Development of IO-Link inductive proximity sensor IC for improved productivity

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Key words
Proximity sensor, IO-Link, analog value output, preventive maintenance, remote monitoring, productivity increase

We have developed a proximity sensor IC for use in inductive proximity sensors that supports general ON/OFF output and IO-Link™ communication. The oscillator circuit in this IC has small temperature characteristics and can generate an oscillation amplitude proportional to the impedance of the sensing coil from a state of close contact with the target object to a state where the target object is absent. This enables the proximity sensor with IO-Link communication to output analog values according to the position of the target object, which is necessary for preventive maintenance and remote monitoring. It also enhances the ability to detect target objects near the sensor and improve adjustment accuracy. In addition, various settings can be made by combining the system with dedicated tools, making it possible to improve equipment productivity.

1. Introduction

From the perspective of productivity improvement in the midst of a labor shortage, the IoT (Internet of Things) implementation for production equipment has become an urgent priority. To that end, IO-Link™ enabled products have been spreading among sensors and actuators used at production facilities in proximity sensors, etc. IO-Link is an industrial interface standard. It is a technology that can connect sensors and actuators to upper-level networks, and is expected to contribute to the realization of IoT implementation at production facilities.

Proximity sensors detect the presence, absence, or proximity of objects. Proximity sensors use a variety of detection principles, including ultrasound, light, and electrostatic capacitance. Among these, inductive proximity sensors are used in environments prone to oil splatter and becoming dirty, such as machining equipment or automobile production lines. These sensors detect metals by electromagnetic induction of a high-frequency magnetic field generated from the sensing coil.

Conventional inductive proximity sensors are equipped with only one ON/OFF output. In addition, the operating distance in their product specifications is fixed and as short as a few millimeters. This makes it necessary to adjust the dog[*1] detection position by adjusting the screw position or using spacers. The result is problems such as time-consuming adjustment work and unstable detection.

The IO-Link proximity sensor model H3C (fig. 1) offers advantages such as the ability to set the dog detection position via communication, which can solve the aforementioned problems. When developing integrated circuits (ICs) for proximity sensors, it is necessary to provide them with specifications suitable for use in IO-Link proximity sensors. From the viewpoints of improving the productivity of equipment, preventive maintenance, and remote monitoring, it is necessary for proximity sensors to output not only ON/OFF signals but also analog values based on the position of the target object, indicating the detection status. In order for a proximity sensor to output analog values according to the position of the target object, the following requirements must be met:

- the oscillation amplitude must be proportional to the impedance of the sensing coil from a state of close contact with the target object to a state where no objects are detected;
- the temperature characteristics of the oscillator circuit must be small; and
- adjustment of the oscillation amplitude must be accurate.

Fig. 1. IO-Link proximity sensor model H3C

*1. A dog is an object provided for position detection by a sensor.

2. Improvement of oscillator circuit performance

2.1 Conventional IC circuits and their problems

A proximity sensor detects metal objects without physical contact. It detects metal objects by oscillating a coil with an open magnetic path at a high frequency. It utilizes the characteristic that the impedance of the sensing coil ($\omega^2 L^2/r$: where L is the inductance of the coil, r is the loss resistance of the coil, and ω is the angular frequency) changes with the proximity of metal (fig. 2). This coil forms an LC resonance circuit, and when a metal object approaches, the impedance decreases (r increases), causing the oscillation amplitude to decrease. This change in amplitude is detected, and an ON/OFF signal is output.

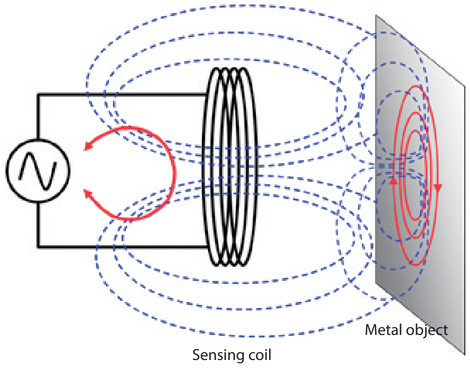


Fig. 2. Detection principle

In a conventional proximity sensor, the feedback current (Ifb) is determined by the resistance value ROP of the resistor connected to the OP terminal and the current mirror circuit, as shown in figure 3. When this current flows to the resonance circuit connected to the OSC terminal, a positive feedback is applied and the circuit oscillates.

This oscillation circuit has the following problems:

Problem 1: Since the oscillation characteristics are realized utilizing the nonlinear characteristics of transistors Q3 and Q4, the oscillation amplitude is not proportional to the coil impedance, and oscillation cannot be achieved when the target object is in close proximity. Therefore, the detection level of the proximity sensor does not change in the area close to the detection target, as is shown in figure 4.

Problem 2: Since the nonlinear characteristics of transistors Q3 and Q4 are utilized, the circuit is susceptible to the effects of changes in device characteristic caused by process variance during IC manufacturing, resulting in poor temperature characteristics.

Problem 3: The oscillation amplitude is adjusted by the resistor connected to the OP terminal. However, high-frequency current flows through the resistor. When adjusting the resistance, variations in the operating point caused by the parasitic capacitance from filling of the potting resin in the surrounding area need to be taken into consideration. This makes it difficult to adjust with high accuracy.

Therefore, it was difficult for IO-Link proximity sensors to output analog values according to the position of the target object.

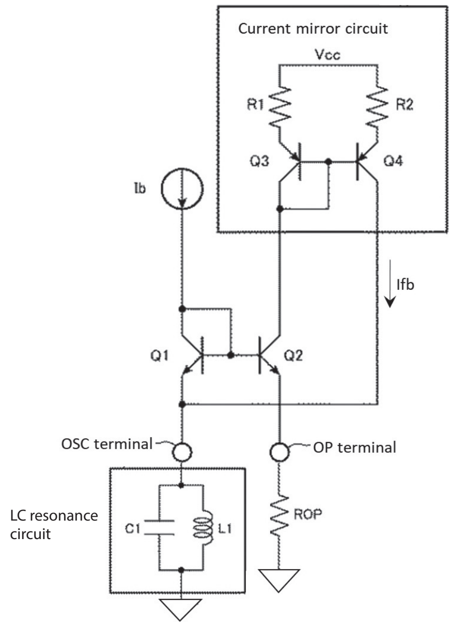


Fig. 3. Oscillator circuit of a conventional IC

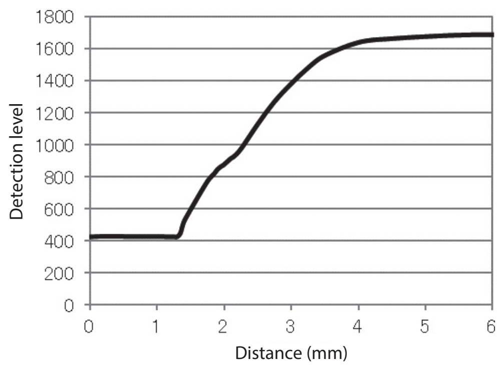


Fig. 4. Distance characteristics of the detection level of a conventional IC

2.2 Oscillator circuit of the new IC

We have developed a new IC to enable an IO-Link proximity sensor to output analog values according to the position of the target object.

The new oscillator circuit (fig. 5) consists of the resonance circuit connected to the OSC terminal, voltage setting circuit that determines the OP terminal voltage, comparator circuit that determines the timing for feedback current Ifb to flow, current mirror circuit that amplifies feedback current Ifb, and resistor ROP that determines the OP current.

First, the oscillator circuit needs to operate with positive feedback in order to maintain oscillation. In order to achieve positive feedback operation, comparator circuit CMP compares the oscillation voltage (VOSC) and the reference voltage (V1). It generates the timing so that the feedback current flows when the oscillation voltage is greater than or equal to the reference voltage and does not flow when the oscillation voltage is less than the reference voltage (fig. 6).

Next, let's explain the current mirror circuit. The current mirror circuit has a switch. This switch toggles the feedback current Ifb ON/OFF based on the timing signal of the comparator. It is also possible to adjust the oscillation amplitude by changing the mirror ratio of the current mirror circuit to amplify the feedback current as designed.

The current (Iop at the OP terminal) used to determine the feedback current Ifb in the current mirror circuit is set by dividing the voltage at the OP terminal, which is set by the voltage setting circuit, by the resistance value of the resistor ROP. This current Iop is amplified in the current mirror circuit based on the timing determined by the comparison results produced by the comparator circuit and turns into feedback current Ifb, flowing to the OSC terminal. The SG voltage becomes the center point of the oscillation amplitude in the oscillator circuit.

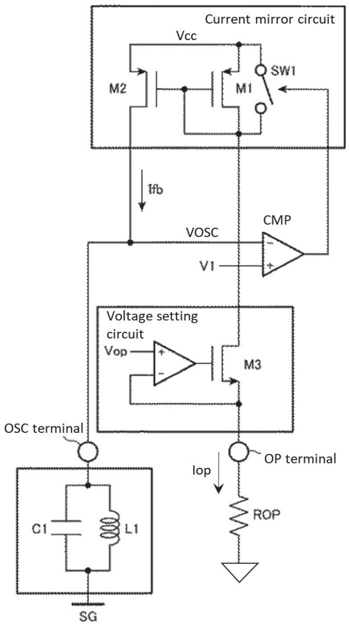


Fig. 5. Oscillator circuit of the new IC

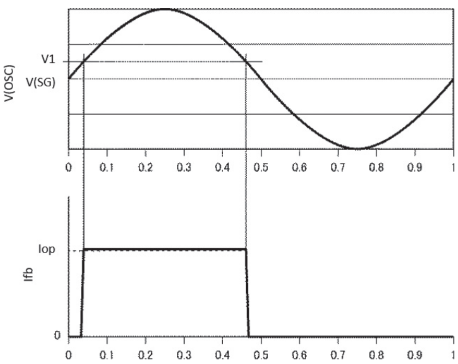


Fig. 6. Operation timing of feedback current

2.3 Problems and their solutions

In the new oscillation circuit, problems 1 to 3 of conventional ICs can be solved in the following ways.

Regarding Problem 1, feedback current Ifb is set by the current obtained by dividing Vop by the resistance value of resistor ROP and becomes constant. Therefore, the oscillation amplitude has a voltage proportional to the product of the resonance circuit impedance and feedback current Ifb (constant), thus exhibiting a characteristic nearly proportional to the impedance of the parallel resonance circuit. In addition, the circuit is configured to allow the feedback current Ifb to flow even when the target object is close, making it possible for the circuit to oscillate.

Regarding Problem 2, the value of feedback current Ifb is the value obtained by dividing the voltage at the OP terminal (≒Vop) by the resistance value of resistor ROP, and the timing when the feedback current flows is determined by comparing the oscillation amplitude with the reference voltage. Moreover, Vop is generated by the bandgap reference, which is an internal circuit of the new IC, and is a stable voltage with small temperature characteristics. This makes it possible to achieve small temperature characteristics.

Regarding Problem 3, the voltage at the OP terminal is output by the voltage setting circuit in this oscillator circuit, and this is a DC voltage. Therefore, even if parasitic capacitance is introduced around the OP terminal due to fillers or other materials, the impact on the oscillation amplitude is very small. In addition, in this oscillation circuit, by allowing the setting voltage to be digitally set using a digital-to-analog converter (DAC) or similar device, the operating point can be adjusted in an analog manner. This makes it possible to adjust the oscillation amplitude more accurately.

As a result, it becomes possible to output an analog value corresponding to the position of the target object using an IO-Link proximity sensor.

2.4 Specifications of the new IC

The newly developed IC (table 1, fig. 7) is integrated with a 0.4 µm BCD (Bipolar-CMOS-DMOS) process. It features a package size of 3.055 mm × 2.055 mm, and uses a 0.5 mm pitch Wafer-Level Chip-Size Package (WLCSP). This makes it possible to realize a compact IO-Link proximity sensor product by combining this IC with electronic parts such as a microprocessing unit (MPU).

Table 1. Specifications of the new IC

Process	0.4 µm BCD process
Operating supply voltage	7 V to 30 V
Absolute maximum rating	40 V
Operating temperature range	-40°C to 93°C
Package	WLCSP

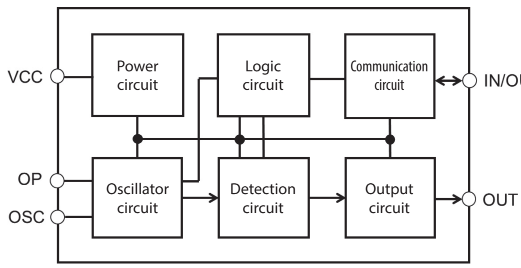


Fig. 7. IC block diagram

3. IO-Link proximity sensor incorporating the new IC and configuration tool

3.1 IO-Link proximity sensor

The IO-Link proximity sensor model H3C uses the new IC, so threshold values can be automatically taught to become optimal through IO-Link communication.

The device configuration of the IO-Link proximity sensor is shown in figure 8.

The sensor consists of (1) the sensing unit (coil/core), (2) the dedicated IC, which is a circuit integrating an oscillator circuit, etc., (3) the MPU unit for computing physical quantities, and (4) the input/output unit (IO-Link device) responsible for handling external input/output, including the IO-Link interface.

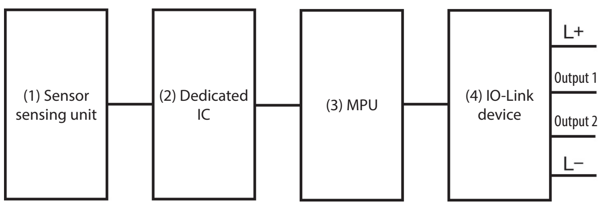


Fig. 8. Device configuration of IO-Link proximity sensor model H3C

3.2 Dedicated configuration tool

We provide a dedicated configuration tool that enables users to configure various settings or perform teaching on a PC via the IO-Link master.

IO-Link communication enables the proximity sensor to output analog values according to the position of the target object. In addition, it also makes it possible to graphically configure various settings or perform teaching with the configuration tool while looking at the analog values output from the sensor.

Examples of the setting screen (fig. 9) and graphical display screen for time series data of analog values (fig. 10) of the setup tool are shown below.

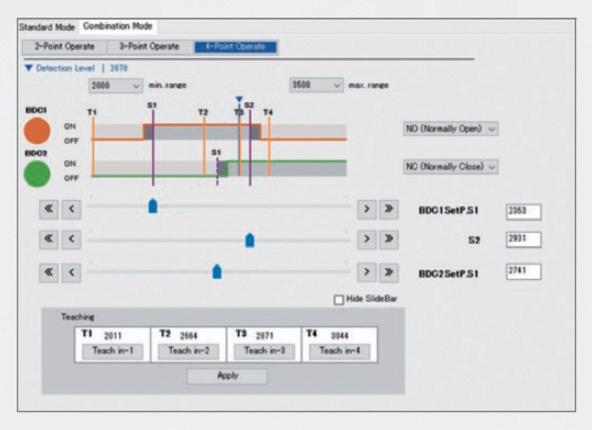


Fig. 9. Configuration tool screen example

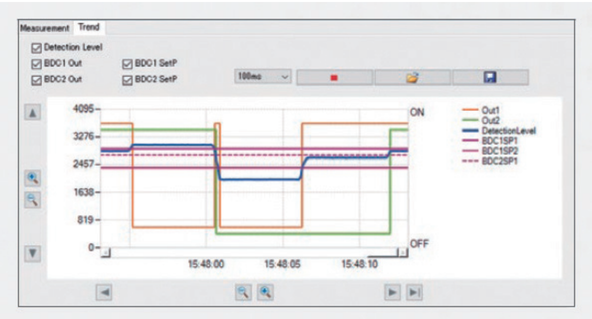


Fig. 10. Graphical display screen for time series data of analog values

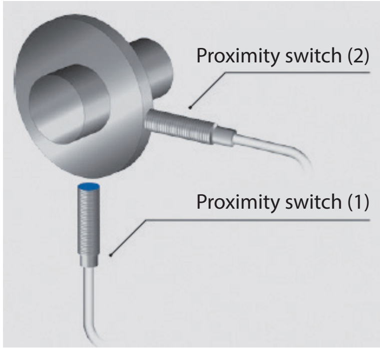
4. Example of productivity improvement

4.1 Example of easy adjustment and workload reduction

Here, we introduce an example of detecting the spindle tool clamp position in a machine tool.

In conventional tool clamping, the position of the drawbar, which corresponds to the clamping state of the tool, was detected using a proximity sensor. One proximity sensor was needed to identify two states, and two proximity sensors were necessary to identify four states (unclamped, misclamped, clamped, or clamped empty) (fig. 11). Moreover, fine adjustments by the operator were necessary, which took a considerable amount of time.

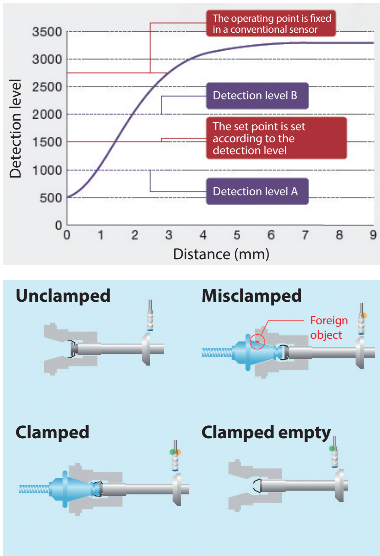
With model H3C-H, the four states can be detected with one sensor by providing the drawbar with a tapered flange section, as shown in figure 12. In addition, by using the teaching function to perform teaching for each state, three threshold values can be automatically set to their optimal values. This reduces adjustment man-hours and minimizes line troubles (fig. 13).



	Unclamped	Misclamped	Clamped	Clamped empty
Proximity switch (1)	OFF	ON	ON	OFF
Proximity switch (2)	OFF	OFF	ON	ON

Fig. 11. Tool clamping example of conventional proximity sensor

Fig. 12. Detection of four states by H3C



	Unclamped	Misclamped	Clamped	Clamped empty
Output (1)	OFF	ON	ON	OFF
Output (2)	OFF	OFF	ON	ON

Fig. 13. Results of easy adjustment / workload reduction

4.2 Example of easy adjustment and predictive maintenance

Next we introduce an example of predictive maintenance through detection of the NC rotary table of a machining center.

In figure 14, the rotary table is stopped and fixed (clamped) by the brake, the workpiece is processed, and the rotary table is rotated by releasing the brake (unclamped) to change the posture of the workpiece.

When the disc spring deteriorates, it becomes difficult for the piston to separate from the rotating disc and the fixed disc even after the pressure is reduced. If the table is rotated in this state, it may seize. With conventional proximity switches, however, it is difficult to detect the disc itself due to the small piston stroke.

In the newly developed IC, the adjustment accuracy has been improved because even a small stroke from a state in close contact with the target object causes a change in the oscillation amplitude. Therefore, teaching can be performed in both clamped and unclamped states, allowing the threshold value to be set in the middle of the detection level for each position. Furthermore, by adjusting the set values it is possible to monitor when the piston stops at the middle position and detect signs of disc spring deterioration as shown in figure 15. This allows preventive maintenance to be performed, reducing downtime and potentially leading to improved productivity.

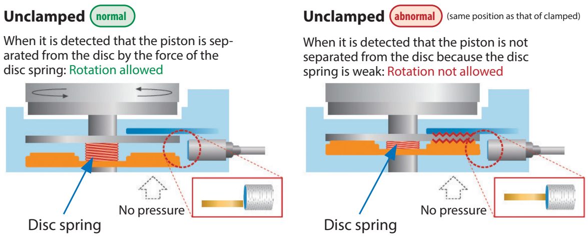


Fig. 14. NC rotary table seizure case example

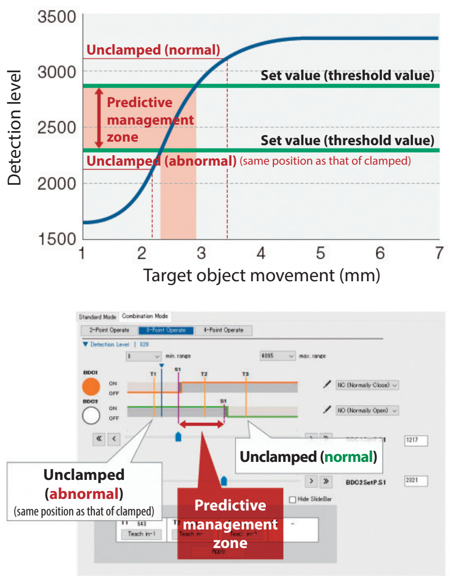


Fig. 15. Predictive detection and visualization of detection level

5. Conclusion

In order to improve the performance of proximity sensors, we have developed a new IC that has an oscillator circuit with small temperature characteristics and an oscillation amplitude proportional to the detection impedance. This IC has made it possible for an IO-Link proximity sensor to output analog values according to the position of the target object. We hope that this sensor will be utilized in preventive maintenance and remote monitoring of our customers' equipment, leading to improved productivity.

References

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[2] *Japanese Patent Application Laid-Open Publication* No. 2021-19282 (P2021-19282A)

Trademarks

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