Technical Note

Current Probe CT6710/CT6711

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***Abstract*—The Current Probe CT6710/CT6711 series (hereinafter called the CT6710/CT6711) is a clamp-on current sensor that offers three current-output voltage conversion rates (henceforth called output rates) which provides three measurement ranges. This enables a broad frequency band that allows the probes to observe currents across a wide range of magnitudes. This paper provides an overview of the product; discusses their functionality, features, characteristics, and architecture; and provides several example measurement applications.**

I. Introduction

Hioki has developed various clamp-on (non-contact) current probes with wideband frequency characteristics that can connected directly to waveform measuring instruments for use in observing current waveforms (including the Clamp on Probes 3273-50/3274/3275/3276 and the Current Probes CT6700/CT6701)[1][2]. These products are used to observe current waveforms in power control circuits and various parts of other electronic devices.

Electrical products, electronic devices, mobile handsets, and other products have offered increasing power savings in recent years thanks to improved energy utilization efficiency and reduced power consumption. Hioki developed the CT6700/CT6701 to meet customer demand for a probe with a high output rate so that it could be used to observe small currents. The drive to deliver increased power savings has accelerated as manufacturers achieve lower current consumption. Current probes must offer characteristics that are conducive to observing ever-smaller currents with a high degree of precision. Development of faster, higher-current power switching devices has been noteworthy in recent years, creating new opportunities for measuring not only small currents, but also normal load currents. Past current probes had a single range, which made it impossible to broaden the range of currents that they could measure. As a result, customers had to purchase multiple current probes based on the applications and currents that they needed to measure. In the observation of current waveforms, which is necessary in order to engineer power savings, it is desirable that current probes offer a broad measurement scope that can accommodate input ranging from small currents to normal load currents, along with wideband frequency characteristics and low noise.

Hioki developed the CT6710/CT6711, which offers three ranges with coverage from high-sensitivity to low-sensitivity measurement, to meet these market needs. Fig. 1 depicts the appearance of the CT6710. In this way, Hioki engineered a device capable of observing currents across a wide range of frequencies and magnitudes at low noise levels.

Fig. 1. Appearance.

II. Overview

The CT6710/CT6711 delivers an output rate of 10 V/A, 10 times that of the previous models, the CT6700/CT6701. It also provides three ranges–10 V/A, 1 V/A, and 0.1 V/A–and wideband frequency characteristics at low noise levels.

In order to observe low-current waveforms, current probes must have a high output rate with low-noise. To that end, it is necessary to limit noise generation inside the current probe. The CT6700/CT6701 series accomplishes that task by using a detection element, which is the principal source of noise in a current probe, with improved characteristics [3], allowing it to achieve a signal-to-noise ratio that enables the device to observe low-current waveforms of about 1 mA. The CT6710/CT6711 also uses this detection element but delivers an output rate that is 10 times greater by using transmission circuits and active elements, achieving both low-noise performance and wideband characteristics. It switches among transmission circuits to provide three ranges: 10 V/A, 1 V/A, and 0.1 V/A. The device provides wideband characteristics from DC to 120 MHz (CT6711) for all output rates, allowing it to be used to observe a variety of current waveforms.

The product also delivers improved convenience with demagnetization, automatic zero adjustment, and warning functionality. In addition, the CT6710/CT6711 further boosts usability because its output terminal can be quickly and easily connected to the BNC input terminal of a waveform measuring instrument.

III. Functions and Features

A. High Output Rate for Observing Low-Current Waveforms

The most noteworthy features of the CT6710/CT6711 are its high output rate and signal-to-noise ratio. The previous Hioki model had a maximum output rate of 1 V/A. As device power efficiency has been increasing in recent years, the operating currents of measurement targets such as electrical devices have fallen below 1 mA. When observing such small currents, the previous model's output rate produced an output voltage of 1 mV when measuring a current of 1 mA. When the output rate is low, minuscule current waveforms are obscured by the measuring instrument's noise floor, making observation at high signal-to-noise ratios difficult.

The CT6710/CT6711's maximum output rate of 10 V/A, which is 10 times that of the previous model, and its low noise level allow the device to observe even smaller current waveforms.

B. Wideband Characteristics

Thanks to broad frequency response characteristics that include DC, the CT6710/CT6711 can be used to observe high-speed response waveforms such as transient response and in-rush current as well as current waveforms that contain a variety of frequency components.

The products' frequency bands conform to the following specifications:

- CT6710: DC to 50 MHz (-3 dB)
- CT6711: DC to 120 MHz (-3 dB)

C. Three ranges: 10 V/A, 1 V/A, 0.1 V/A

Past Hioki current probes all had a single range. The CT6710/CT6711 adds a new 10 V/A range to the previous models' 0.1 V/A range (3273-50/3276) and 1 V/A range (CT6700/CT6701), for a total of three ranges.

Whereas it was necessary in the past to provide multiple current probes in accordance with the nature of the measurement target and its current level, the CT6710/CT6711 offers a single-probe solution.

D. Demagnetization and Automatic Zero Adjustment

The CT6700/CT6701 series' demagnetization and automatic zero adjustment functionality is also provided by the CT6710/CT6711.

Users can perform demagnetization and then zero adjustment with a single key press, simplifying operation. A shorter key press triggers zero adjustment alone.

The sensor consists of parts including a magnetic core and Hall element. Measurement of large currents and changes in temperature cause the magnetic core's magnetization and the element's offset voltage to shift, changing the zero point of the current probe's output. Consequently, until now it was necessary to demagnetize the core and then to perform zero adjustment while observing the device's output value prior to measurement. The CT6710/CT6711 allows these operations to be performed with a single key press. Additionally, the products' demagnetization and automatic zero adjustment sequence has been improved with faster processing than that of the CT6700/CT6701 so that demagnetization and automatic zero adjustment can be performed quickly.

E. Warning Functionality

The CT6710/CT6711 provides the following warning functionality:

- *Overload (input rating exceeded):* The OVERLOAD LED flashes quickly.
- *Relay box internal overheat:* The OVERLOAD LED flashes quickly.
- *Jaw unlock:* The JAW UNLOCKED LED illuminates.

These LED indicators either flash or illuminate in order to warn the user when the device detects an anomaly.

F. Protective Mode

Each of the CT6710/CT6711's three ranges has a maximum rated current. A user may leave the probe affixed to a wire while unanticipated input or erroneous operation is causing the defined current level to be exceeded. In the event such measurement continued, the current detector resistor and other components could become hot, damaging the device and posing a burn hazard. The CT6710/CT6711's circuit board includes a temperature IC that monitors the device's internal temperature. In the event a predetermined temperature is exceeded, the device enters a protective mode that limits heat generation by immediately transitioning to an internal configuration that produces the least amount of heat.

G. Output Terminal That's Easy to Connect and Disconnect

The CT6710/CT6711 uses the same BNC mechanism as the CT6700/CT6701 so that its output terminal can be easily connected to, and disconnected from, a waveform measuring instrument's BNC input terminal. When connecting the terminal, press until the termination box locks the connector in place. When disconnecting the terminal, pulling on the termination box while pulling on a lever disengages the lock.

The shells on BNC input terminals incorporate a pair of protruding studs that creates a bayonet-style lock whose orientation varies by the waveform observing instrument. The CT6710/CT6711's BNC mechanism allows the cable from the waveform measuring instrument to be connected without changing the orientation of the termination box, regardless of whether the studs are fixed in a horizontal or vertical orientation.

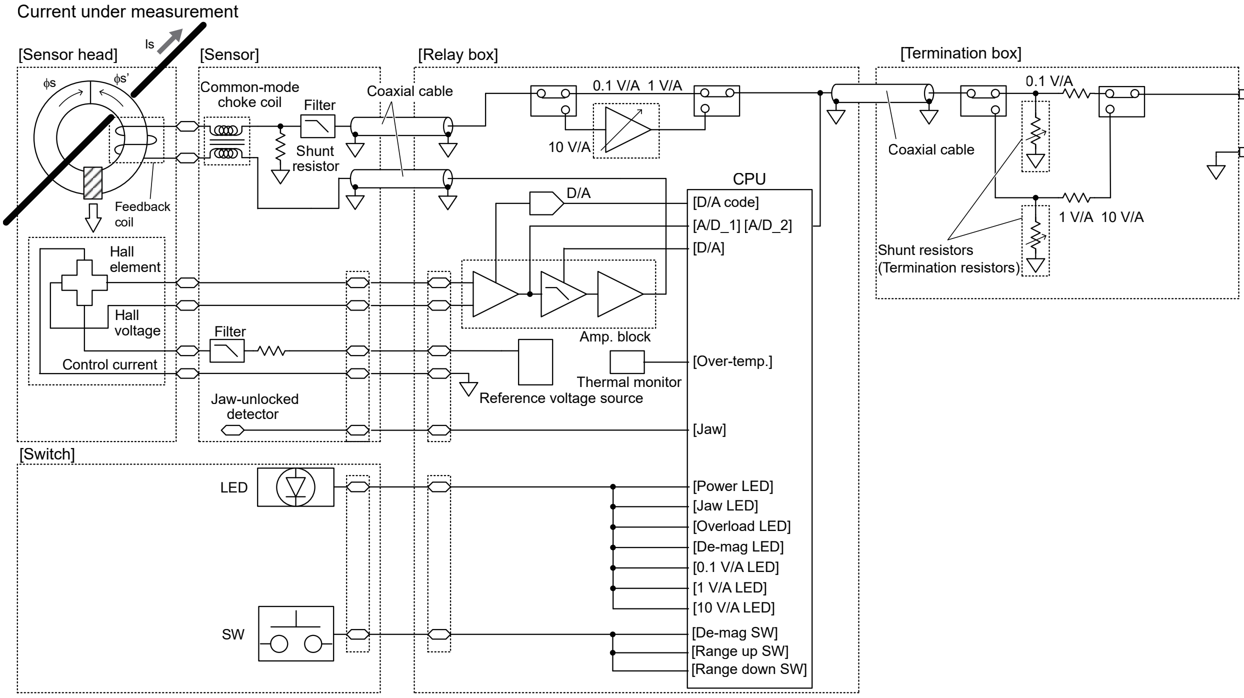

Fig. 2. Circuit block diagram.

IV. Architecture

A. Circuit Architecture

Fig. 2 provides a circuit block diagram for the CT6710/CT6711.

1) Operating principle: Like the 3273-50, 3274, 3275, 3276, CT6700, and CT6701, the CT6710/CT6711 is an AC/DC zero-flux current probe that uses a thin-film Hall element (Fig. 3). Since the zero-flux method utilizes a negative-feedback circuit that includes the magnetic circuit, the operating magnetic flux level can be kept extremely low. Consequently, the effect of the magnetic core's nonlinear magnetic characteristics can be minimized. As a result, the CT6710/CT6711 offers excellent performance in terms of linearity, measurement range, sensitivity, and frequency characteristics [4].

2) Circuit architecture: The circuit architecture offers the following features:

- Built-in demagnetization and automatic zero adjustment functions
- Various built-in warning functions
- Low-noise negative-feedback circuit
- Multiple output rates
- Separate negative-feedback and output circuits for reduced heat generation
- Signal transmission circuits that deliver wideband characteristics

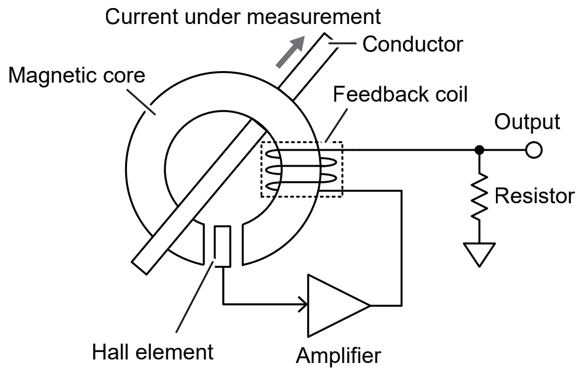

Fig. 3. Operating principle.

Together, the following two enhancements made possible the three output rates that are the most noteworthy feature of the CT6710/CT6711:

- Switching between two current detection resistors, one for large currents and one for small currents
- Amplifying the output signal with a high-speed amplifier

Because the CT6710/CT6711 requires a feedback current of up to about 1 A, its circuitry generates substantial thermal loss. To keep its temperature from rising excessively, the device consists of two separate circuits: a negative feedback circuit, which is the principal source of heat, and two current detection resistors.

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The circuitry also incorporates a number of optimizations, including shielding, filtering, and grounding, to counteract the effects of factors such as external electromagnetic noise and external noise voltages from the current under test.

3) Negative feedback circuit: The negative feedback circuit is essentially the same as that used in the previous models (the CT6700/CT6701).

4) Transmission circuits: To deliver wideband characteristics of a probe, it is necessary to design the terminal resistor values so that they match the characteristic impedance of transmission lines such as cables. However, since all three ranges use the same sensor head, it is necessary to switch the output rate without changing the number of turns in the sensor's internal winding. In other words, the device must switch between terminal resistors, with the result that there are ranges where impedance matching is not possible. To address this issue, Hioki designed an impedance-matching circuit only for the high-frequency zone where the effects on transmission characteristics are the most pronounced, thereby realizing flat, wideband frequency characteristics.

Additionally, inter-range errors have been minimized by aligning the frequency characteristics of the three ranges. This approach makes it possible to obtain similar waveforms from all ranges when observing step response and other transient response phenomena.

5) Digital circuit: The CT6710/CT6711 uses simple key operations to perform demagnetization and automatic zero adjustment as well as range selection. The device also provides an overload detection function to warn users if each range's rated input current is exceeded and a jaw unlocked detection function to warn users if the jaws are unlocked.

- *Demagnetization and automatic zero adjustment function:* Demagnetization and automatic zero adjustment can be performed successively by pressing and holding the DEMAG/AUTO ZERO key for about 1 second. Alternatively, automatic zero adjustment can be performed alone by pressing and then immediately releasing the key. Either way, the procedure is performed for all three ranges, so it can be initiated regardless of the currently selected range.

  a) Demagnetization function: When large currents are measured, the magnetic core becomes magnetically charged, causing an offset to affect measured values. This function eliminates that charge. Because it is necessary to inject a sufficiently strong demagnetization signal into the magnetic core in order to eliminate its magnetic charge, an analog switch in the negative feedback amplification circuit is used to temporarily cut off negative feedback, and a demagnetization current is generated using the 30 A range.

  b) Automatic zero adjustment function: Automatic zero adjustment is performed by measuring a reference zero level with the A/D converter built into the CPU and controlling D/A converter output so that the output level is zeroed out. The execution sequence has been optimized so that zero adjustment and demagnetization can be performed in a short period of time for all three ranges.

- *Overload detection function (rating exceeded):* The CT6710/CT6711 features an overload detection function similar to the one provided by the previous models (the CT6700/CT6701). When overload input is detected, the OVERLOAD LED flashes quickly to warn the user.

- *Overload detection function (temperature exceeded, protection function):* The device could become hot if a current in excess of the range's rating is measured, for example due to erroneous setting of the measurement range, or if measurement is performed continuously in a high-temperature environment. To prevent damage to the device, the internal temperature is measured by a temperature IC, and LED indicators flash quickly in the event a predetermined temperature is exceeded. Furthermore, to keep the temperature from continuing to rise if current measurement continues, the device enters a protective mode that limits heat generation by immediately transitioning to the internal configuration in which measurement produces the least amount of heat.

- *Jaw unlock detection function:* The CT6710/CT6711 features a jaw unlock detection function that is the same as the one provided by the previous models (the CT6700/CT6701).
  If the jaws are not locked, the JAW UNLOCKED LED illuminates. The indicator goes out once the jaws are locked.

B. Sensor Heads

The CT6710/CT6711 uses the same construction for its upper and lower sensor heads, which detect current, as the previous models (the CT6700/CT6701). The unit consists of ferrite cores, a thin-film Hall element situated in the ferrite core's gap, windings, shield cases, and other components.

Once these components have been assembled to form the magnetic core, the core is placed inside the shield case and filled with epoxy resin, which is then hardened. The mating surfaces of the upper and lower sensor heads are then polished.

C. Open/close Mechanism and Termination

The CT6710/CT6711 uses the same sensor construction, open/close mechanism, and termination as the previous models (the CT6700/CT6701).

V. Characteristics

A. Low-current Observed Waveforms

Fig. 4 provides waveforms for a minuscule current as observed by the CT6711 using the 10 V/A range and the previous model (the CT6701). For the CT6701, which has an output rate of 1 V/A, the observed waveform for area (a) has been obscured by the noise floor of the digital storage oscilloscope (DSO). Although the amount of noise can be reduced by narrowing the DSO's band setting, doing so will adversely affect the instrument's response. By contrast, the CT6710/CT6711 series' 10 V/A range, which is 10 times greater than the previous model's, allows the DSO's measurement sensitivity to be reduced to 1/10 that when using the older device, improving the signal-to-noise performance of the DSO. In other words, there is less need to narrow the DSO's band since the measured current waveform is not obscured by the noise floor, making it possible to observe minuscule and high-frequency current waveforms. In this way, the CT6710/CT6711 can be combined with a DSO to observe minuscule waveforms.

B. Frequency Characteristics

Figs. 5 and 6 illustrate the frequency characteristics of the CT6710 and the CT6711, respectively. There is little error among the three ranges, and the devices maintain a broad frequency band.

C. Linearity

Figs. 7 through 9 illustrate the CT6711's output voltage linearity relative to current input.

- *Output rate: 0.1 V/A (Fig. 7):* The device exhibits excellent linearity up to 10 A. Linearity above 10 A is impacted by the sensor head's construction and differs from the characteristics exhibited up to 10 A. This difference derives from the CT6710/CT6711's most noteworthy features: the sensor head's construction was specifically designed for reproducibility during minuscule-current measurement and reduction of the effects of external magnetic fields in order to take maximum advantage of the high output rate.
- *Output rates: 1 V/A and 10 V/A (Figs. 8 and 9):* The device exhibits excellent linearity for both DC and AC input, without any dependence on input current level.

D. Sensitivity vs. Temperature Characteristics

The sensitivity (output rate) of the CT6710/CT6711 varies due to the effects of the ambient temperature, as illustrated in Figs. 10, 11, and 12.

E. Effects of Conductor Position

Figs. 14, 15, and 16 illustrate the effects of conductor position. The letters A through G in the figure indicate

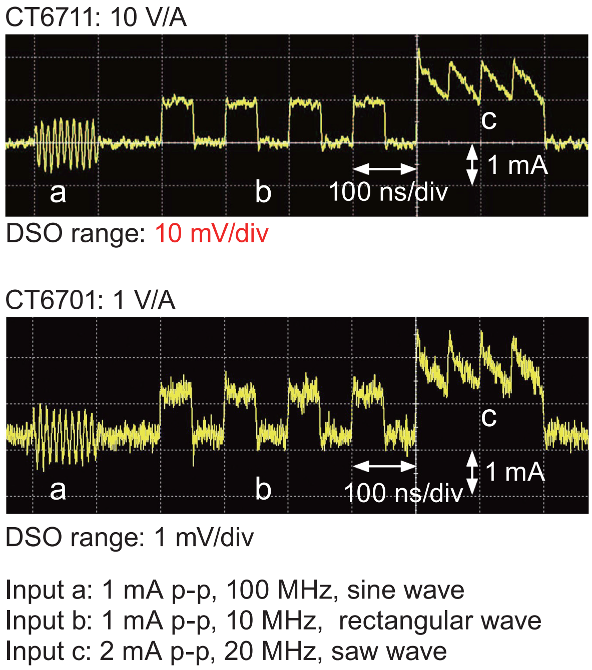


Fig. 4. Example of low-current measurement.

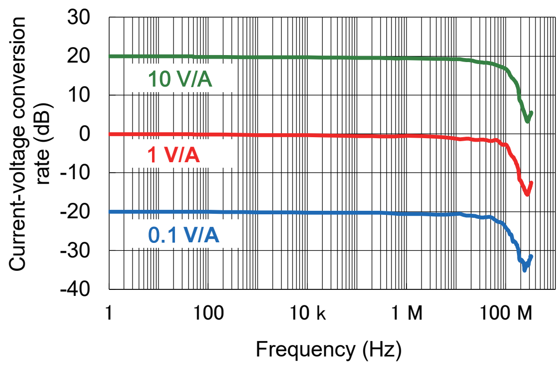


Fig. 5. Frequency characteristics (CT6710).

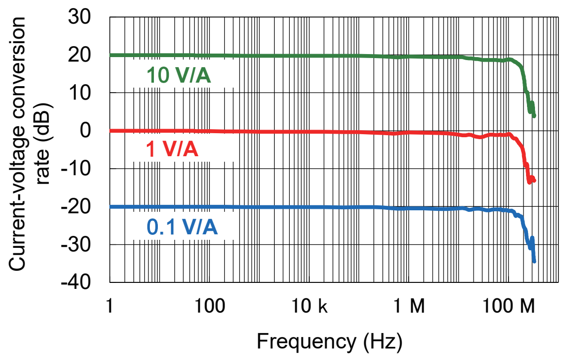


Fig. 6. Frequency characteristics (CT6711).

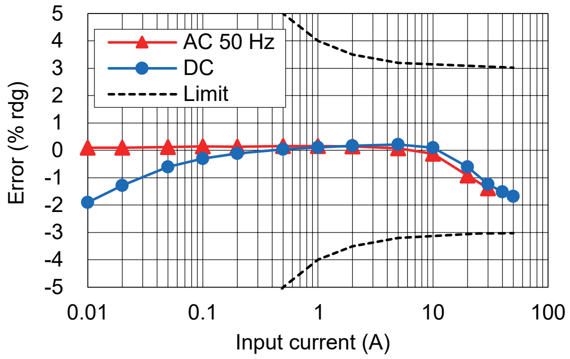


Fig. 7. Example linearity (CT6711, 0.1 V/A).

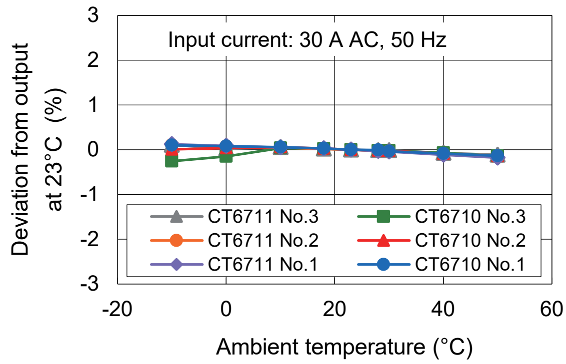


Fig. 10. Example temperature characteristics (0.1 V/A).

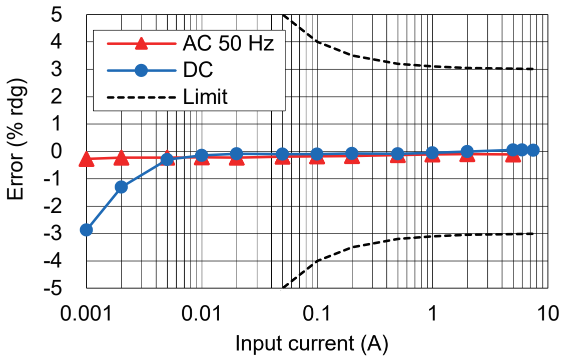


Fig. 8. Example linearity (CT6711, 1 V/A).

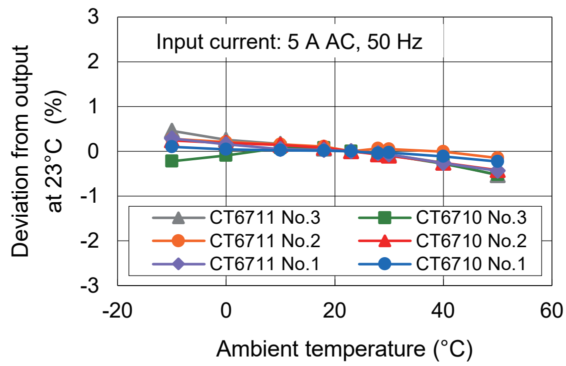


Fig. 11. Example temperature characteristics (1 V/A).

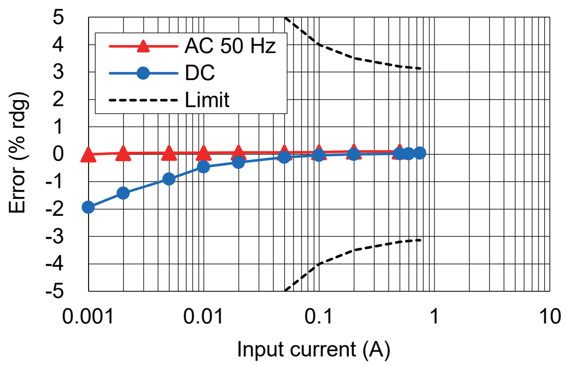


Fig. 9. Example linearity (CT6711, 10 V/A).

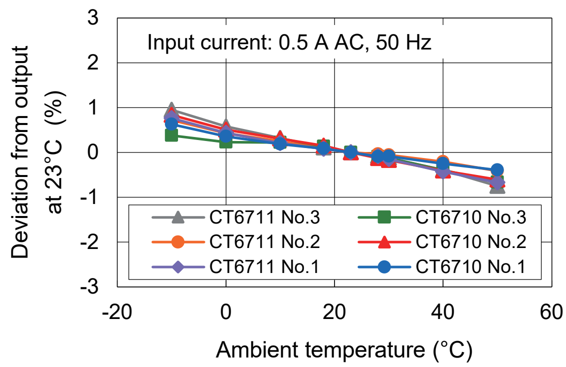


Fig. 12. Example temperature characteristics (10 V/A).

the position of the conductor in the clamp "window" as illustrated in Fig. 13. The secondary winding (feedback coil) in the sensor head has been designed so as to minimize the effect of conductor position on measured values.

F. Offset Voltage vs. Temperature Characteristics

The Hall element is primarily responsible for offset voltage. The Hall element is susceptible to the effects of temperature because it is a semiconductor, and the

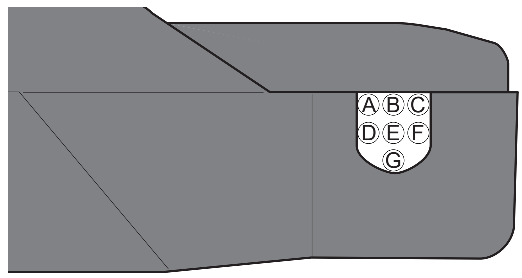


Fig. 13. Conductor position.

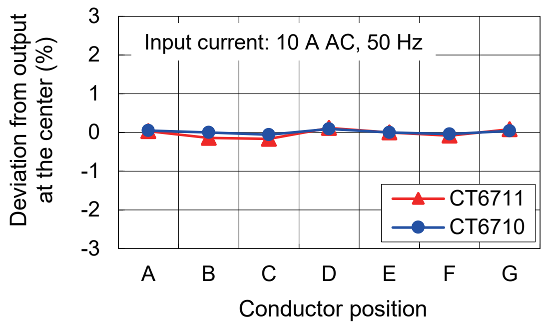


Fig. 14. Effects of conductor position (example measurement, 0.1 V/A).

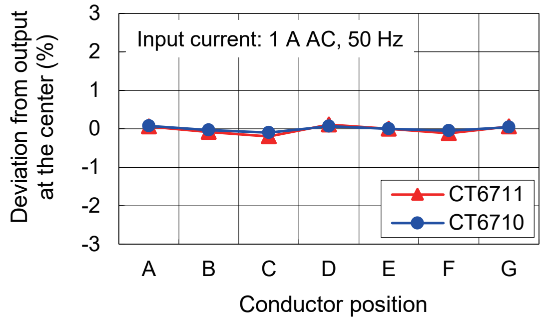


Fig. 15. Effects of conductor position (example measurement, 1 V/A).

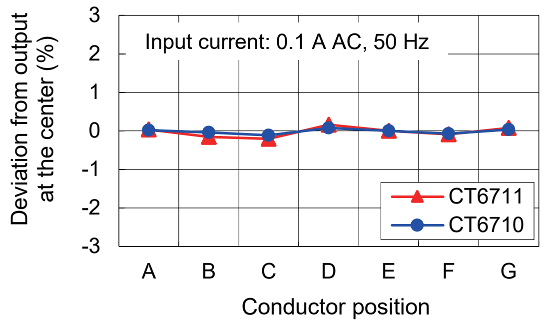


Fig. 16. Effects of conductor position (example measurement, 10 V/A).

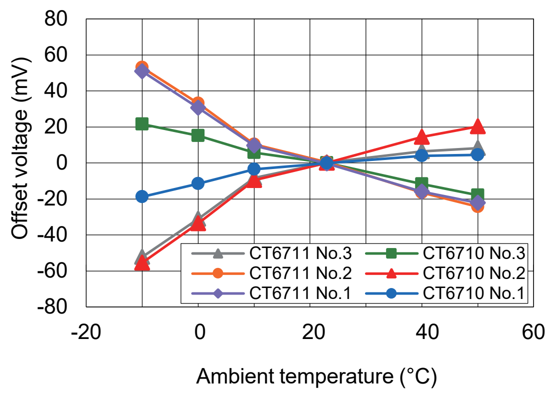


Fig. 17. Temperature characteristics (example of offset voltage, 1 V/A).

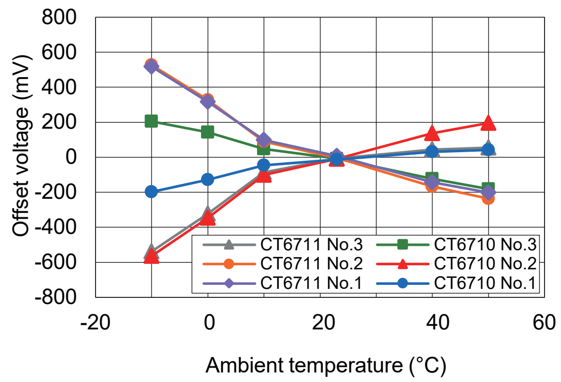


Fig. 18. Temperature characteristics (example of offset voltage, 10 V/A).

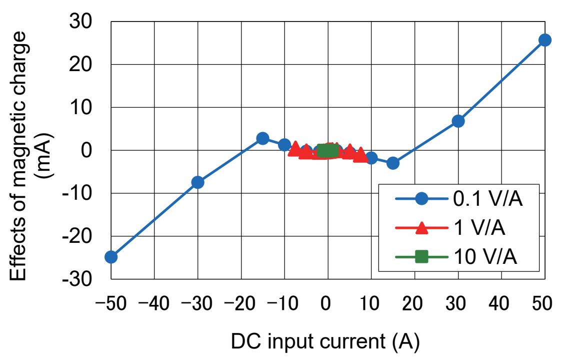


Fig. 19. Effects of magnetization (example measurement with CT6711).

characteristics of those effects vary with the ambient temperature. Figs. 17 and 18 provide examples of these characteristics. The amount of fluctuation in the offset voltage varies from device to device and is dependent on the condition of the films in the Hall element.

G. Effects of Magnetization

The magnetic material used in the magnetic core exhibits hysteresis characteristics, and values output by the sensor after the current changes are affected by those characteristics. Fig. 19 illustrates converted current values for the residual offset voltage after application of a DC current. These values provide an example of the effects of magnetization.

H. Insertion Impedance

Figs. 20 and 21 provide examples of the device's insertion impedance characteristics. The figures indicate that clamp-type current sensors exhibit increased load on the circuit under measurement as the frequency increases. The CT6711 is characterized by lower input impedance than the CT6710.

I. Effects of External Noise Voltages

Fig. 22 provides an example of the effects of external noise voltages (common-mode voltages). The magnitude of the effect is expressed as the ratio of the voltage applied to the conductor positioned in the clamp window, *E*, to the associated output voltage, *V*o.

J. Effects of External Magnetic Fields

Fig. 23 provides an example of the effects of external magnetic fields. All output is given as converted current values. The strength of the magnetic field applied for these measurements, *H*, was 400 A/m, which is equivalent to about 10 times the Earth's magnetism.

K. Frequency Deratings

Figs. 24 and 25 illustrates the maximum current values that can be input to the device continuously by frequency. These values have been determined based on the temperature rise that occurs inside the device and on its surface due to self-heating during current measurement. The figures indicate maximum values assuming sine wave current input at an ambient temperature of 23°C. If the current waveform being measured includes high-frequency components, or if the device is being used in a hot environment, the current value that can be input continuously will decrease due to the increase in internal and surface temperatures.

Additionally, the CT6710 and CT6711 use different sensor heads. The CT6711's head exhibits a smaller temperature rise. Consequently, the CT6711 has a higher maximum current value.

VI. Example Measurement Applications

A. ECU and Electric Equipment Current Measurement

In developing devices to control electric equipment in automobiles and similar applications, it is necessary to measure currents of a variety of magnitudes, including motor drive currents on the order of several amperes, in-rush currents on the order of tens of amperes, and minuscule control signal and standby currents of about 1 mA. Thanks to the broad measurement scope made possible by its three output ranges, the CT6710/CT6711 can be used in an array of measurement applications.

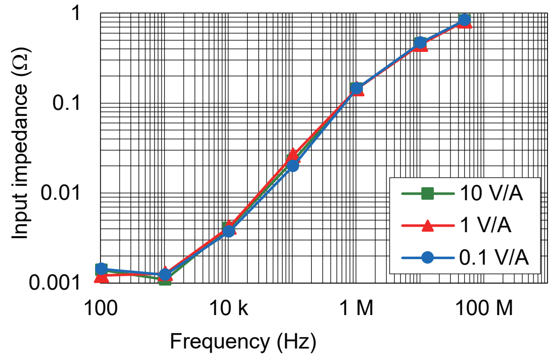


Fig. 20. Example insertion impedance characteristics (CT6710).

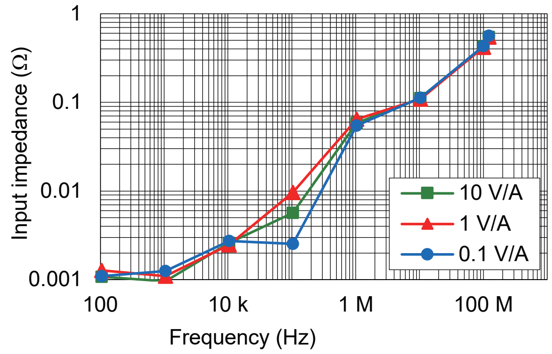


Fig. 21. Example insertion impedance characteristics (CT6711).

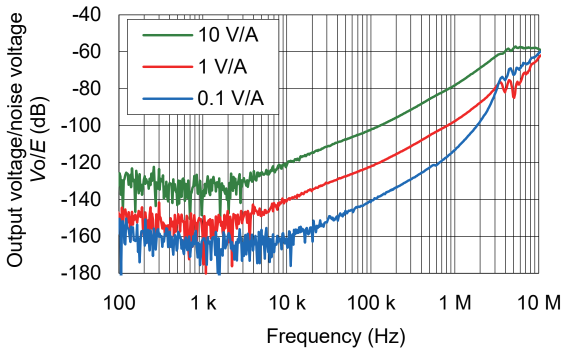


Fig. 22. Effects of external noise voltage (example measurement with CT6711).

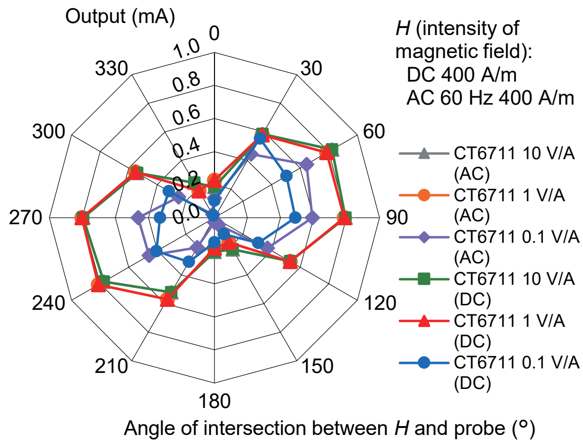


Fig. 23. Effects of external magnetic fields (CT6711).

B. Measuring the Current Consumption of Wearable Devices

In developing devices that can operate for extended periods of time under battery power, it is necessary to measure current consumption in a variety of device configurations, including active, standby, and data communication modes. The CT6710/CT6711 has a high output rate of 10 V/A (outputting 1 mV per 100 μA), allowing it to detect minuscule current variations on the order of 100 μA.

Fig. 26 illustrates an example setup in which the CT6711 is being used to measure the current consumption of the Hioki Humidity Sensor Z2011. Fig. 27 illustrates the associated current consumption waveform as observed by a Hioki Memory HiCorder MR6000. The Z2011 sends temperature and humidity data measured by the sensor to a measuring instrument via serial communications. By combining the CT6711 with the MR6000, it is possible to detect minuscule current variations on the order of 100 μA during command transmission and measurement operation.

With devices that are required to exhibit low current consumption, it is important to ascertain current consumption while processing is being performed. The CT6711 can be used to measure the minuscule current consumption of wearable devices.

C. High-speed Switching Device Response Performance

Evaluating the performance of high-speed GaN and SiC switching devices requires wideband current sensors that can accurately capture current waveforms without being affected by switching noise. The CT6710/CT6711 uses a magnetically shielded sensor to minimize susceptibility to nearby switching noise and current-induced magnetic fields. Consequently, it can observe current waveforms at a high signal-to-noise ratio. When detecting currents using a shunt resistor, one may inadvertently short-circuit the measurement circuit when connecting the voltage detection probe. However since this current probe has a clamping (non-contact) design, it solves this problem, ensuring safety.

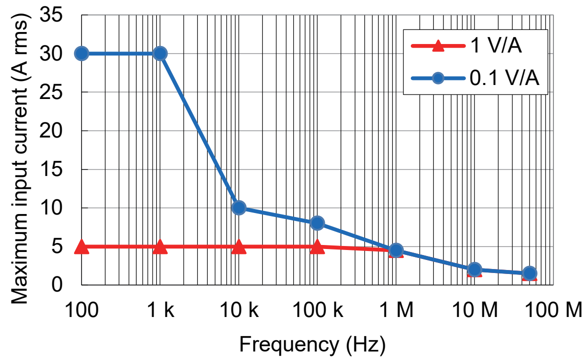


Fig. 24. Frequency derating (CT6710).

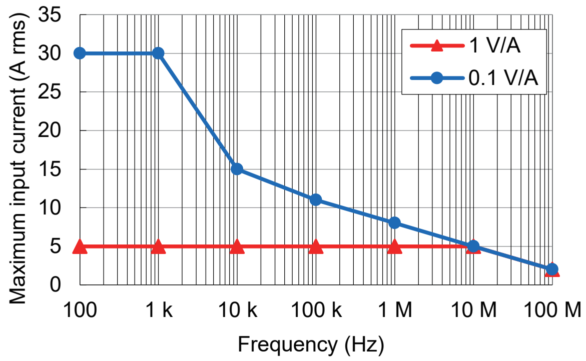
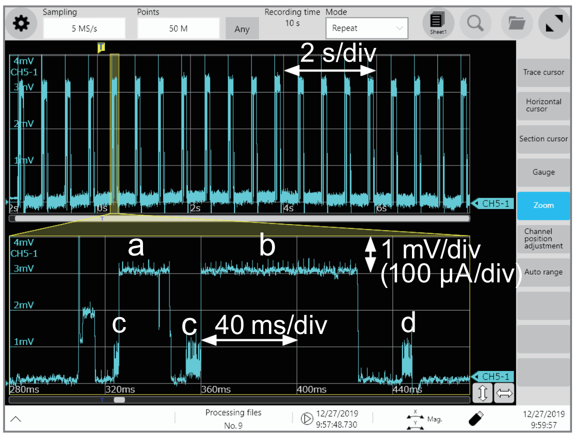


Fig. 25. Frequency derating (CT6711).

Fig. 26. Example measurement of the current consumption of a temperature and humidity sensor.



a: During temperature measurement
b: During humidity measurement
c: While sending command
d: While replying with temperature and humidity information

Fig. 27. Current consumption waveform of a temperature and humidity sensor.

Fig. 28 illustrates a representative circuit for a double-pulse test. Fig. 29 illustrates the current waveform measured by the CT6711, *I*d, at the position labeled "Clamp" in Fig. 28. The CT6710/CT6711 can observe turn-on and turn-off current waveforms while minimizing the effects of switching noise.

These wideband current sensors can observe current waveforms from devices that perform switching at high speeds at a high signal-to-noise ratio.

VII. Conclusion

Hioki developed the CT6710/CT6711 wideband current probe with three ranges, one of which provides a high output rate, so that it could observe even lower currents. The device can observe minuscule current waveforms that were difficult to observe in the past because they were obscured by noise, while minimizing band limitations. Additionally, a broad current measurement scope means that a single probe can be used to measure not only minuscule currents in wearable devices and standby currents of electronic devices, but also current consumption during ordinary use.

Hioki expects the CT6710 and CT6711 to enjoy broad use in research and development targeted at generating additional power savings and efficiency gains in electronic devices and other products.

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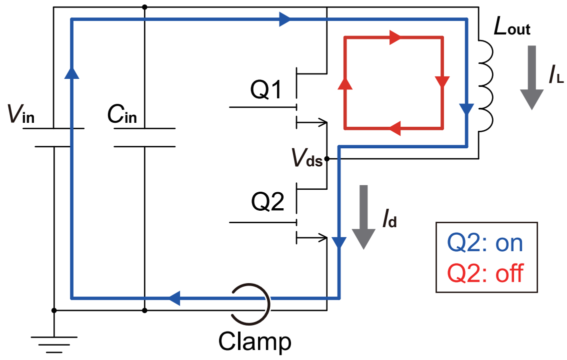

Fig. 28. Example circuit for a double-pulse test.

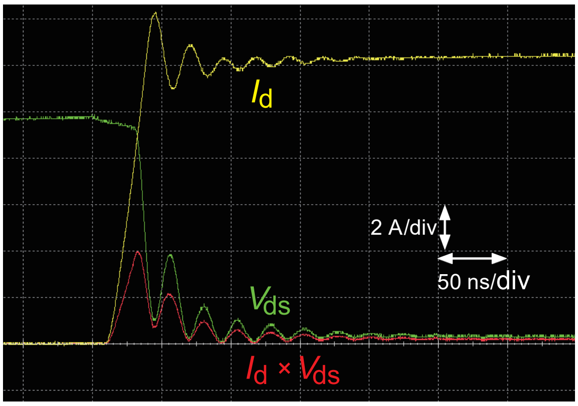

Fig. 29. Example measurement of turn-on loss (CT6711).

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