, the electrification of hydraulic actuators and dampers used in hydraulic equipment and transportation equipment has been progressing.

Electro-Hydraulic Actuators (EHA) that drive cylinders with hydraulic pressure generated by electric motors, and active suspension that adjusts damping force and thrust according to the behavior of automobiles and railroad cars, are typical. “Displacement” is one of their control parameters. By detecting the displacement of the hydraulic cylinder in real time, it can be used for more detailed operation and fail-safe mechanisms in case of abnormalities, so its importance is considerable.

On the other hand, hydraulic cylinders are often used in harsh environments under vibration, operating temperature range, etc., so the mounted control equipment is also required to have environmental resistance.

KYB adopted the “Magnetic Scale Method” as a stroke sensor method that can handle such harsh external environments. However, since it is an “Increment Type” sensor that relatively detects the displacement amount of the stroke, there is a problem in that normal output that outputs the “absolute value” of the stroke amount cannot be performed.

“Absolute output” is required as an essential function for hydraulic equipment control.

Therefore, we adopted a magnetic scale that can detect the reference point of the absolute value of the displacement, and developed a Stroke Sensing Cylinder that can output the absolute value of the stroke amount even though it is a magnetic scale method.

1 Introduction

Hydraulic equipment such as actuators and dampers are widely used in transportation equipment including construction machinery, automobiles, railroad cars and aircrafts. From the viewpoint of energy saving and greater functionality, electrification and sophistication of hydraulic equipment, which have been conventionally controlled in a mechanical way, have recently been progressing.

Electro-hydraulic actuators, often called “EHAs”, use hydraulic power generated by electric motors, not by conventional diesel motors, to drive hydraulic equipment such as cylinders. EHAs can also use electromagnetic change-over valves to electronically control hydraulic circuits.

EHAs can help achieve higher-efficiency and more-complexed control than before.

For automobiles and railroad cars, more and more active suspensions that can properly control the damping force and thrust in response to the behavior of running vehicles have been used to ensure a more comfortable ride and handling stability.

Both EHAs and active suspensions provide electronic control while detecting the status of hydraulic actuators and dampers (control parameters) with sensors.

One of the parameters detected by sensors is “displacement (or stroke length)” of cylinders.

For electronic control of hydraulic cylinders, the cylinder displacement is an essential parameter to determine where the piston rod is located. The displacement data is normally used by the control system to provide feedback control and is used for a fail-safe mechanism should the cylinder position be out of control.

Particularly for construction machinery and transportation equipment, the importance of such fail-safe mechanisms is considerable because safety is the top priority.

Then, we set about development of a stroke sensing cylinder (hereinafter “SSC”) that can detect the cylinder displacement for applications in construction machinery and transportation equipment.

Sensors for use in construction machinery or transportation equipment are required to have high durability under vibration or high/low temperature environment. They also need to be compact because only limited space is available for sensors in many of such equipment.

To meet these demands, we decided to use a design of hydraulic cylinders called “Magnetic Scale Method” in which a sensor can read an evenly spaced magnetic scale provided on the piston rod to detect the displacement.

However, the magnetic scale based sensor we used was inevitably of increment type because of its physical structure. There arose a problem that the sensor could not output the “absolute value” for the cylinder position.

In general, distance sensors such as a stroke sensor can be roughly divided into “increment” and “absolute” types by their output format.

The former, typified by a pulse counter, counts signals that are input at regular intervals to detect a change in distance from a certain point (displacement). The latter is designed to always output the absolute position from a reference point.

Therefore, the term “absolute output type” means “being able to detect the absolute position of the hydraulic cylinder”.

We then developed a “semi-absolute type SSC” using the magnetic scale method that can detect the absolute position of the cylinder with a magnetic scale of a special shape and a sensor signal processing algorism. This paper explains details of the SSC.

The paper also describes later why the word “semi” was added to the general term “absolute type”.

2 System Overview

2.1 System Configuration

The semi-absolute type SSC system consists of three components: a piston rod with a magnetic scale, which will be described later, a magnetic sensor that senses the magnetic scale, and a signal processing board that computes signals from the magnetic sensor and converts them into the displacement of the hydraulic cylinder (Fig. 1).

The magnetic sensor is mounted on one of the sides of the hydraulic cylinder and has a sensing member on the tip that is installed in such a manner that can slide with the piston rod. Signals detected by the magnetic sensor are input to the signal processing board installed downstream, where the signals are converted into displacement data and then sent to a higher-order controller that actually controls the hydraulic cylinder.

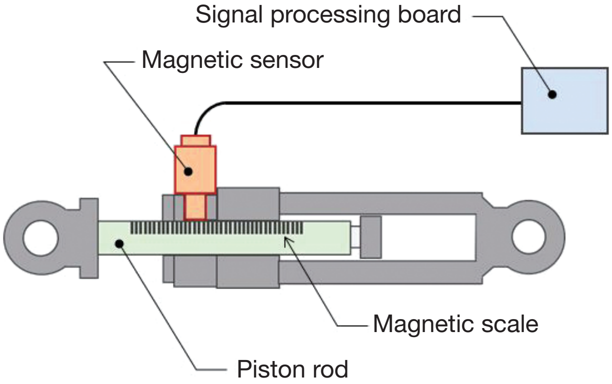

Fig. 1 System configuration

2.2 Piston Rod and Magnetic Scale

Photo 1 shows the appearance of a prototype of the piston rod provided with the magnetic scale. In the photo, the central banded portion is the magnetic scale engraved into the surface of the piston rod to form grooves. The piston rod is then plated with non-magnetic material to fill in the grooves, creating a structure as shown in Fig. 2.

Thus, the piston rod has a cross section where magnetic material and non-magnetic material alternately appear at fixed intervals, constituting a magnetic scale.

The piston rod used in the system introduced in this paper is provided with a 2 mm spaced magnetic scale.

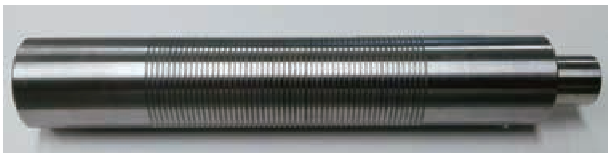

Photo 1 Appearance of piston rod prototype before plating

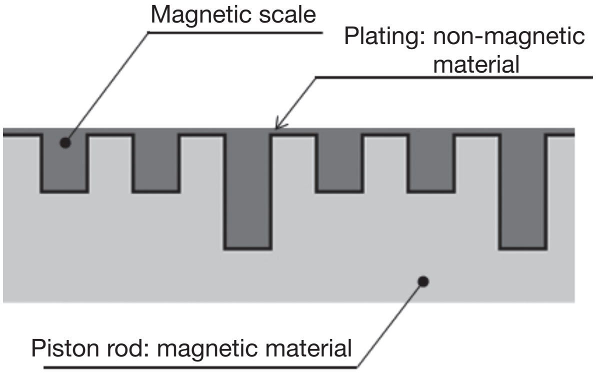

Fig. 2 Structure of magnetic scale

2.3 Magnetic Sensor

The magnetic sensor is designed to detect the magnetic scale by its sensing member installed in such a manner that the tip is made contact with the piston rod.

The sensing member to detect the magnetic scale has an internal structure as shown in the section view of Fig. 3. Lines of magnetic flux from an internal permanent magnet pass through a magnetoresistance IC via a yoke to reach the piston rod surface.

The principle of detection, which will be described in detail later, is that the magnetic sensor detects changes in the number of lines of magnetic flux that occur according to the positional relationship with the magnetic scale provided on the piston rod.

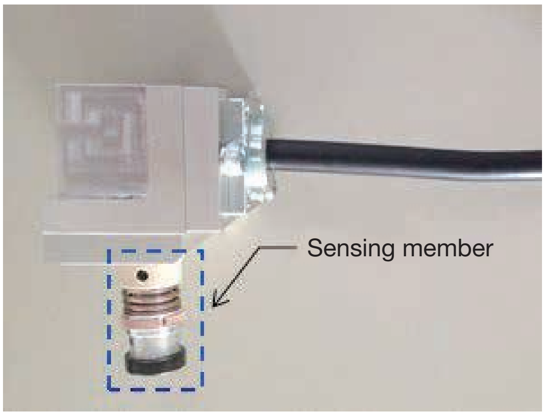

Photo 2 Appearance of magnetic sensor (prototype)

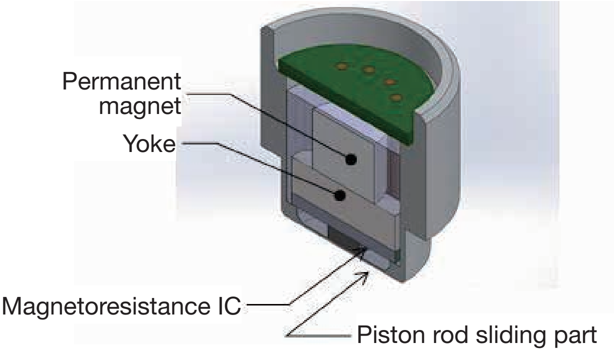

Fig. 3 Section view of sensing member of magnetic sensor

3 Principle of Displacement Detection

3.1 Magnetic Scale Detection with Magnetoresistance IC

The internal magnetoresistance IC of the magnetic sensor has four magnetoresistance elements. These four magnetoresistance elements are spaced at intervals of 0.5 mm, which is 1/4 of the pitch (2 mm) of the magnetic scale on the piston rod. The four elements may be divided into two pairs: one pair is called A-phase magnetoresistance elements and the other B-phase magnetoresistance elements. The A- and B-phase magnetoresistance elements are arranged as shown in Fig. 4.

As mentioned above, the magnetic sensor has a mechanism that lines of magnetic flux from the permanent magnet penetrate the magnetoresistance IC via the yoke. Since more lines of magnetic flux are attracted by magnetic material than by non-magnetic material, the inclination of the lines of magnetic flux passing through individual magnetoresistance elements depends on their position relative to the magnetic scale as in the example shown in Fig. 4.

As the magnetic resistance changes with the inclination of the lines of magnetic flux, the value detected by the magnetic sensor changes accordingly.

Therefore, when the hydraulic cylinder operates to move the magnetic scale, the inclination of each line of magnetic flux changes sequentially.

Assuming that the A- and B-phase magnetoresistance elements output an A- and a B-phase signal respectively, when the piston rod (magnetic scale) moves at a fixed speed, a sine wave output can be obtained, a cycle of which is complete every 2 mm of travel that is equivalent to the magnetic scale pitch as shown in Fig. 5 (for explanatory convenience, hereinafter the piston rod is assumed to travel at a fixed speed unless otherwise noted).

Since the B-phase magnetoresistance element is installed with an offset of 0.5 mm (1/4 of the magnetic scale pitch) from the A-phase magnetoresistance element, the B-phase signal is represented by a cosine wave with a phase-shift of 90 degrees from the A-phase signal.

These A- and B-phase signal values are determined from the difference in the inclination of the lines of magnetic flux between the two magnetoresistance elements. In fact, the sine and cosine waves shown in Fig. 5 may be obtained only with a single magnetoresistance element each. In this case, however, it is difficult to ensure accurate detection because the detected value may change if the gap between the magnetoresistance IC and the magnetic scale fluctuates due to vibration or other disturbance under service conditions. To avoid this, a pair of magnetoresistance elements is used so that the difference in detected values between the two can be taken to eliminate the effect of any variations of the gap between the magnetoresistance IC and the magnetic scale.

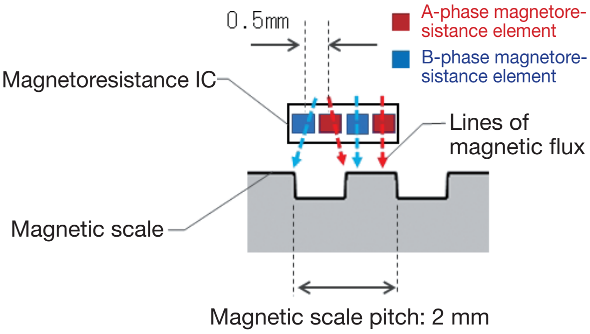

Fig. 4 Positional relationship between magnetoresistance elements and magnetic scale

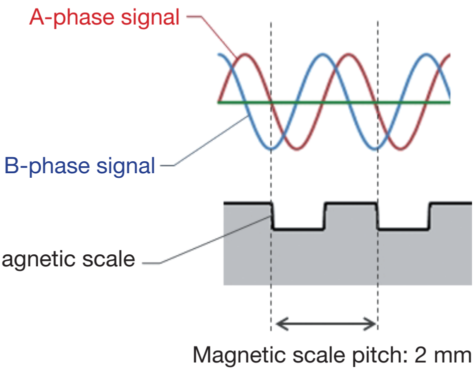

Fig. 5 Magnetic scale and output signal

The A- and B-phase signals greatly depend on the positional relationship between the magnetoresistance IC and the magnetic scale. Therefore, a magnetic field analysis setup shown in Fig. 6 was used to optimize the design.

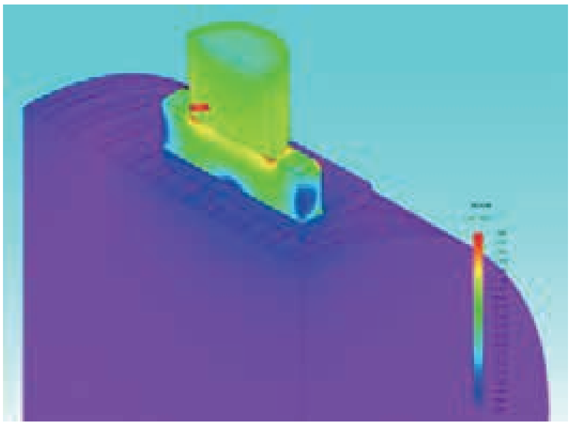

Fig. 6 Magnetic field analysis of magnetic sensor

3.2 Basic principle of displacement detection

The magnetic scale detection signal obtained as described in 3.1 (A- and B-phase signals) are converted into displacement of the hydraulic cylinder by the signal processing board, which is one of the system components.

First, the median value of the amplitude of the A- and B-phase signals is defined as "the zero-crossing level". A pulse generation circuit in which a pulse occurs every time the A- or B-phase signal intersects with the zero-crossing level is provided in the signal processing board. The pulse then is defined as a zero-crossing pulse.

In other words, a zero-crossing pulse takes place every time the piston rod (magnetic scale) moves 0.5 mm (Fig. 7).

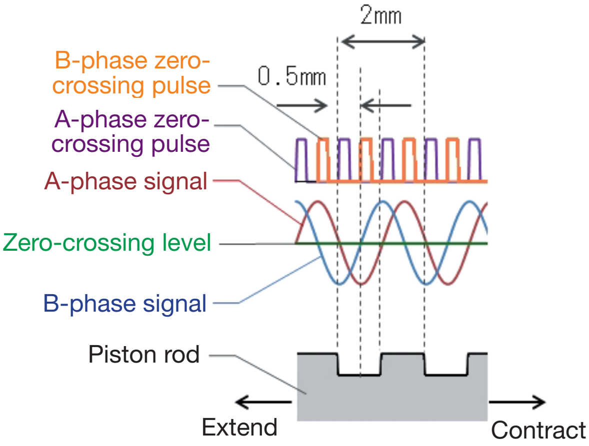

Fig. 7 Zero-crossing pulse

The number of inputs of this zero-crossing pulse can be obtained by a computing unit such as a microprocessor, thereby making it possible to measure the stroke amount (displacement) with a resolution of 0.5 mm.

Which direction the hydraulic cylinder moves (extends or contracts) can be determined by making use of the phase shift between the A- and B-phase signals. When an A-phase zero-crossing pulse is detected, the direction of stroke can be uniquely defined by the combinations of whether the polarity of the A-phase signal changes from positive to negative or vice versa and whether the polarity of the B-phase signal then is positive or negative.

For example, assuming that, in Fig. 7, the motion of the magnetic scale from the right-hand side to the left-hand side is defined as "extension" and the motion from the left-hand side to right-hand side as "contraction", a change-over of the A-phase signal from positive to negative indicates "extension" if the B-phase signal is negative, or "contraction" if the B-phase signal is positive.

Applying similar judgment to the detection of B-phase zero-crossing pulses always allows the judgment of the direction of stroke.

For the displacement detection using this magnetic scale method, the zero-crossing pulse cycle can be uniquely determined by the mechanical dimension. The method brings about a benefit to the system introduced in this paper that an accuracy of +/-0.5 mm can be ensured.

In general, hydraulic cylinders are subjected to a wide range of temperatures because of their frequent outdoor use and/or temperature variations of the hydraulic fluid. Therefore, their related sensors are likely to be affected by a temperature drift.

The possible effect of the temperature drift is almost negligible when the magnetic scale method is introduced. This is also one of the reasons for using the magnetic scale method.

3.3 Semi-Absolute Output

In general, the absolute type sensor refers to a sensor that "always" outputs the absolute value for displacement.

For example, if the hydraulic cylinder is actuated to move to a certain position with the sensor power off (displacement detection disabled), the sensor will be able to output the value for the cylinder position (displacement) immediately after the sensor is restarted.

However, the stroke sensor introduced in this paper is of an increment type that basically measures the displacement by counting the number of zero-crossing pulses as described in 3.2 above. Therefore, it is usually impossible for the sensor to detect the absolute position of the hydraulic cylinder.

Then, the principle below has been utilized to allow the sensor to detect the absolute value.

Firstly, as shown in Fig. 8, two different magnetic scales are engraved into the surface of the piston rod: regular shallow grooves and reference deep grooves. The reference deep grooves are consequentially filled with thicker non-magnetic material, resulting in A- and B-phase signals with a larger amplitude than those from the regular shallow grooves. This difference in amplitude can be used to identify the reference scale.

Secondary, the reference scale has a groove at the absolute zero (0) mm position of the hydraulic cylinder as the reference point and several others on the both sides of the reference point each. These grooves for the reference scale are located at irregular intervals like one pitch, two pitches and three pitches.

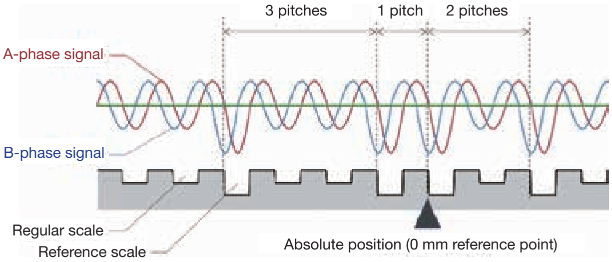

Fig. 8 Example of reference scale arrangement

With this arrangement, when the hydraulic cylinder operates and the magnetic sensor detects any two grooves of the reference scale, the number of pitches between the first and second grooves can be determined from the number of zero-crossing pulses detected during the time, which uniquely determines the second reference groove. That is, the cylinder can be located with its absolute position.

In Fig. 8 for instance, when the magnetic scale moves toward the left-hand side and two pitches of the magnetic scale (two zero-crossing pulses) have been detected until the detection of the second reference groove, this means that the right-most reference groove has been detected. Thus, another absolute position that is 4 mm away from the original absolute position 0 mm is established.

Once established, an absolute position may be used as reference to detect displacement thereafter.

Thus, the SSC in this paper operates as an increment type sensor immediately after the system start-up, but will turn into an absolute type once any two reference grooves have been detected as the hydraulic cylinder operates. That's why the SSC in this paper is called a "semi-absolute type".

In fact, it is theoretically possible to locate the cylinder with its absolute position just by providing only one reference groove at the absolute position 0 mm instead of providing several reference grooves.

However, when assuming actual service conditions, for example, a case in which the SSCs are used for suspension dampers of transportation equipment, the SSCs may extend/contract only with a very small amount of stroke during driving on a flat road where the vehicle is only subjected to small vibration. In this case, the reference scale with only one groove is not necessarily detected and the sensor may be unable to output the absolute position data.

Hydraulic actuators are another example. If the system is started up with its hydraulic actuator located away from the only one groove for the reference scale, the system must be moved by a considerable distance in order for the sensor to detect the reference point.

To solve the problem, several grooves for the reference scale are distributed over the length of the piston rod so that any of the possible reference points can be detected as soon as possible after start-up of the system.

It should be noted that, in the example of Fig. 8, the absolute position 0 mm is located in the midst of the piston rod based on an assumption that the cylinder bidirectionally operates (extension and contraction). For an application where the piston rod is always located at either side during start-up, the location may be given the absolute position 0 mm for one-directional detection.

3.4 Improvement of Measurement Resolution

The sections above have explained the principle of measuring the displacement at a resolution of 0.5 mm by counting the number of zero-crossing pulses obtained from A-phase and B-phase signals.

However, the 0.5 mm resolution may be insufficient to ensure adequate performance control of actual hydraulic cylinders. Then, the SSC has been improved to deliver a finer measurement resolution by means of software computation. Firstly, the zero-crossing pulses as well as the analog voltage values for A- and B-phase signals are simultaneously input to a computing unit such as a microprocessor. These A- and B-phase signals are plotted on the X-axis (horizontal) and the Y-axis (vertical) of a two-dimensional plane respectively and drawing a line sequentially from A1, B1, A2, B2... will create a Lissajous curve as shown in Fig. 9.

As stated in the previous section 3.3, the magnetic scale consists of two different scales: regular and reference. The system can use these scales to output A- and B-phase signals with different amplitudes, producing the curve like a double circle.

A round of the Lissajous circle is equivalent to a cycle of the A- or B-phase, namely, 2 mm displacement. So, a quadrant of the Lissajous circle is equivalent to the zero-crossing pulse interval of 0.5 mm (the sensor output value is shifted by 90 degrees along the trail of the Lissajous circle every 0.5 mm of displacement).

Therefore, determining the angle which forms the line segment from the point on the trail of the Lissajous circle given by the A-/B-phase voltage value obtained to the center point with the horizontal line will allow determine the displacement at a resolution of 0.5 mm or less.

A problem related to this detection of the magnetic scale is that the Lissajous circle is substantially warped in the part of transfer from detection of the regular scale (the inner Lissajous circle) to the detection of the reference scale (the outer Lissajous circle) or vice versa, resulting in a poor accuracy of positional detection.

Still, the system is able to recognize that an A- or B-phase signal being detected is on the warped part of the Lissajous circle when the SSC operates as an absolute type after the establishment of a reference point. So, the effect of the warp can be eliminated by the use of a correction map or other device specifically prepared for exception handling.

This modified software computation allows the semi-absolute type SSC in this paper to detect displacement with a resolution of 0.1 mm.

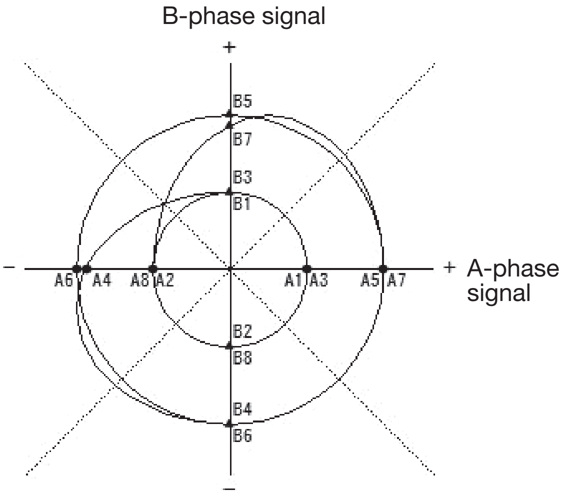

Fig. 9 Lissajous wave of output from magnetoresistance elements

3.5 Automatic Adjustment of Zero-Crossing Level

It is feared that the semi-absolute type SSC in this paper that operates with the piston rod sliding against the magnetic sensor may have wear in its sensing member on the tip of the magnetic sensor due to age deterioration, leading to a larger gap between the magnetic scale and the magnetoresistance elements. Machining variations of the magnetic scale is also another concern.

So, the median value and amplitude of A- and B-phase signals are not always constant.

If the zero-crossing level is out of the median value of A- and B-phase signals, the zero-crossing pulses would not be timed properly, resulting in poor accuracy of displacement detection. Therefore, the zero-crossing level always needs to be adjusted to the median value of the amplitude of actual A- and B-phase signals.

This zero-crossing level adjustment is automatically done by the computing unit on the signal processing board such as a microprocessor by calculating the proper value on an as-needed basis. Fig. 10 shows a block diagram of the zero-crossing level adjustment function:

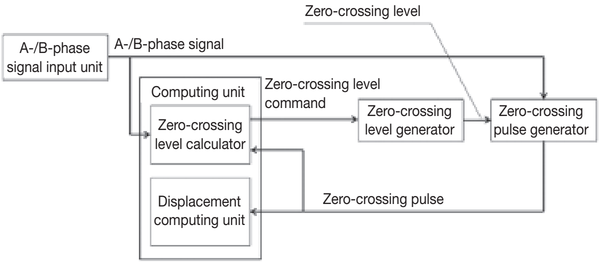

Fig. 10 Block diagram of zero-crossing level adjustment

For example, assume that the zero-crossing level of the A-phase needs to be adjusted. Obtain the value for the A-phase signal at the time when the zero-crossing pulse of the B-phase is input. This value is always a maximum or minimum value of the amplitude because there is a phase difference of 90 degrees between the A- and B-phase signals.

So, these values can be used to calculate the amplitude value for the A-phase signal. Similarly, the amplitude value for the B-phase can be determined by obtaining the value for the B-phase signal at the time when the zero-crossing pulse of the A-phase is input.

Note that this function is only enabled after the absolute type sensor function is enabled with the detection of the reference scale.

The system can recognize which magnetic scale on the piston rod is being read by the sensor only after the SSC turns into an absolute type. Now the system is able to learn amplitude measurements for each magnetic scale.

Based on the amplitude measurement data for each magnetic scale, the system calculates the proper median value of amplitude and then outputs the result as the zero-crossing level.

Continuing to execute this control will allow zero-crossing pulses to take place at proper timing, ensuring the displacement detection accuracy. Also, the automatic correction of the zero-crossing level will allow stable detection of displacement over a long time without manual tuning by user such as zero-point correction, leading to easier maintenance.

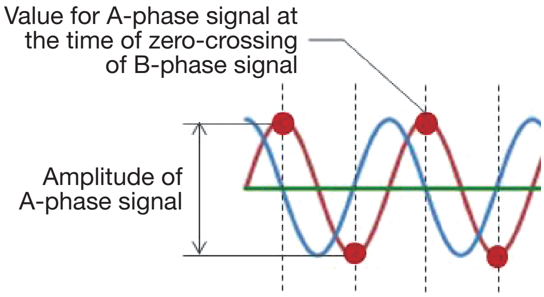

Fig. 11 Obtaining amplitude of A-phase signal

4 Results of Displacement Detection

As an example of detection of the displacement of a cylinder with a reference point (absolute position 0 mm) established in the central part of the piston rod, the cylinder is stroked at a fixed speed by 40 mm in the directions of extension and contraction each. The result is plotted in Fig. 12 with time on the horizontal axis and stroke on the vertical axis.

The output values of a displacement gauge installed as a reference for evaluation (the blue line in Fig. 12) and the output values of the semi-absolute type SSC (the red line in Fig. 12) overlap one another, which implies that the displacement is stably detected.

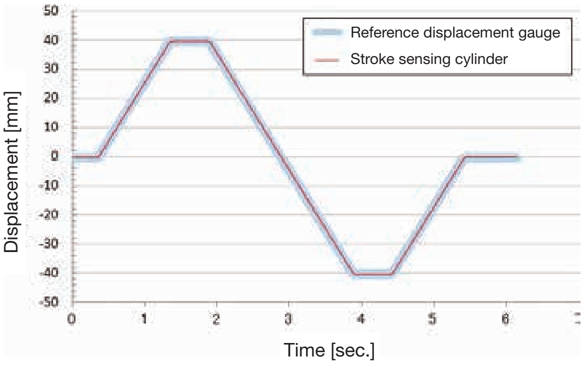

Fig. 12 Example of displacement output

The semi-absolute type SSC outputs the displacement in the form of analog voltage signals. However, it can also support digital output such as CAN and serial communication by adjusting the specifications of the signal processing board to the interface of the main machine.

5 Future prospects

For today's automobiles and construction machinery, new solutions have been developed including remote control through high-speed communications, artificial intelligence (AI) and Internet of Things (IoT).

Among these, hydraulic equipment is required to be even higher value added equipment. Electronic control systems used in such equipment will have to obtain more diverse information (control parameters) than ever from a variety of sensors, in order to be more advanced and more sophisticated.

In this sense, various sensing devices that can detect the status of equipment will be a critical element for hydraulic equipment to have higher-added-value functions. The displacement detection by the semi-absolute type SSC is also one of them.

For example, the conventional suspension of automobiles adjusts its damping force and thrust by estimating the damper behavior according to the magnitude of acceleration (rolling of vehicle) input from acceleration sensors. The active suspension in turn can directly detect the displacement to provide even more accurate control, with which the ride comfort is expected to be further improved.

The developed semi-absolute type SSC is still at a prototype level. For mass production, some challenges must be overcome including the machining process to provide the magnetic scale on the piston rod and the assembly of the magnetic sensor. Still, the SSC is expected to be effectively used as a sensing device that can greatly contribute to higher-value-added hydraulic equipment in the future.

6 Concluding Remarks

Taking a cue from the Industry4.0 proposed by Germany, the Japanese government has also proposed Society5.0.

Under these social circumstances, IoT technology that communicates a variety of information at high speeds and AI technology that processes collected information have rapidly advanced.

These "communications" and "information processing" together with "sensors" are three critical elements of information technology (IT) or may be collectively called "the Three Sacred Treasures of IT". Each of them is very important.

"Sensors" should not be simply used as parts to obtain parameters for electronic control, but should be combined with "communications" and "information processing" to make up "the Three Sacred Treasures", making it possible to build new solutions.

In hydraulic equipment for instance, data obtained with cameras (image sensors) can be transferred to a remote place (communications) for AI analysis (information processing). Some hydraulic equipment using these automated driving and remote control technologies are on their way to be commercialized.

One among them is the semi-absolute type SSC introduced in this paper, whose effectiveness will probably be higher. We would like to make the most of it as an element to build AI x IoT solutions.

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