High-speed multichannel optical telemetering system

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ABSTRACT

An optical telemetering system which measures the temperature of the rotating spindle of machine is proposed. Our system uses an optical data transmission to realize high-speed precise telemetering, it is robust for the external electric-magnetic field. Moreover it can measure the temperatures at different eight positions simultaneously and the data is transmitted with only two pairs of infrared LED and photodiode by using an asynchronous serial data transmission. We have made an experimental system and measured some fundamental characteristics. The time required for the data transmission is 48 μs a channel. It is confirmed us experimentally that the accuracy in temperature measurement is 0.4 ° C.

Keywords: telemeter, optical data transmission, temperature measurement, rotating spindle

1. INTRODUCTION

The rotating parts such as spindle of machine tool are widely used for the precise manufacturing. Recently, the performance of the spindle is improved and many kinds of high-speed spindles[1] whose rotational velocity exceeds a hundred thousand rpm are available. They are deformed with heat which is generated by the high-speed rotation. Since the machining accuracy is deteriorated with the thermal expansion of the spindle, it is required to measure the inside temperature of the rotating spindle for the sake of compensation of the accuracy.

The analysis of the deformation of machine tools have been studied for many years[2]. But it is unexpectedly rare to find the example that reports the temperature measurement under the rotation in the machine tool. This is caused by the problem in the measurement tools. Generally, the measurement of temperature in a rotating spindle are carried out with a slip ring. But the measurement with a slip ring has some problems such as a generation of heat and a change in resistance at the point of contact between brush and ring, a low durability, and an expensiveness. Although the electromagnetic wave is used for the noncontacting measurement, it is disturbed by the external electric-magnetic field and expensive because it requires a complicated signal processing.

On the other hand, since the optical data transmission is robust for the external electric-magnetic field and it can be realized inexpensively. It has used for the measurement of cutting force in the rotating machine tool[3,4] or automatic wheel balancer[5]. The system proposed here also uses the optical data transmission to measure the temperature in the rotating spindle of machine tool, but it is able to measure the temperatures at much higher speed compared with the above systems[3,4] and to transmit the data of multiple channels. That is, the measured temperatures are converted to the 12 bit digital data and transmitted serially at a rate of 500 kBPS by using an infrared light. The total number of measurement channel, which can be designated by a host computer, is eight in the present investigation. The measurable range of the temperature is between 0 and 100 °C, and the resolution is 0.025 °C. The accuracy in a temperature measurement was experimentally confirmed 0.4 °C.

In these experiments, we measured the temperatures as an example, but our system is easily applied to the measurement of various physical quantities. Moreover, the measurement is implemented at high speed in our system, it is possible to construct so called an intelligent machine tool which controls the rotational speed or pre-load of the spindle with a feedback control based on the measurement data.

2. CONSTITUTIONS OF THE SYSTEM

2.1 Whole constitutions and the arrangement of optical devices

The whole measurement system is shown in Fig.1. It consists of a personal computer (PC), an input-output (I-O) interface board, a stationary head, and a rotating head which is attached on an end of rotating spindle. The stationary head and the rotating one, which are faced each other, have a pair of optical devices LED and photodiode (PD). The optical data is transmitted as follows by an asynchronous serial data transmission. Since the system has multiple measurement channels, the PC first gives the data for the selection number of measurement channel. The number is transmitted from the LED on the stationary head to the PD on the rotating one. Then the temperature data is transmitted from the LED on the rotating head to the PD on the stationary one. The temperature data is received by the PC through the I-O interface board.

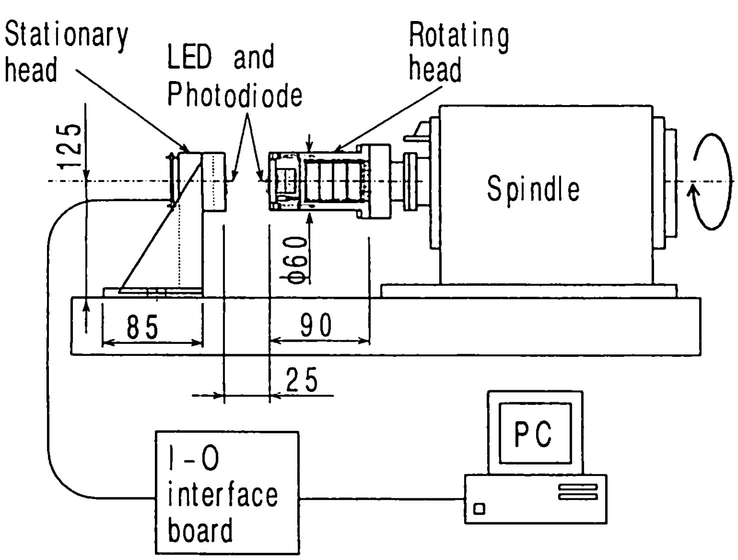

Fig.1 Optical telemetering system.

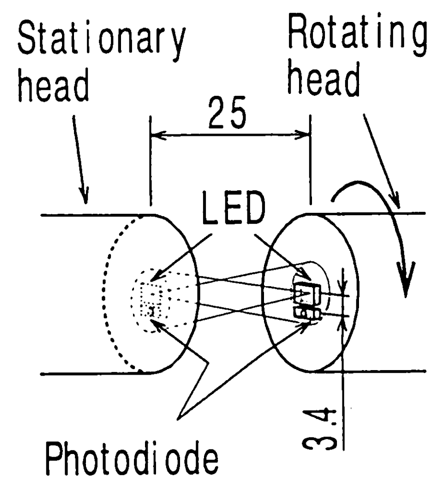

Fig.2 Arrangement of the optical devices.

The arrangement of the optical devices is shown in Fig.2. The LED's on the both head are arranged on the rotation axis, respectively. The PD is arranged nearby the each LED. Since the PD on the rotating head moves along the circumference where the distance from the rotation axis is constant, the intensity of light radiated from the LED is constant on the PD.

2.2. Signal processing

The block diagram of the I-O interface board is shown in Fig.3. The shift-resistor 1 (SR1) converts the 8 bit parallel data, which is used for the selection of measurement channel, to the serial data. The data is transferred to the LED driver synchronous with the transmission clock. On the other hand, the serial data of temperature is received by the PD, and is transferred to the synchronous clock generator (SCG) and SR2. The SCG generates the clock pulse which is synchronous to the serial data series transmitted from the rotating head. The data series are sampled by the generated clock in SR2. Then the serial data is converted to the 12 bit parallel data and transferred to the PC. Since the data conversions from parallel to serial and from serial to parallel are carried out in the I-O interface board, the burden of the PC is lightened.

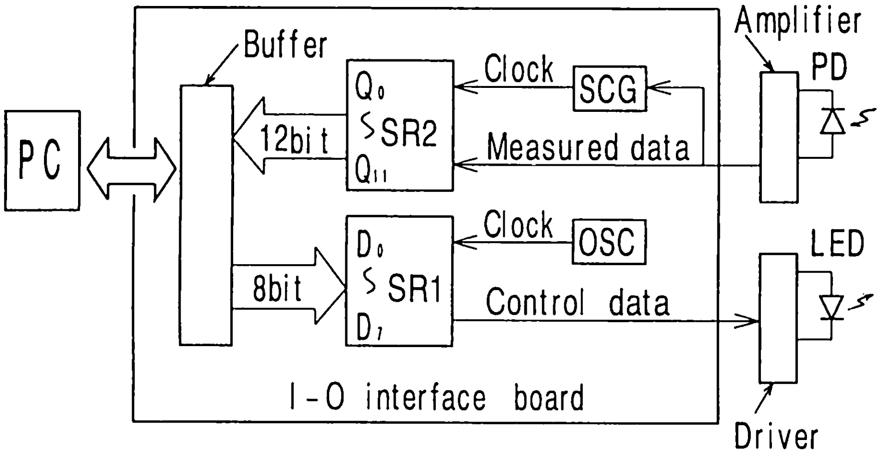

Fig.3 Block diagram of the I-O interface board.

The block diagram of the electrical circuit in the rotating head is shown in Fig.4. It mainly consists of the SCG, an A-D converter of eight channels, and eight amplifiers for thermocouples. The function of SCG is as same as that in I-O interface board. The serial data for the channel selection is detected by the

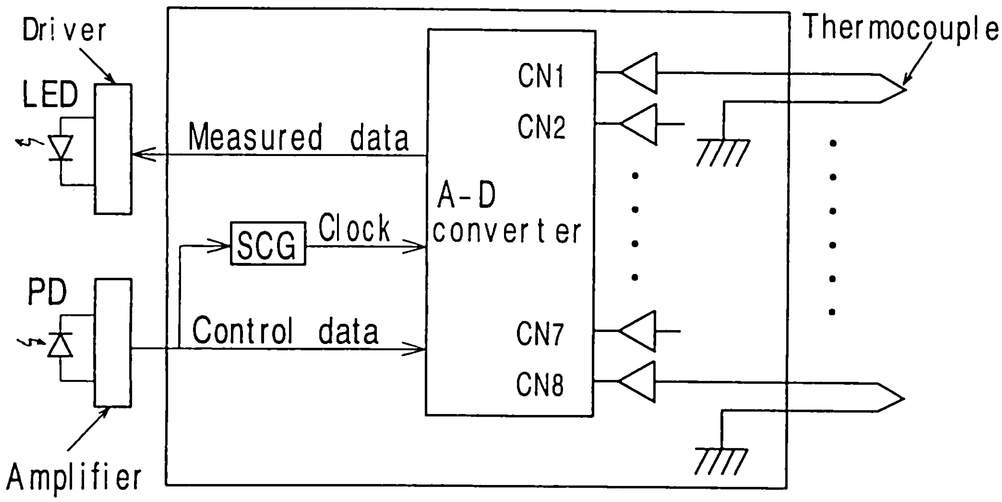

Fig.4 Block diagram of the electrical circuit in the rotating head.

PD and transferred to the SCG and the A-D converter. The A-D converter converts the measured data, which is fed into the designated channel, to the 12 bit serial digital data. The digitized data is transferred to the LED driver and transmitted to the stationary head.

2.3. Specifications of the system

The dimensions of the system is shown in Fig.1. All the electrical circuits and cells are installed in an aluminum cylinder whose inner diameter is 50 mm. The outer diameter and the length of the rotating head are 60 mm and 90 mm, respectively.

The specifications of the system are shown in Table 1. An infrared light whose wavelength is 880 nm is used. The optical devices are covered with an infrared filter to remove the external visible light. Since the frequency of the data transmission clock is 250 kHz, the rate of the data transmission is 500 kBPS. The total number of the clocks required for the data transmission is 24, which consists of a control byte (8 bit) for the channel selection, a start bit (1 bit), the data bits (12 bit), and the idle bits (3bit). Consequently, the time required for one measurement is 48 μs. The total number of channel is eight. Since the measurement range is from 0 to 100 °C, the resolution of the temperature is calculated to 0.025 °C. The power for the circuit in the rotating head is supplied from the series of two lithium cells and its voltage is 6 V. The current supplied from the battery is ~27 mA at the idle state, while it becomes ~34 mA at the communicating state. The life of the battery is ~10 min in a continuous operation. But the life of the battery expected to grow longer by improving the circuit related to the battery. The used thermocouple is the J-type one and the cold junction compensation is made by an electrical circuit.

Table 1 Specifications of the system.

Wavelength	880nm
Channel number	8ch
Transmission rate	500kBPS
Measurement time	48 μs
Measurement rang	0~100 ℃

3. EXPERIMENTS

3.1. Response of the optical devices

We first measured the response characteristics of the optical devices. The continuous rectangular wave was applied to the LED driver from an oscillator and the wave form detected by the PD was observed. The duty cycle of the rectangular wave was 50 %. Since this is equivalent to digital data that repeats high and low alternately, it creates severe conditions for communications. The frequency of the rectangular wave was set at 500 kHz, which is equivalent to a 1000 kBPS transmission rate. The observed results are shown in Fig.5. The upper trace is the wave form of the rectangular current injected to the LED. The wave form detected by the PD is shown in the lower trace. Its pulse width agrees well with that of the upper trace. The detected signal was delayed by ~1 μs throughout the observation. This delay, however, exerts no influence on the asynchronous data communication because the data is transmitted correctly, so long as the pulse width is unchanged. The results shown in Fig.5 confirmed that the optical devices had sufficient ability to transfer data at the rate of 500 kBPS.

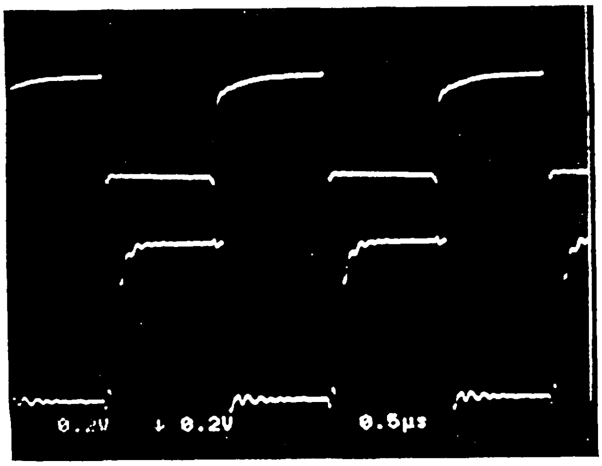

Fig.5 Response of the optical devices.

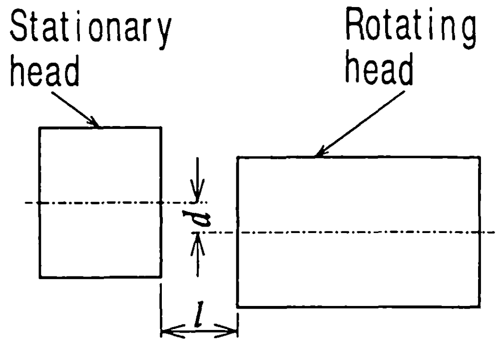

Fig.6 Relative position between the both heads.

3.2. Robustness for the misalignment of the optical devices

The relative position between the both heads is shown in Fig.6. Since the rotating head revolves at high speed, there is always the possibility that the relative position between the optical devices is changed. In optical communications, the pulse width of the data received by PD is easily changed with the intensity of light transmitted from the LED. To clarify the influence of radial misalignment d and gap length l, we applied a known voltage to each channel of the A-D converter, instead of the output voltage of the thermocouple. Then we carried out a total of 80 different communication exercises, by varying d or l.

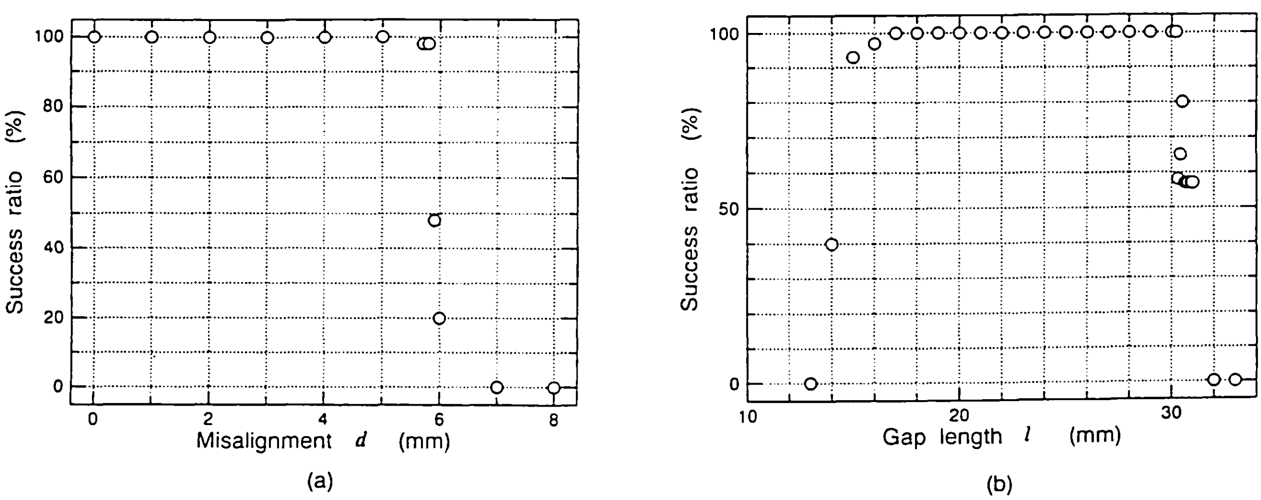

Fig.7 Success ratios versus (a) d and (b) l.

The success ratios for each value of *d* and *l* are shown in Fig.7(a) and (b), respectively. Figure 7(a) shows that the success ratio versus *d* is always 100 % when *d* is below 5 mm. On the other hand, Fig.7 (b) shows that the success ratio versus *l* is always 100 % when *l* lies in a region between 17 mm to 30 mm. Consequently, the margin of misalignment and gap length are 5 mm and ±7 mm, respectively.

3.3. Compensation of the nonlinearity of thermocouple

Since the thermocouple itself contains a nonlinearity, we have linearized it by using a table of the electromotive force (emf) of the J-type thermocouple shown in the Japanese Industrial Standard (JIS C1602-1981). This table shows the thermocouple's generating voltage at every 1 °C. We dipped the thermocouple in the water of homogeneous temperature in a thermos bottle and measured the amplified voltage of thermocouple at different two temperatures. The temperatures of water, θ_1 and θ_2, are monitored simultaneously with a standard thermometer. We compensated the curve given by the JIS, so as to pass the two points obtained by the above measurement. The equations for the compensation are given as;

$$k\{v(\theta_1)+c\}=V_1, \quad (1)$$

and

$$k\{v(\theta_2)+c\}=V_2, \quad (2)$$

where θ_1 and θ_2 are the known temperatures measured by the standard thermometer, $v(\theta)$ is the thermal emf shown in the JIS, V_1 and V_2 are the amplified voltages of the thermocouple, and k and c are coefficient and constant which correspond to the gradient and the offset voltage, respectively. From Eqs.(1) and (2), k and c are calculated as follows:

$$k=\frac{V_1-V_2}{v(\theta_1)-v(\theta_2)}, \quad (3)$$

$$c=\frac{V_2}{k}-v(\theta_2)\ . \quad (4)$$

These coefficients are determined with the voltage measured at θ_1~10 °C and θ_2~80 °C, and we calculated the compensated emf shown in the JIS at intervals of 5 °C. Moreover, we approximated them with a 3rd order equation

$$\theta=a_3V^3+a_2V^2+a_1V+a_0 \quad (5)$$

to simplify the conversion from voltage to temperature, where θ is a desired temperature and V is a measured voltage. Consequently, the nonlinearity is compensated including that of electrical circuits such as amplifiers.

3.4. Measurement of the temperature

The experimental setup and the measurement positions of temperature are shown in Fig.8. The numbers shown in the figure correspond with the channel numbers. All the measuring junctions of the thermocouples rotate with the rotor of the spindle. The first channel (CN1) and the eighth channel (CN8) are used to measure the temperature of the open air and that of the closed air in the spindle, respectively. We compared the temperature measured by CN1 with that measured by a data logger (ETO DENKI, Thermodac-E, Type 5001A), whose resolution and measurement accuracy are 0.1 °C and 0.2 °C, respectively. The sensor head of the Thermodac was settled with the magnet base at close the measurement junction of CN1. In this experiment, a hair drier was used at the position shown in Fig.8 to ensure warming the air.

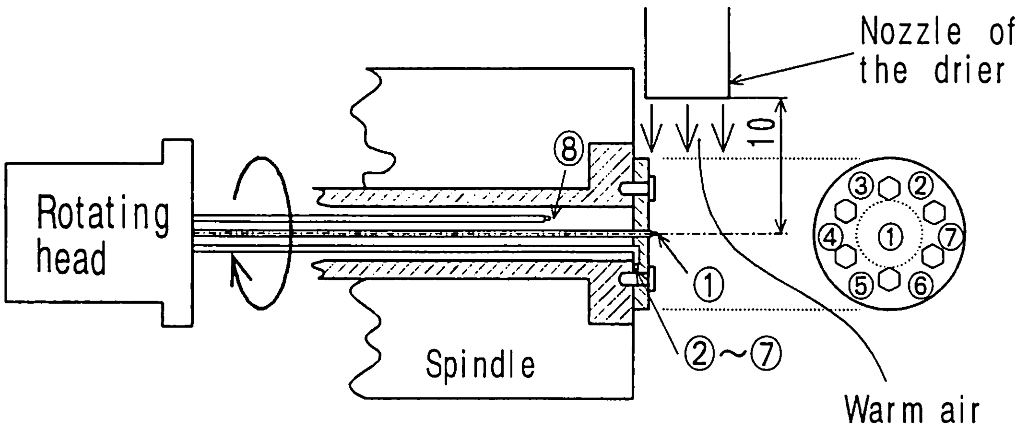

Fig.8 Experimental setup and the measurement positions of temperature.

We measured the temperatures by rotating the spindle at a speed of 1000 rpm. The experimental results are shown in Fig.9. The power of the rotating head is supplied with the battery and the measurement time was less than 10 min in the present system. The drier was operated from 40 sec to 6.5 min. Figure 9(a) shows the temperatures of the open air measured with CN1 and the Thermodac. The both temperatures

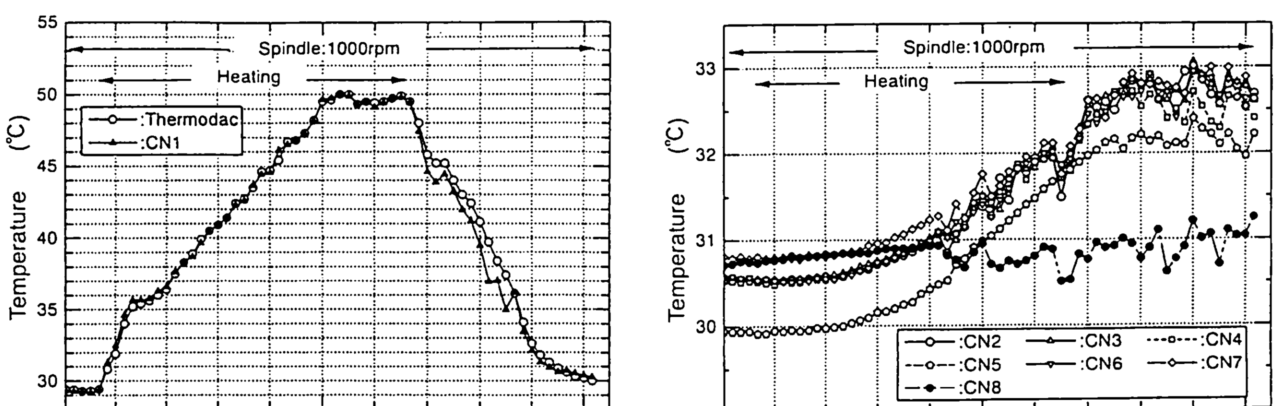

Fig.9 Temperatures measured with (a) CN1 and Thermodac, and (b) CN2 ~ CN8.

agree quite well, and it is clarified that telemetering system has a good performance. The temperatures measured with the other channels are shown in Fig.9(b). Although the temperature measured with CN8 shows a little fluctuations, the rise of the temperature can be scarcely found. Since the thermocouples for CN2 to CN7 are settled at the axisymmetrical positions on the front end surface of the rotating spindle, it is expected that these channels show the same temperature at each measuring instance. The temperatures measured with CN2, CN3, CN4, and CN6 are agree quite well at each instance. The maximum difference of the temperature between these channels is ~0.4 °C. The results of CN5 and CN7 show the same tendency as those of aforementioned channels, but they have some offset temperatures compared with the other channels. It is supposed that these differences come from the error in the experiment described in Sec.3.3. Moreover, it is supposed that the fluctuations observed in Fig.9(b) after ~4.5 min come from the drop in voltage of the battery. From the above discussions, the accuracy in the temperature measurement is confirmed 0.4 °C in our system.

4. CONCLUSIONS

The optical telemetering system which is effective for the temperature measurement in a rotating spindle of machine tool was described. Our system has following some attractive features: 1) it is realized to measure the temperatures at multiple channels which is designated by a host computer, 2) since the communication is carried out simply with two pairs of LED and PD, the system is inexpensive and can be realized easily, and 3) the data form, serial digital data, used in our system matches the computer. The extension of the measurable time and the improvement of the measurement accuracy are required for the practical use. We described the temperature measurement, but our system can be applied for the measurement of the various physical quantities other than temperature if the thermocouple is replaced by other sensors, for example, acceleration sensor, strain gauge, and so on.

5. ACKNOWLEDGMENTS

The authors greatly appreciate the financial support by the Electro-Mechanic Technology Advancing Foundation. We are grateful to Kazuhiro Honda, Isao Hamashima, and Satoru Endo for their help with the experiments.

6. REFERENCES

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