Current Probe CT6700/CT6701

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Abstract—The Current Probe CT6700/CT6701 is a clamp-on current sensor whose principal features are high current detection sensitivity, which makes possible observation of low-current waveforms, and broad frequency band. This paper describes the features, architecture, and characteristics of the CT6700/CT6701.

I. INTRODUCTION

Hioki has developed a number of clamp-on current probes with wideband characteristics that can be connected directly to waveform observation instruments to observe current waveforms (including the Clamp On Probe 3273-50, 3274, 3275, and 3276) [1]. These products are used to observe current waveforms in power control circuits and a range of electric equipment.

In recent years, there has been considerable progress in boosting energy efficiency and reducing power consumption in devices such as electric products, electric devices, and portable devices. These developments have made it desirable for current probes to exhibit characteristics that enable observation of lower-level current waveforms.

The Current Probe CT6700/CT6701 was developed in response to market needs such as these in order to enable observation of low-current waveforms thanks to its higher current/output voltage conversion rate (“output rate”).

II. OVERVIEW

Compared to previous products (the 3273-50 and 3276), the CT6700/CT6701 delivers wideband characteristics as well as 10 times the output rate (1 V/A).

In order to enable observation of low-current waveforms by increasing the output rate, it is necessary to reduce the noise generated by the current probe itself. With the CT6700/CT6701, Hioki sought to improve the characteristics of the detection element, which is a primary source of noise. The result is a sensor with an S/N ratio that makes it possible to observe low-current waveforms of about 1 mA.

In addition, the sensor offers wideband characteristics from DC to 120 MHz (−3 dB [CT6701]) and can be used in current waveform observation applications, including those involving currents containing a variety of frequency components.

In terms of functionality, Hioki has improved convenience by equipping the sensor with demagnetization and automatic zero-adjustment as well as warning functionality. In addition, the CT6700/CT6701’s output terminal can be connected to, and disconnected from, the BNC input terminal on the host waveform observation instrument smoothly and easily.

III. FEATURES AND FUNCTIONS

A. High Output Rate to Enable Observation of Low-Current Waveforms

The CT6700/CT6701’s most noteworthy features are its high output rate and S/N ratio. Previous Hioki products had an output rate of 0.1 V/A. Since the output voltage for a current of 1 mA was 0.1 mV, it was difficult to observe low-current waveforms with those products.

The CT6700/CT6701’s output rate is 1 V/A, or 10 times the previous model rate. Combined with the sensor’s low noise level, this high output rate makes it possible to observe low-current waveforms.

B. Wideband Characteristics

The CT6700/CT6701 has broad frequency response characteristics, including for DC waveforms. The two products offer the frequency band specifications listed below.

The sensor can be used for the purpose of observing high-speed response waveforms such as transient response waveforms and inrush current waveforms, or current waveforms that include a variety of frequency components.

• CT6700: DC to 50 MHz (−3 dB)
• CT6701: DC to 120 MHz (−3 dB)

C. Demagnetization and Automatic Zero-Adjustment Functions

The CT6700/CT6701 lets users perform demagnetization followed by zero-adjustment with the press of a single key,
simplifying an otherwise bothersome process. Users can also perform zero-adjustment alone by pressing the key for a shorter period of time.

The sensor consists of a magnetic core and Hall element. The zero-point characterizing the current probe’s output varies as a result of the magnetization of the magnetic core after a large current is input and variations in the element’s offset voltage. Consequently, it is necessary to demagnetize the sensor and then to perform zero-adjustment while observing output values before measurement. The CT6700/CT6701 allows these operations to be completed by operating a single key.

D. Warning Function

The CT6700/CT6701 provides functionality for alerting the user to an overload (indicating that the input current value exceeds the sensor’s rated value) or jaw unlocked condition (indicating that the clamp’s sliding jaw mechanism has not been locked in place) by means of an LED lamp that may flash or turn on continuously.

E. Output Terminal That Can Be Connected and Disconnected Easily

The CT6700/CT6701’s output terminal can be easily connected to, and disconnected from, the BNC input terminal on the waveform observation instrument being used. When connecting the terminal, the user simply pushes on the termination box to lock it in place. The terminal can then be unlocked to disconnect it by pulling on the termination box while simultaneously pulling a lever.

In addition, the BNC input terminal’s shell incorporates a pair of studs that fit into a bayonet lock so that the connection can be established without changing the orientation of the termination box, regardless of whether the pair of studs are fixed in the horizontal or vertical orientation.

IV. Architecture

A. Circuit Architecture

1) Operating principles: Like the 3273-50, 3274, 3275, and 3276, the CT6700/CT6701 is an AC/DC zero-flux current probe that uses a thin-film Hall element (see Fig. 1). Since the zero-flux design allows formation of a negative feedback circuit that includes the magnetic circuit, the operating magnetic flux level can be kept extremely low. Consequently, this design is characterized by the ability to minimize the effects of its unique nonlinearity on the magnetic core’s magnetic characteristics. As a result, the sensor offers outstanding linearity, measurement range, sensitivity, frequency characteristics, and other characteristics [2].

2) Circuit architecture: Fig. 2 provides a diagram for the CT6700/CT6701 circuit block. The circuit architecture’s features include the following:

- Demagnetization and automatic zero-adjustment functions
- A variety of built-in warning functions
- A low-noise negative feedback circuit
- A signal transmission circuit that delivers wideband characteristics

Aspects such as filtering, a shielded structure, and grounding play an important role in the design as ways to counter external electromagnetic noise, common-mode noise from the measurement circuit, and other potential issues.

3) Negative feedback circuit: In order to increase the output rate and make possible observation of low-current waveforms at a high S/N ratio, it is necessary to lower the noise from the current probe itself and to increase the detection sensitivity of the magnetic field emitted by the current being measured.

In addition, stable operation is required since a negative feedback circuit that includes the magnetic circuit is formed to route a negative feedback current to the winding and cable.

The principal sources of noise in the negative feedback circuit are the Hall element, its drive circuit, and the amplifier. Concerning the Hall element, Hioki dramatically reduced noise by studying optimal manufacturing conditions [3]. The circuit that drives the Hall element, which uses a reference voltage source and high-frequency cutoff filter, has been set to the optimal drive level. The negative feedback circuit, which serves to amplify the minute Hall element output voltage, consists primarily of a pre-amplifier and an power amplifier. By using a differential setup for the pre-amplifier, it is possible to reduce common-mode noise. The power amplifier consists of a low-noise operational amplifier and a current buffer that uses a power transistor so that it can achieve its objective of stable, low-noise operation.

4) Transmission circuit: In order to implement wideband characteristics, the characteristic impedance of signal
transmission lines such as the sensor circuitry, terminal circuitry, and cables is roughly matched to the termination resistance, which has been set to 50 Ω.

In addition, since heat is generated when the negative-feedback current flows to the terminal resistor, Hioki has worked to design compact termination circuitry while keeping the thermal resistance of heat transfer routes to the heat dissipation unit low.

5) Digital circuit: The CT6700/CT6701’s termination unit incorporates a compact CPU with a built-in A/D converter and a D/A converter as well as an external D/A converter (see Fig. 2). Characteristic of this design is the ability to automatically perform demagnetization and zero-adjustment, which in previous models required manual switch and dial operation, by means of a simple key operation. The circuit also incorporates an OVERLOAD detection function for warning users when the rated input current is exceeded and a JAW UNLOCKED detection function for warning users when the slider has not been closed, leaving the jaws unlocked.

- Demagnetization and zero-adjustment functions

By pressing and holding the DEMAG/AUTO ZERO key, it is possible to perform demagnetization and then zero-adjustment. Conversely, zero-adjustment alone can be performed by pressing the key and then releasing it quickly. Since adjustment completes in an extremely short amount of time, this function provides a convenient way to perform zero-adjustment for measurement once demagnetization has already been performed.

a) Demagnetization function: The demagnetization waveform, which previously was generated by an analog circuit, is generated digitally in the CT6700/CT6701 using the CPU and external D/A converter. Fig. 3 illustrates (an example of) amplitude variations in this demagnetization waveform. By temporarily stopping the supply of control current to the Hall element, negative feedback is canceled, and demagnetization is performed. Current is supplied to
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the Hall element after demagnetization, and then zero-
adjustment is performed automatically after waiting for the
offset drift to become sufficiently small.

Furthermore, demagnetization is performed a total of
two times in order to cancel the unintentional magnetization
that results when supply of the control current to the Hall
element is initiated.

b) Zero-adjustment function: In the past, zero-
adjustment was performed by connecting the sensor to
an oscilloscope or other waveform display device and
then operating a dial while observing the device’s output
voltage. The CT6700/CT6701 performs zero-adjustment
automatically by using the CPU’s built-in A/D converter to
measure the zero level that will serve as the reference and
then controlling the D/A converter’s output so that the output
level goes to zero. To shorten the amount of time required to
perform zero-adjustment while simultaneously increasing
the operation’s precision, the sensors use the CPU’s built-in
D/A converter to perform a coarse adjustment and then use
the external D/A converter to perform a fine adjustment.

- OVERLOAD detection function

When demagnetization or zero-adjustment has not been
performed, the output signal is digitally sampled by the
CPU’s built-in A/D converter, and its RMS value and crest
value are simultaneously calculated. The square sum buffer
is extracted after being divided by the number of sampling
points M, and the RMS value \( AD_{rms} \) of the A/D value is
calculated (1). Here \( S \) indicates the sample point number.

\[
AD_{rms} = \sqrt{\frac{1}{M} \sum_{s=0}^{M-1} AD_S^2} \quad (1)
\]

Over-range input detection is performed using the
calculated RMS value and crest value as references, and
the OVERLOAD LED flashes to alert the user if necessary. Once the over-range input state ceases, the DEMAG/AUTO
ZERO LED flashes to encourage the user to demagnetize
the sensor to allow more accurate measurement. The over-
range input detection range consists of DC as well as 50
Hz/60 Hz commercial frequencies. The sensor also includes
a temperature detection IC, and over-range input of high-
frequency current that cannot be detected adequately
by means of digital sampling is detected based on heat
dissipation from the circuit to increase device safety.

- Jaw unlocked detection function

A contact PCB built into the slider detects high/low by
switching the connected state of contact brushes (on the
sensor PCB) to detect whether the jaw is unlocked. The
detection signal line is pulled up so that when the sensor
heads are not closed the contact fixture will be isolated from
ground, resulting in high detection and causing the JAW
UNLOCKED LED to light up. When the sensor heads are

\[ \sum_{s=0}^{M-1} AD_S^2 = AD_{rms} \]

Fig. 4 illustrates the structure of the upper and lower
sensor heads, which comprise the current detection unit.
The heads consist of a ferrite core, a thin-film Hall element
mounted in its aperture, windings, shielding cases, and
other parts.

Once these parts have been assembled to form the
magnetic core, they are placed in the shielding cases and
filled with epoxy resin, which is then hardened. Then the
mating surfaces of the upper and lower sensor heads are
polished.

C. Jaw Mechanism and Termination Unit

1) Sensor construction: As illustrated in Fig. 5, the
sensor consists of upper and lower cases, the slider, and the
sensor PCB. The lower sensor head is contained in the upper
case, while the upper sensor head is contained in the slider.

2) Jaw mechanism: Fig. 6 illustrates the construction of
the slider.

The slider opens when the opening lever is pulled and
closes by means of a spring. When the slider closes, the
slider’s pawl fits into an indentation in the upper case. When
the lock is released, the pawl moves inward and out of the
indentation, allowing the mechanism to slide (top of Fig. 7).
When the lock is engaged, the opening lever blocks the space
into which the pawl would otherwise move, preventing the
mechanism from sliding (bottom of Fig. 7).
The act of engaging and releasing the lock is accompanied by the following functionality:

—The arm moves together with the opening lever. In the lock state, the flat spring pushes against the upper sensor head via the arm, pushing the upper and lower sensor heads closer together.

—The contact PCB contacts the contact brushes on the sensor PCB and moves together with the opening lever. A short or open state is obtained between the contact brushes depending on the position of the contact PCB, and the JAW UNLOCKED LED lights up or turns off as appropriate.

—In the lock state, the upper sensor head’s shielding case is in electrical contact with the contact PCB via the arm and other parts. One of the contact brushes is connected to ground, keeping the sensor head shielding case at the ground potential.

3) Termination unit construction: As illustrated in Fig. 8, the termination unit consists of left and right cases, two PCBs, shielding plates, and a BNC connector. The main PCB, digital PCB, and three shielding plates are layered together and then sandwiched in between the left and right cases with the BNC connector and held in place with screws.

4) BNC connector lock mechanism: Fig. 9 illustrates the BNC connector’s architecture.

The arms and lock members can be rotated around the axis of rotation and the BNC connector’s central axis, respectively.

When the BNC connector is connected, the protrusions on the BNC connector press against the protrusions on the lock members (see Fig. 10), causing them to rotate. Once the BNC connector is inserted as far as it will go, the lock members are returned to their original position by a spring, causing the protrusions on the BNC connector to catch on
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Fig. 8. Termination unit construction.

Fig. 9. BNC connector construction.

the protrusions on the lock members so that the connector is in the lock state.

Pulling on the lever causes the lock members to rotate via the arms. In this way, the protrusions on the lock and BNC connector are disengaged, causing the lock to be released and allowing the connector to be removed.

V. CHARACTERISTICS

A. Observed Low-Current Waveforms

Fig. 11 depicts a 1 mA p-p 1 kHz sine wave current as observed by the CT6701 and 3276. The 3276 has an output rate of 0.1 V/A, and the low amplitude of its output waveform makes it difficult to observe this waveform. By contrast, the CT6701 yields 10 times the output voltage, and the instrument’s low-noise performance is clear. The CT6700 and CT6701 share the same low-noise characteristics.

B. Frequency Characteristics (Output Rate)

As shown in Figs. 12 and 13, the probes have a broad frequency band, although amplitude attenuation and gain are evident above approximately 2 MHz.

C. Linearity of Output Voltage Relative to Input Current

The instrument yields excellent linear characteristics for both DC and AC, neither of which is dependent on the input current level (see Fig. 14).
With the CT6700/CT6701, variations in the alignment of the sensor heads have a significant impact on output values. The alignment of the heads is affected by factors such as the presence of foreign materials, damage to the mating surfaces of the heads, mechanical stress (for example, when the sensor is dropped), and variations in the ambient temperature and humidity.

**D. Temperature Characteristics (Sensitivity)**

As shown in Fig. 15, the CT6700/CT6701’s sensitivity (output rate) is affected by the ambient temperature.

**E. Influence of Conductor Position**

Since the diameter of the clamp window is small, the influence of conductor position on measured values is also small (see Fig. 16).

**F. Temperature Characteristics (Offset Voltage)**

The Hall element is the principal cause of offset voltage. Since its characteristics vary with the ambient temperature, the offset voltage varies as shown in the measurement example depicted in Fig. 17 and is additionally subject to individual differences.

**G. Influence of Magnetization**

The magnetic material used in the magnetic core exhibits hysteresis characteristics, affecting output values when the current changes. Fig. 18 illustrates the residual offset voltage following application of a DC current. This is an example of the influence of magnetization.

**H. Insertion Impedance**

Fig. 19 depicts example characteristics for insertion impedance. These characteristics illustrate that clamp-on current sensors become part of the load of the circuit under measurement.

In addition, the characteristics bear out the fact that the CT6701 has lower insertion impedance than the CT6700.
I. Influence of External Noise Voltage (Common-Mode Voltage)

Fig. 20 indicates \( V_o / E \), the ratio of the voltage \( E \) applied to a conductor positioned in the clamp window and the resulting output voltage \( V_o \).

J. Influence of External Magnetic Fields

Fig. 21 depicts an example measurement made with the CT6701. The magnetic field intensity \( H \) applied during the measurement shown is equivalent to approximately 10 times the Earth’s magnetism.

K. Frequency Derating

Because the temperature of the sensor’s internal components and outside surface rises during current measurement due to self-heating, a series of maximum current values that can be input continuously have been set for each sensor, as shown in Fig. 22. However, note that these maximum values apply to sine wave current input. When the current waveform under measurement contains high-frequency components, the temperature will increase, reducing the current value that can be continuously input.

In addition, because the CT6700 is characterized by a larger rise in temperature, it has lower maximum current values than the CT6700.

VI. Conclusion

This paper has described the features and characteristics of a pair of current probes with high current detection sensitivity that were developed by Hioki in order to enable observation of low-current waveforms. Hioki expects these products to enjoy broad use in the market going forward.

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References


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