

Application Circuit of Low Noise Op-amp TC75S67TU for Current Sensor

Design guide

RD161-DGUIDE-01

Overview

This Design Guide describes the design of current sensors using low-noise op-amp TC75S67TU. Current sensors are classified into several types, such as shunt-resistor type, Hall type, and air-core type, depending on the elements used for sensing. This section describes designs of circuits that apply TC75S67TU to shunt-resistor type current sensors with the simplest construction.

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

Op-amps are still used in a variety of situations even today in the digital age, and a particularly important application is their use in a variety of sensors.

There are various types of information that can be obtained from nature, such as sound and light, and there are various types of sensor elements accordingly. Generally, the output signal from a sensor element is very weak, and it is hard to handle as it is, so in most cases it is amplified and processed.

Op-amps are used for this amplification. In addition to amplification, op-amps are used for filters and I-V conversion in various sensors, and it is not an overstatement to say that most modern electronic devices cannot be realized without an op-amp.

Noise characteristics are important in applications with these sensors. If the op-amp itself is noisy, critical sensor signals may be masked by noise, resulting in a decrease in detection sensitivity or false detection, preventing the desired sensing performance from being attained. Therefore, the op-amps used in such applications require low noise levels.

In order to meet these requirements, Toshiba have developed an op-amp TC75S67TU with a low noise level of 6 nV/ $\sqrt{\text{Hz}}$ (@f=1 kHz, G_v=40 dB, typical).

This Design Guide describes the design of current sensors using TC75S67TU. For more information on TC75S67TU, refer to the data sheet of the link destination below.

→ TC75S67TU datasheet from here

[Click Here](#)

2. Circuit Design

2.1. About Low-noise Op-amp TC75S67TU

The low-noise op-amp TC75S67TU used in the ultrasonic distance sensors described in this guide took measures from both the circuits and manufacturing processes, and succeeded in reducing the noise level to a greater extent than our existing products.

Generally, noise has 2 ways on the frequency component contained point of view:

1. 1/f noise which is distributed in the low frequency region
2. White noise which is distributed in the wide region from low frequency to high frequency.

TC75S67TU realizes low noise levels such as 16 nV/ $\sqrt{\text{Hz}}$ (@f=10 Hz) in the low frequency region where 1/f noise is mainly used, and 6 nV/ $\sqrt{\text{Hz}}$ (@f=1 kHz, typ.) in the region where white noise is mainly used. Fig. 2.1 shows a graph comparing the noise level-frequency characteristics of TC75S67TU and our existing product.

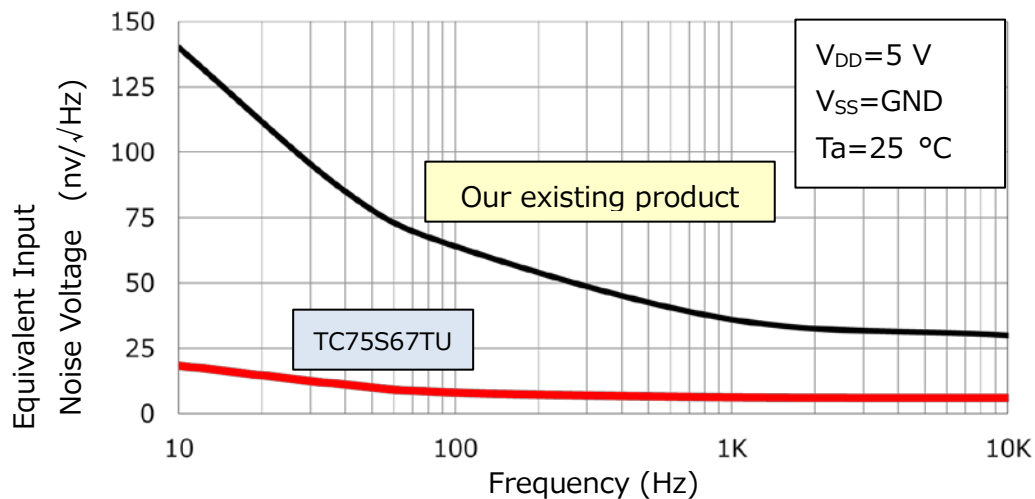


Fig. 2.1 TC75S67TU Input-Converted Noise Voltage-Frequency Characteristics

As shown in Fig. 2.1, the noise of TC75S67TU is greatly improved compared to existing products, making it an optimum op-amp for amplifying the signal of sensors that handle weak signals. In addition to this noise characteristic, TC75S67TU has a very small input bias current of 1 pA, and the offset voltage is also small.

For sensors that handle weak signals, the effect of the offset voltage is also large, which may cause deterioration of the sensor performance. Therefore, a resistor for offset correction may be required at the input terminals. Since the resistor generates thermal noise, the noise may deteriorate in this case. However, since the offset voltage is small for TC75S67TU, it is not necessary to add a resistor for offset compensation.

By using TC75S67TU with the above features, high-sensitivity and high-performance sensors can be designed.

Please also refer to the application notes below for more information on TC75S67TU noise.

To download the application notes on TC75S67TU noise →

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2.2. About the Current Sensor

There are various types of current sensing, such as a magnetic sensing system using a Hall element and a shunt resistor system. In the current sensor of this guide, a shunt resistor system using a minute resistor for the sensing element is adopted. Figure 2.2 shows the current sensing mechanism of the shunt resistor type current sensor.

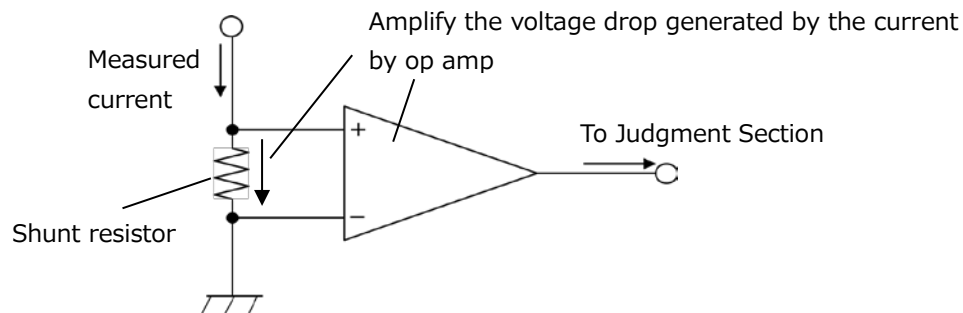


Fig. 2.2 Detection Method of Shunt Resistor Type Current Sensor

As shown in this figure, the measurement current is detected by the voltage drop generated by the shunt resistor, and the configuration is very simple.

Fig.2.3 shows TE Connectivity resistor RL73H3AR10FTE used for shunt resistors with this sensor.



Fig. 2.3 Shunt Resistor (RL73H3AR10FTE Made by TE Connectivity)

Taking advantage of its low noise op-amp, the current sensors in this guide is designed for highly accurate detection of current around 0 A and GND sensing. And f_T of TC75S67TU is 3.5 MHz, so current ringing can be detected.

In addition, Arduino is used as the microcontroller that controls the operation of the entire current sensor, and displays the measured results on the computer. If you prepare the software, you can use any other type of microcontroller you like, but please check the operation thoroughly.

2.3. Current Sensor Specifications

Table 2.1 shows the specifications of this sensor.

Table 2.1 Current Sensor Circuit Specifications

Item	Specification
I/F	Arduino connectivity
Control method	Control from Arduino and Shield connected PCs
Power supply voltage	Arduino and Shield board feed 5 V
Measured current	Maximum 2 A
Shunt resistor	RL73H3AR10FTE of TE Connectivity 100 m Ω , \pm 1% accuracy, 1 W@70 °C
On-board op-amp	Toshiba Device & Storage TC75S67TU

2.4. Circuit Design of the Current Sensor

Fig.2.4 shows the board photograph of the current sensor in this guide, and Fig.2.5 shows the overall circuit, respectively. This sensor consists entirely of a single board. This section explains the operations and settings of the voltage gain, cut-off frequency of filters, etc., sequentially for each part enclosed by a dotted line.

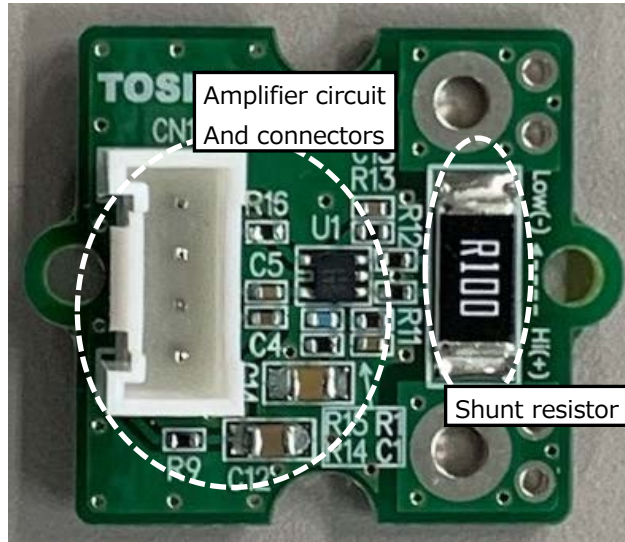


Fig. 2.4 Current Sensor Board Photograph

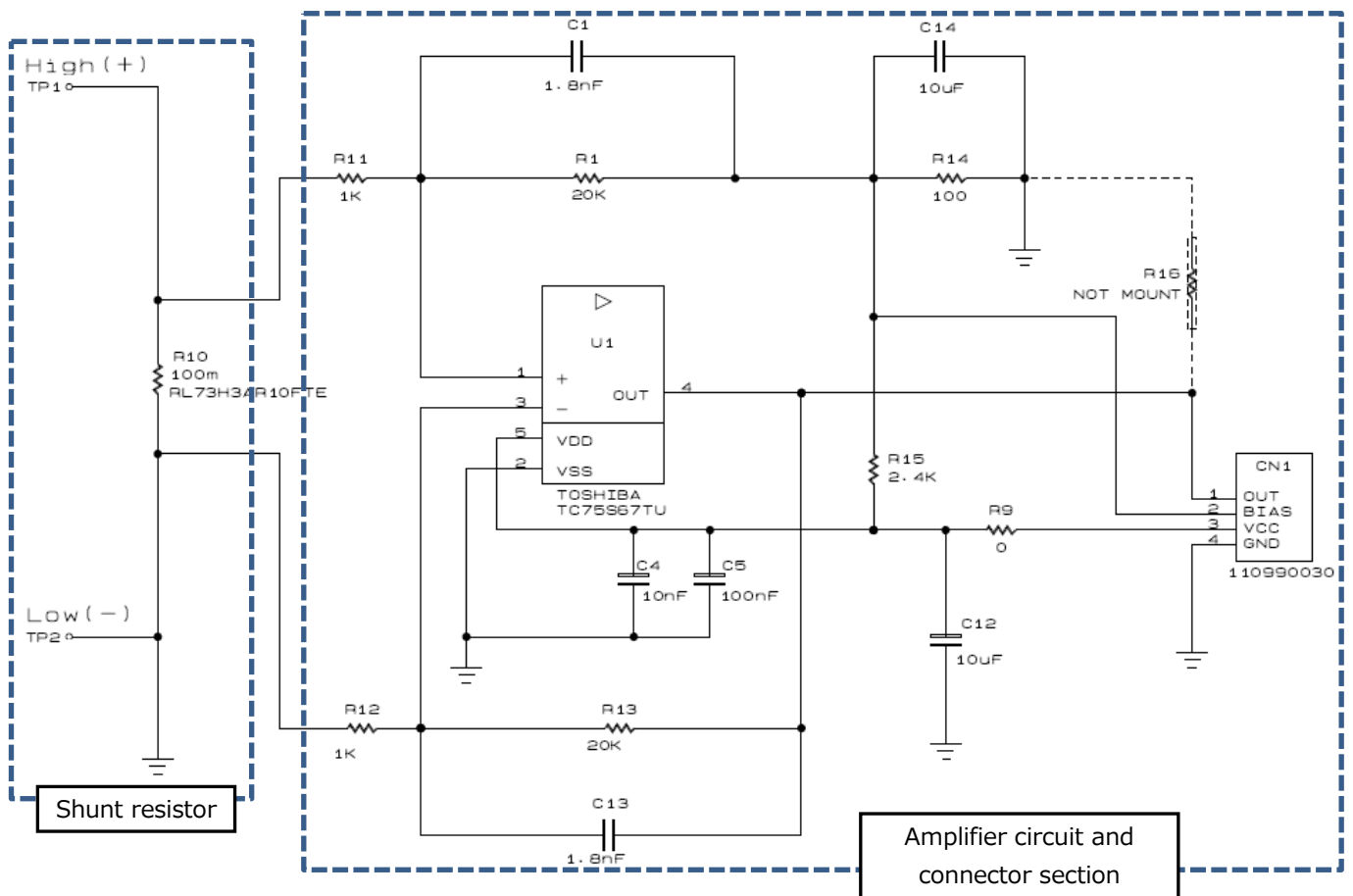


Fig. 2.5 Overall Current Sensor Circuit Diagram

Fig.2.6 shows the shunt resistor section.

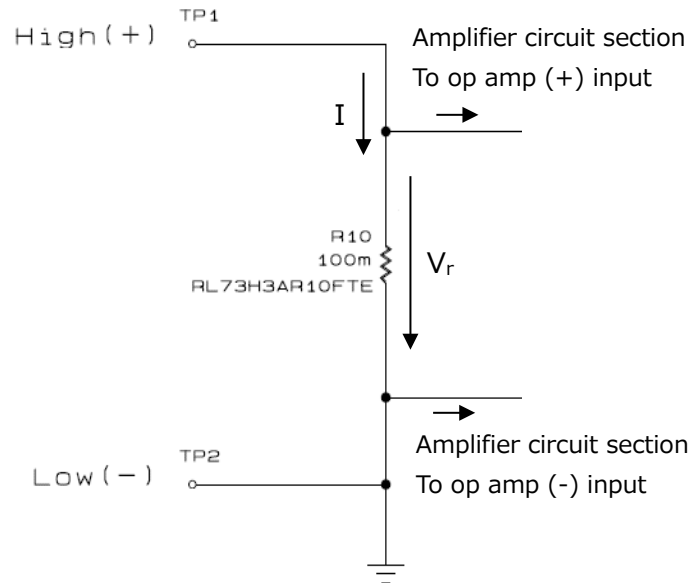


Fig. 2.6 Shunt Resistor Section

For shunt resistor type current sensors, consideration for voltage drops caused by resistance values of current paths other than shunt resistors, and consideration for resistance accuracy and heat generation are the points of design. The higher the shunt resistor, the more accurate the current is measured, but the greater the heat generation according to I^2R and the greater the voltage drop, the more likely it affects the measured current. Therefore, the value of the shunt resistor is set as small as possible, and the voltage drop generated is not kept as it is, but in a configuration in which it is amplified and measured.

In this sensor, the voltage drop V_r generated by the shunt resistor R10 by current I flowing from High (+) terminal to the Low (-) terminal in Fig. 2.6 is amplified with the op-amp at the later stage and output to the microcontroller. Since the maximum measured current of this sensor is 2 A, the value of the shunt resistor is set to 100 mΩ, and the voltage drop when the maximum current flows is suppressed to 0.2 V.

At this time, the power consumed by the shunt resistor is 0.4 W, so the shunt resistor is RL73H3AR10FTE made of TE Connectivity with a power dissipation of 1 W, taking into account a margin of about twice.

The voltage drop V_r of the shunt resistor R10 is calculated by the following equation 2.1 with the sensed current as I .

$$V_r = I \times R10 \quad \dots (2.1)$$

R10: 100 mΩ

Voltage drop V_r generated at R10 are entered into the op-amp. Fig. 2.7 shows the amplifying circuits of the sensors using TC75S67TU as an op-amp, and the connector unit that outputs the amplified signals to the microcontroller.

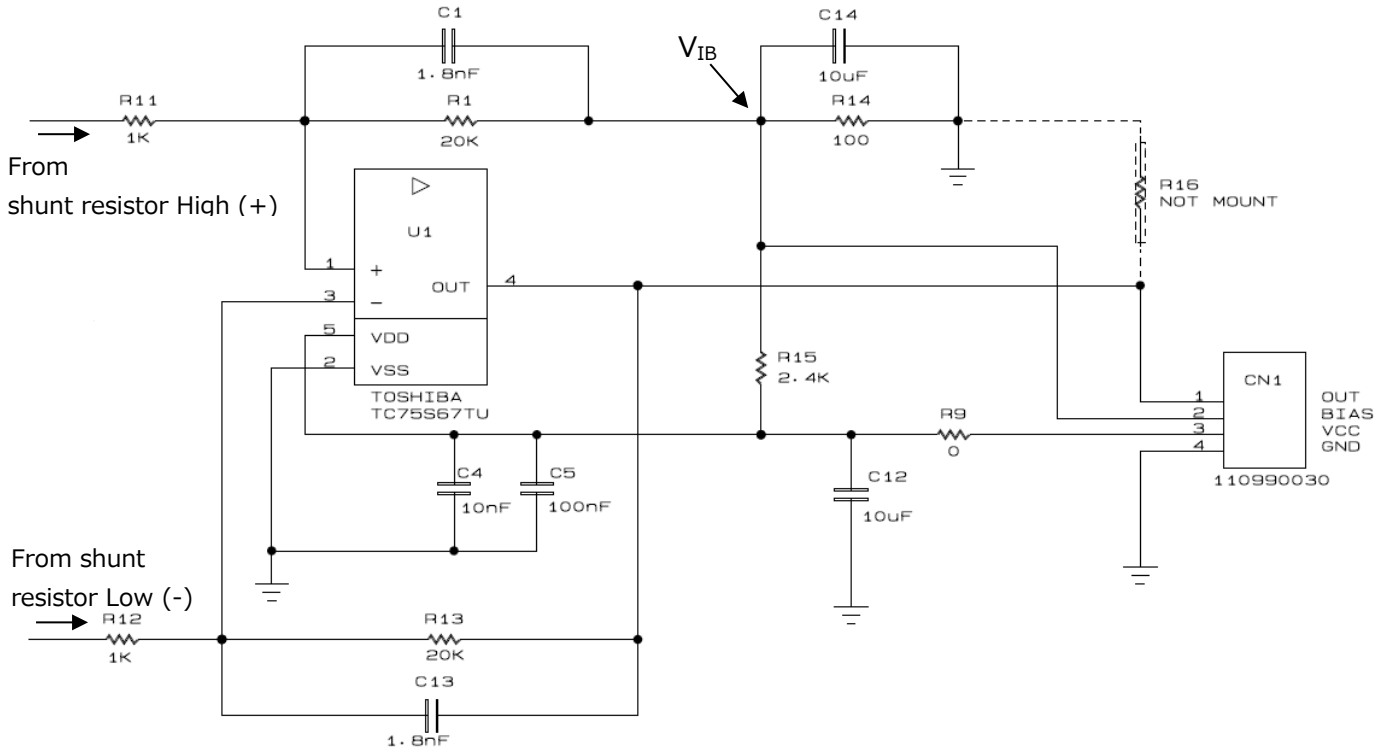


Fig. 2.7 Amplifier Circuits and Connectors

This sensor is a differential amplifier circuit in which the voltages across the shunt resistor are input to the non-inverting and inverting input terminals of the op-amp U1 via R11 and R12, respectively. The gain is set so that the output amplitude at the maximum measured current does not exceed the dynamic range of the output. Since the power supply voltage of this sensor is 5 V, assume that the gain is 20 times (26 dB) so that the output amplitude becomes 4 V when the maximum measured current of 2 A flows (0.2 V is generated in the shunt resistor) considering the allowance.

The gain G_v is determined by R11 and R1, R12 and R13 as shown in the equation 2.2 below.

$$G_v = \frac{R1}{R11} = \frac{R13}{R12} = \frac{20 \times 10^3}{1 \times 10^3} = 20 \text{ 倍 (about 26 dB)} \quad \dots (2.2)$$

$$R1=R13: 20 \text{ k}\Omega, R11=R12: 1 \text{ k}\Omega$$

In addition, to improve the accuracy of current detection around 0 A and GND sensing, the non-inverting input terminal of U1 is biased by the voltage obtained by dividing V_{CC} by R14 and R15 to raise the DC voltage. V_{IB} of the raised voltage is set as shown in the equation 2.3 below.

$$V_{IB} = \frac{R14}{R14 + R15} \times V_{CC} = \frac{100}{100 + 2.4 \times 10^3} \times 5 = 200 \text{ (mV)} \quad \dots (2.3)$$

$$R14: 100 \Omega, R15: 2.4 \text{ k}\Omega, V_{CC}: 5 \text{ V}$$

This voltage V_{IB} is superimposed on the output of the U1, but V_{IB} is monitored through BIAS pin on the connector CN1 and is subtracted when calculating the result.

To remove unwanted radiofrequency components, the LPFs are composed of R1 and C1, R13 and C13, and the cutoff frequency f_c is determined in the equation 2.4 below.

$$f_c = \frac{1}{2 \times \pi \times R1 \times C1} = \frac{1}{2 \times \pi \times R13 \times C13} = \frac{1}{2 \times \pi \times 20 \times 10^3 \times 1800 \times 10^{-12}} \\ \cong 4.42 \text{ (kHz)} \quad \dots (2.4)$$

$$R1=R13: 20 \text{ k}\Omega, C1=C13: 1800 \text{ pF}$$

The bypass capacitor connected to the power supply terminal of U1 has two types of capacitors in parallel: C4=10 nF and C5=100 nF. This is to effectively eliminate power supply noises in a wide frequency range by lowering the impedance for each of the lower frequency domains below that for a large 100 nF capacitor in the higher frequency domain above 1 MHz with a small 10 nF capacitor.

Finally, the measurement resolution of this current sensor is described.

The resolution of the measurement result is determined by the number of bits of the input A/D converter of the microcontroller that receives the output of this sensor. For Arduino, the input A/D converter has 10 bits and the power supply voltage is 5 V, so the voltage V_{LSB} per LSB (Least significant bit) 1 count is approximately 4.9 mV as shown in the equation 2.5 below.

$$V_{LSB} = \frac{V_{CC}}{2^{10}-1} = \frac{5}{1023} \cong 0.0049 = 4.9 \text{ (mV)} \quad \dots (2.5)$$

$$(2^{10} = 1024)$$

Thus, the value of the current at which the output voltage of the op-amp becomes approximately 4.9 mV is the resolution of this sensor.

Since the gain G_v of U1 is 20 times and the shunt resistor R10=100 m Ω , the resolution of this sensor is about 2.4 mA as shown in the equation 2.6 below by dividing V_{LSB} by these.

$$\frac{V_{LSB}}{G_v \times R10} = \frac{4.9 \times 10^{-3}}{20 \times 100 \times 10^{-3}} = 0.0024 = 2.4 \text{ (mA)} \quad \dots (2.6)$$

Note that TC75S67TU has an offset voltage of 0.5 mV (typical) in terms of input, so the output will have a voltage multiplied by this gain. The gain of the op-amp of this sensor is set to 20 times, and there is a possibility that an offset voltage exceeding V_{LSB} may occur at the output, resulting in a zero-point deviation or a measurement error of the current. This can be corrected by the software of the microcontroller.

Refer to the reference guide for more information on correcting methods.

3. Board Design

3.1. Example of Substrate Pattern

This board is double-sided two-layer boards of the top and bottom sides. Fig.3.1 shows an example of a pattern on the top side and Fig.3.2 shows an example of a pattern on the bottom side. Each item shown in the blowout above is described in detail in Section 3.2.

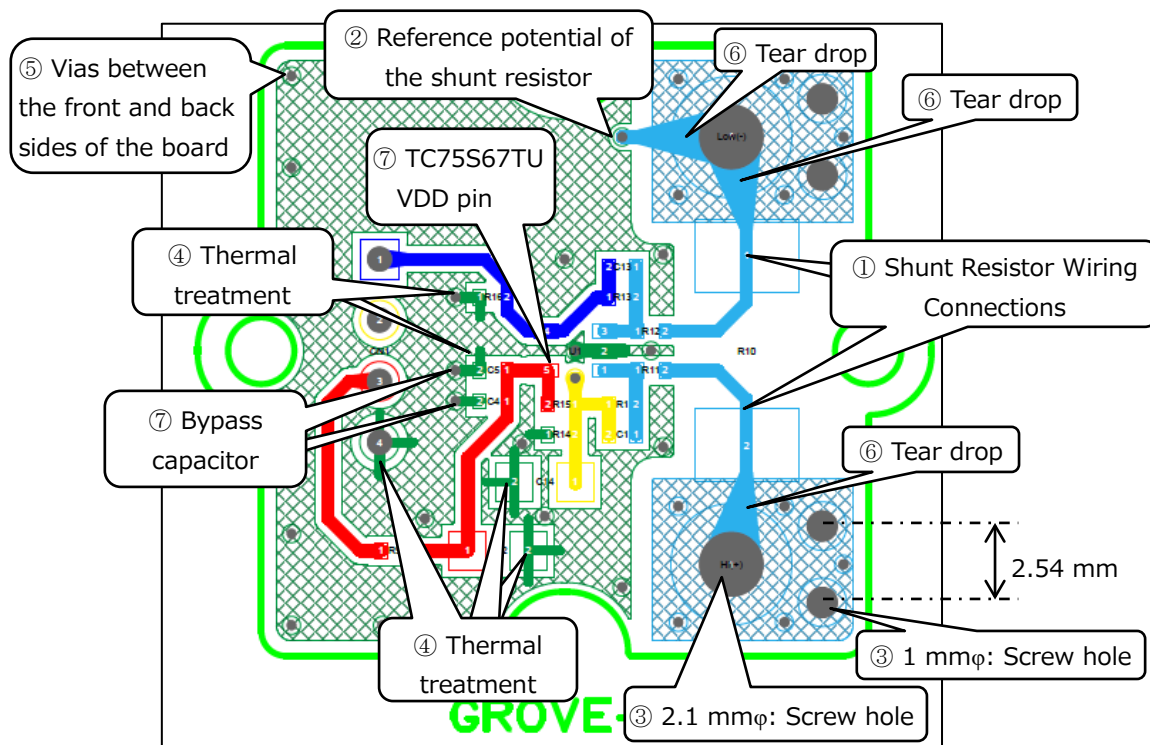


Fig. 3.1 Board Top Pattern

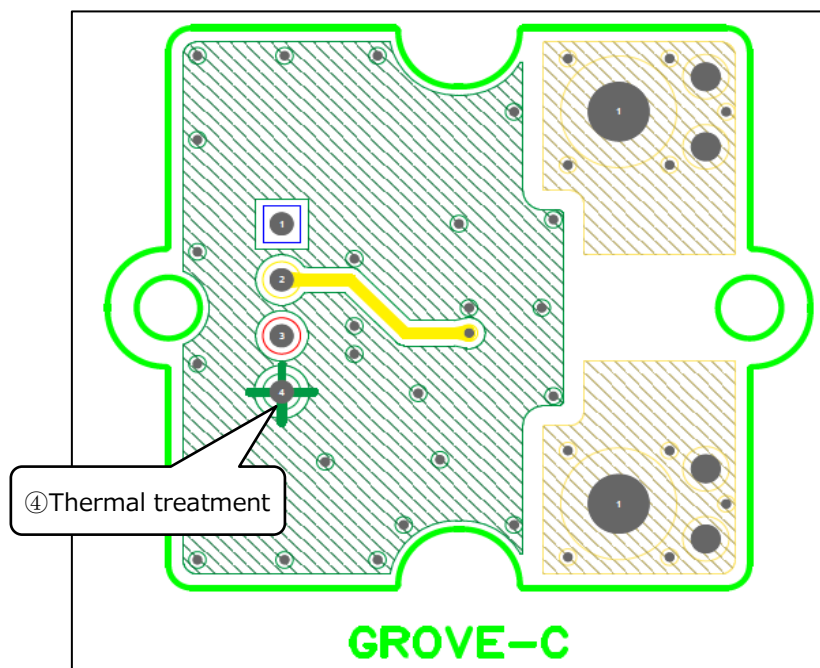


Fig. 3.2 Board Bottom Pattern

3.2. Precautions for Board Design

This section describes the precautions for this board.

① Shunt resistor wiring connections (see Fig.3.1)

The shunt resistor detects the current as a voltage drop. Since the detection voltage is input to the op-amp without error, the wiring to the op-amp should be separated from the wiring in which the current flows at the root of the shunt resistor so that the minimum distance is achieved. Such a connection is called a Kelvin connection, which is commonly used in shunt resistors for current sensing. In this pattern example, the wiring is passed through the inside of the shunt resistor pad to the input terminal of the op-amp at the shortest distance.

② Reference potential of shunt resistor (see Fig.3.1)

Coincide the GND of the current sensor circuit and the reference side of the shunt resistor with the same potential. In this pattern example, the low side of the shunt resistor is laid out at the same potential as the GND of the sensor circuit (reference potential portion in Fig.3.1).

③ Installation of screw holes (see Fig.3.1)

Provide threaded holes at the end of the pad of the shunt resistor so that a terminal or the like can be connected.

④ Thermal treatment (see Fig.3.1 and Fig.3.2)

In the pattern example, the section marked with " Thermal treatment " is drawn with a cross or T-shaped pattern to prevent heat from escaping during reflow soldering, instead of a solid pattern in the wiring from each PAD to GND. This is to prevent the parts from overheating and being damaged due to the heat escaping through the pattern, deteriorating soldering workability and taking time to work. Usually, the cross and T-shaped layout parts are buried in the solder after soldering, making them invisible.

⑤ Impedance reduction (see Fig.3.1)

For a two-layer board, provide as many vias as possible between the top and bottom of the board. The entire GND impedance is lowered to enhance the solid GND as a reference to prevent potential differences from occurring in the area and to prevent noise from spreading.

⑥ Teardrop shape (see Fig.3.1)

In the example pattern, a tear-drop shape is used to widen the routing pattern of the land and pad to wire connections. This is intended to prevent current singularities from occurring on the pads and to increase the connection strength between the pads and the wires.

⑦ Location of the bypass capacitor (see Fig.3.1)

To eliminate noise superimposed on the power supply voltage line, connect the two bypass capacitors (C4 and C5) of the op-amp as close as possible to the power supply voltage terminal of the device and to the power supply voltage line side.

Select a capacitor with the lowest ESR possible. ESR of 1 Ω or less is recommended.

⑧ Guard ring

Although not included in the pattern example in this guide, it is recommended that a guard ring be provided around the area that handles minute signals if noise jumping into the input of the op-amp is concerned. The guard ring prevents noise, etc. from entering the input terminal from other wiring due to line capacitance or stray capacitance, or leakage current from flowing due to potential generation.

As for the guard ring, in order to prevent noise from jumping out as a loop antenna, some cuts may be put in the middle, but the presence or absence of cuts should be judged by experiments on actual boards, etc. If no cuts are made, the area surrounding the loop should be as small as possible to reduce the magnetic flux passing through the loop.

4. Product Overview

4.1. TC75S67TU

- Low Equivalent Output Noise Voltage:
 $V_{NI}=16 \text{ nV}/\sqrt{\text{Hz}}$ (typ.) @ $f=10 \text{ Hz}$, $R_S=100 \ \Omega$, $R_f=10 \text{ k}\Omega$, $V_{DD}=2.5 \text{ V}$, $V_{SS}=\text{GND}$, $G_V=40 \text{ dB}$
 $V_{NI}=6 \text{ nV}/\sqrt{\text{Hz}}$ (typ.) @ $f=1 \text{ kHz}$, $R_S=100 \ \Omega$, $R_f=10 \text{ k}\Omega$, $V_{DD}=2.5 \text{ V}$, $V_{SS}=\text{GND}$, $G_V=40 \text{ dB}$
- Low-input-bias current: $I_I = 1 \text{ pA}$ (typ.)
- Low supply current: $I_{DD} = 430 \ \mu\text{A}$ (typ.) @ $V_{DD}=2.5 \text{ V}$, $V_{SS} = \text{GND}$
- Low power supply voltage drive: V_{DD} , $V_{SS}=2.2 \text{ to } 5.5 \text{ V}$

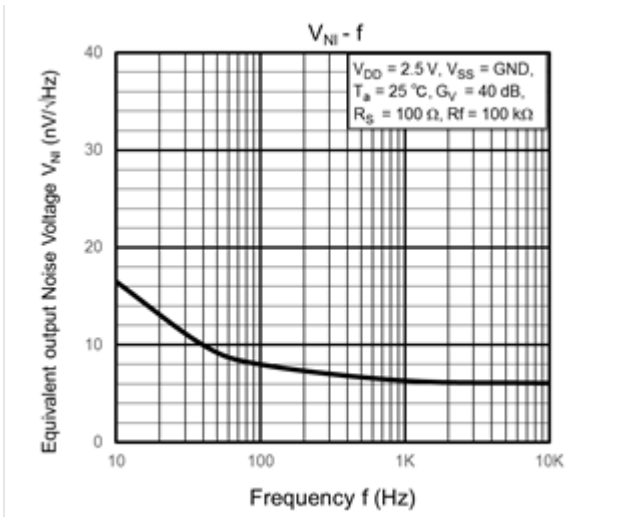


Fig. 4.1 Equivalent Output Noise

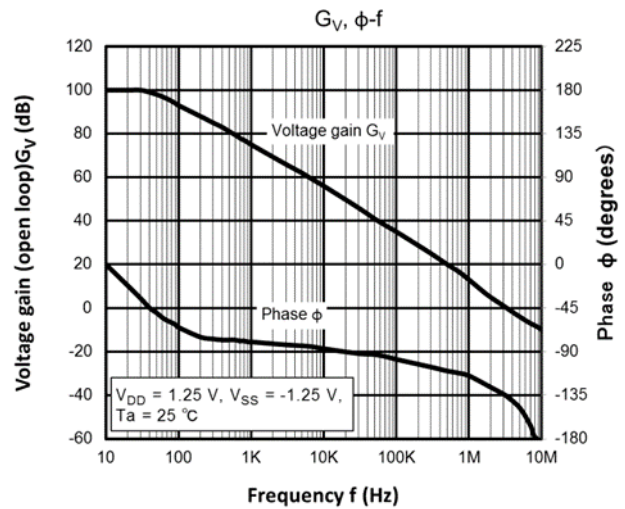


Fig. 4.2 Phase Margin & Gain

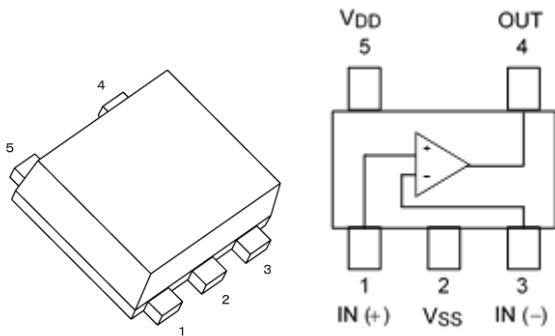


Fig.4.3 External View and Pin Assignment

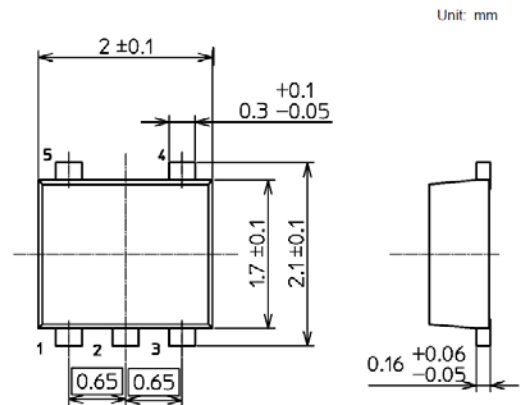


Fig.4.4 Dimensions

Refer to the data sheet for details of each characteristic.

To download the datasheet for TC75S67TU →

[Click Here](#)

4.2. Pin Description

Table 4.1 Pin Description of TC75S67TU

Pin number	Pin name	Function
1	IN (+)	Non-inverting input pin
2	V _{SS}	Connect this pin to GND when using a single power supply with a negative power supply terminal.
3	IN (-)	Inverting input terminal
4	OUT	Output terminal
5	V _{DD}	The maximum rating for use with a single power supply with a positive power supply terminal is 6 V. For stable operation, it is recommended to use a bypass capacitor of 0.1 μ F and a capacitor of 0.01 μ F or more (ESR=1 Ω or less).

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