CMOS Low-Noise Operational Amplifier for Sensor Signal Amplification

Outline:

Outputs of various sensors such as optical sensors, ultrasonic sensors, and vibration sensors, which are widely used in IoT equipment, are very small analog signals, so it requires high gain amplification by low-noise amplifier circuits.

This application note explains the noise properties fo TC75S67TU as an example.

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1. Introduction

IoT and other applications incorporate various types of sensors to collect ambient data.

Commonly used sensors include motion sensors; pyroelectric infrared sensors for smoke alarms; ultrasonic and light sensors for distance measurement; infrared sensors for security systems and remote controllers; gas sensors for gas detectors; load cells for weight sensing; and shock sensors for vibration detection. In many cases, a small signal from a sensor is amplified with an op amp before being fed to an analog-digital converter (ADC).

Because most sensors provide a small analog signal, low-noise op amps are required for high-precision amplification.

This application note uses Toshiba's TC75S67TU ultra-low-noise CMOS op amp to describe how to obtain the best performance from low-noise op amps for the amplification of a small sensor signal.

2. Overview of a sensor and an amplifier circuit for a small signal

Since the output of a sensor is a small signal, a low-noise op amp is required for high-precision amplification. Figure 2.1 shows a diagram of a sensor circuit block.

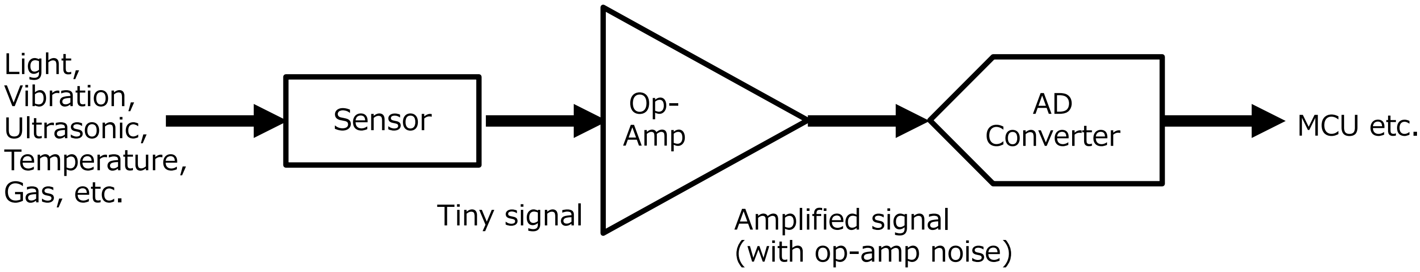


Figure 2.1 Example of a sensor circuit block

Examples of typical sensor circuits are described below:

(1) Vibration sensor circuit

Figure 2.2 shows an example of a shock sensor circuit (charge amplifier circuit) using an op amp, which causes the charge output (Q_S) to change in proportion to the magnitude of vibration applied to the shock sensor. This circuit consists of an op amp that amplifies a signal from the shock sensor and a feedback capacitor (C_f).

(2) Ultrasonic sensor circuit

Figure 2.3 shows an example of an ultrasonic sensor circuit (inverting amplifier circuit) using an op amp, which receives ultrasonic with an ultrasonic sensor and converts it into voltage. This circuit comprises an AC-coupling capacitor (C_C), an input resistor (R_S), and a feedback resistor (R_f) in addition to a sensor.

(3) Light sensor circuit

Figure 2.4 shows an example of a light sensor circuit (current-to-voltage converter circuit) using an op amp, in which a small current (I_S) flows in proportion to the intensity of light received by a light sensor (photodiode, or PD for short). This circuit consists of a light sensor, an op amp that amplifies a signal from the sensor, a resistor (R_f) for current-to-voltage conversion, and a capacitor (C_f) for oscillation prevention.

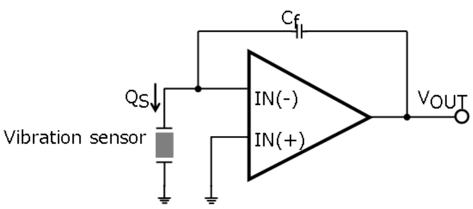


Figure 2.2 Example of a typical shock sensor circuit (charge amplifier circuit)

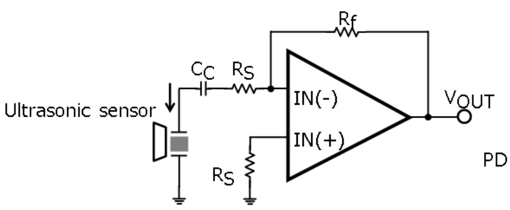


Figure 2.3 Example of a typical ultrasonic sensor circuit (inverting amplifier circuit)

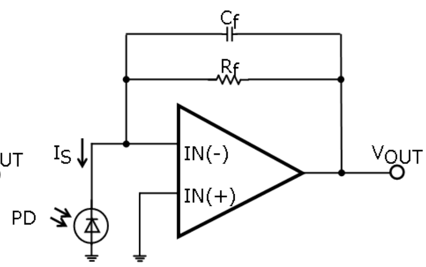


Figure 2.4 Example of a typical light sensor circuit (current-to-voltage converter circuit)

The next section discusses the performance required for op amps for major sensor applications.

3. Performance requirements for op amps for sensor signal amplification

3.1 Impact of the noise of op amp circuits on sensing accuracy

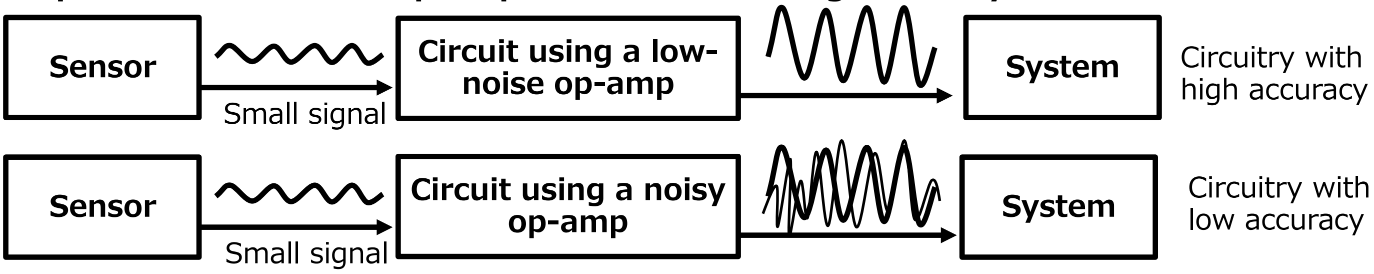


Figure 3.1.1 Impact of the noise of op amp circuits on sensing accuracy

Figure 3.1.1 shows the impact of op amps on sensing accuracy. When a small signal from a sensor is amplified by a noisy op amp, its noise is superimposed on the amplified sensor signal, degrading sensing accuracy. Resistors in the sensor circuit also affect the value of noise.

Op amp noise can be classified into external or internal noise, depending on its source. Internal noise is generated in the op amp whereas external noise is caused by a feedback resistor and other external components. Figure 3.1.2 shows the sources and types of op amp noise.

Figure 3.1.3 shows the noise frequency characteristics of an op amp. 1/f noise is present in the low-frequency region whereas white noise is present across the whole frequency spectrum (see Table 1).

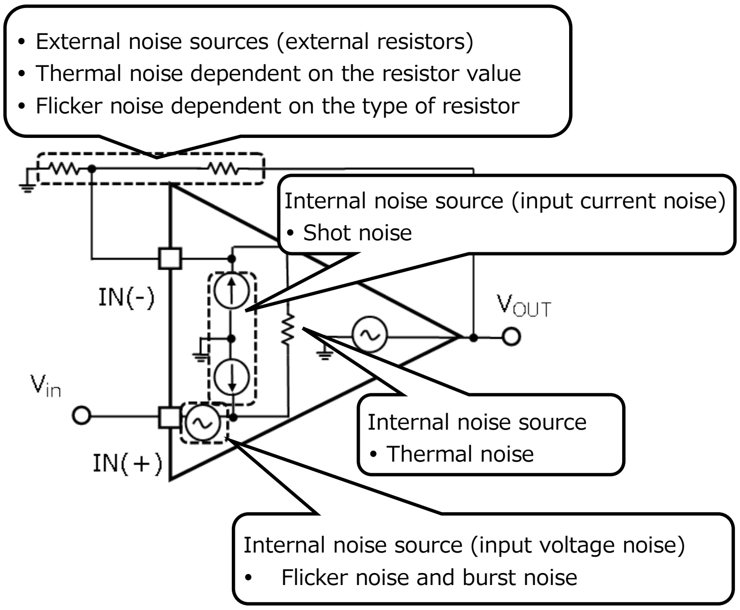


Figure 3.1.2 Op amp circuit noise model

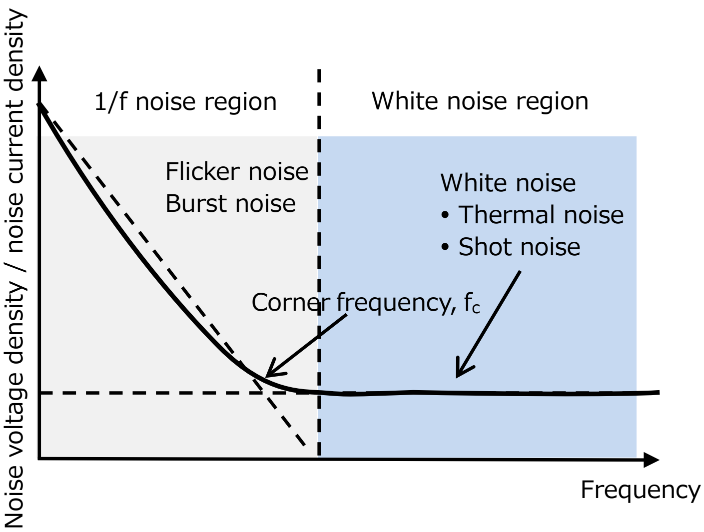


Figure 3.1.3 Frequency characteristics of op amp circuit noise

Table 1 Noise frequency characteristics

Source	Frequency Region	Dominant Noise	Cause of Noise
Internal	1/f region (low-frequency region)	Flicker noise, Burst noise	Effect of lattice defects in semiconductor
External		Flicker noise	Resistors
Internal	White noise region (whole frequency spectrum)	Shot noise	Current passing across the p-n junction of semiconductor
Internal External		Thermal noise	Op amp and external resistors; dependent on the resistor value

3.1.1 What is internal noise?

Internal noise is the noise generated within an op amp circuit. There are four main sources of internal noise.

(1) Thermal noise

Thermal noise is generated by resistors and MOSFETs that constitute an op amp circuit. Thermally excited electrons move irregularly among the atoms in a resistor, causing noise voltage to appear across the resistor even when there is no current flowing through it. Thermal noise (V_{NT}) is expressed as:

$$V_{NT} = \sqrt{4\mathrm{kTB}}$$

where k is the Boltzmann constant (1.38×10^{-23}) in J/K, T is absolute temperature in K, R is resistance in Ω, and B is the frequency bandwidth in Hz.

This equation indicates that thermal noise increases with the resistor value.

(2) Flicker noise and burst noise

Flicker noise and burst noise are generated by the MOSFET and other elements in a CMOS op amp.

(3) Shot noise

Shot noise results whenever current crosses the potential barrier of a p-n junction.

Take, for example, a shock sensor circuit that is affected by internally generated noise.

The shock sensor circuit shown in Figure 2.2 uses a charge amplifier circuit. Let the output charge of the shock sensor be Q_S coulombs and the feedback capacitor value be C_f. Then, the output voltage of the op amp is expressed as $V_{OUT} = \frac{Q_S}{C_f}$. Letting the capacitance of the shock sensor be C_j, the noise gain (G_N) of this circuit can be expressed as $G_N = \frac{C_j}{C_f}$. The equivalent input noise voltage of the op amp is increased G_N times, causing a sensor error. To reduce the sensor error, a low-noise op amp must be selected for this shock sensor circuit.

3.1.2 What is external noise?

External noise means the noise generated by resistors external to an op amp.

(1) Flicker noise

Resistors generate 1/f noise.

(2) Thermal noise

Resistors external to an op amp generate thermal noise (V_{NT}), which is affected by the values of the above resistors and the ambient temperature.

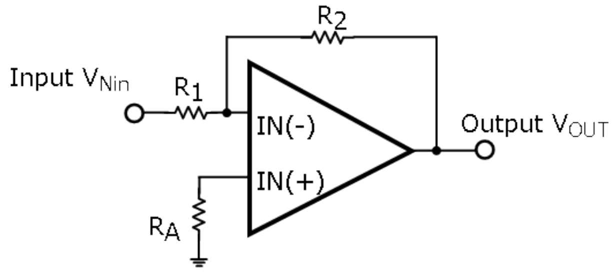
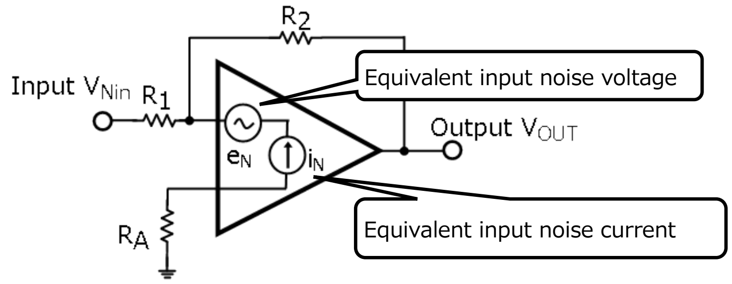


Figure 3.1.4(a) Example of an inverting amplifier circuit Figure



3.1.4(b) Example of an inverting amplifier noise model

The equivalent input noise voltage (V_{Nin}) of the inverting amplifier circuit shown in Figure 3.1.4(b) can be calculated as follows:

- Thermal noise voltage density at the output due to resistors: V_{RN} ($\mathrm{Vrms}/\sqrt{\mathrm{Hz}}$)

$$V_{RN}=\sqrt{\left((-\frac{R_2}{R_1})\sqrt{4kTR_1}\right)^2+\left\{\sqrt{4kTR_A}\,(1+\frac{R_2}{R_1})\}^2+4kTR_2\right\}}$$

- Output noise voltage: V_{eN} ($\mathrm{Vrms}/\sqrt{\mathrm{Hz}}$)

$V_{eN}=e_N(1+\frac{R_2}{R_1})$, where e_N is the equivalent input noise voltage density of an op amp.

- Output current noise voltage density: V_{iN} ($\mathrm{Vrms}/\sqrt{\mathrm{Hz}}$)

$V_{iN}=\sqrt{\{i_N+R_A\left(1+\frac{R_2}{R_1}\right)\}^2+(i_N-R_2)^2}$, where i_N is the equivalent input noise current noise density.

Total noise voltage density at the output of an op amp (V_{NOUT}) is expressed as follows in $\mathrm{Vrms}/\sqrt{\mathrm{Hz}}$:

$$V_{NOUT}=\sqrt{{V_{RN}}^2+{V_{eN}}^2+{V_{iN}}^2}$$

Hence, the equivalent input noise voltage of this circuit (V_{Nin}) is calculated as follows in $\mathrm{Vrms}/\sqrt{\mathrm{Hz}}$:

$$V_{Nin}=\frac{V_{NOUT}}{\left|-\frac{R_2}{R_1}\right|}$$

For example, an ultrasonic sensor is affected by internally and externally generated noise.

The ultrasonic sensor shown in Figure 2.3 uses an inverting amplifier circuit. Let the output voltage of the ultrasonic sensor be Vc, the input resistor value be RS, and the feedback resistor value be Rf. Then, the output voltage of the op amp can be expressed as $V_{OUT}=-\frac{R_f}{R_s}\cdot V_C$. This circuit is affected by the noise generated by external resistors in addition to the internal noise of the op amp.

It is therefore necessary to reduce both internally and externally generated noise.

3.2 Selecting an op amp with low input bias current to reduce a sensing error

The light sensor circuit shown in Figure 2.4 uses a current-to-voltage converter circuit. Let the output current of the sensor be IS and the feedback resistor value be Rf. Then, the output voltage of the op amp can be expressed as $V_{OUT} = \mathrm{I}_S \cdot R_f$. The output current of a photodiode, which varies with the input light intensity, is small—on the order of a few nanoamperes to a few microamperes. Consequently, if the input bias current (IB) of the op amp is large, $\mathrm{V}_{OUT} = \mathrm{I}_B \cdot \mathrm{R}_f$ appears as a sensing error. It is therefore necessary to select an op amp with minimal input bias current for this light sensor circuit.

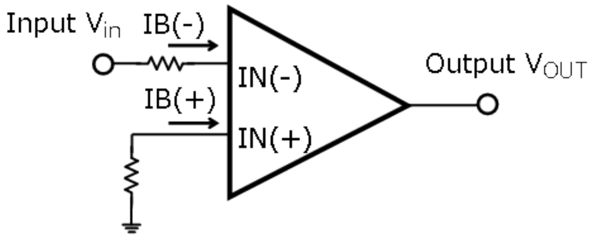


Figure 3.1.5 Input bias current

Toshiba's TC75S67TU op amp provides a solution that meets all the requirements discussed in Section 3. The next section describes the TC75S67TU.

4. Op amp ideal for sensor signal amplifier circuits

4.1 Selecting an op amp with low internal noise

The TC75S67TU provides better noise performance than Toshiba's previous CMOS op amps because of improvements in semiconductor process technology and op amp circuitry. Its typical equivalent input noise is 16 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (at f = 10 Hz) in the 1/f region and 6 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ (at f = 1 kHz) in the white noise region. The outstanding noise performance of the TC75S67TU makes it ideal for high-precision amplification of a sensor signal across the whole frequency spectrum. Equivalent input noise voltage (V_{NI}) is dependent on the supply voltage (V_{DD}). Figure 4.2 shows the V_{NI}–V_{DD} curve of the TC75S67TU.

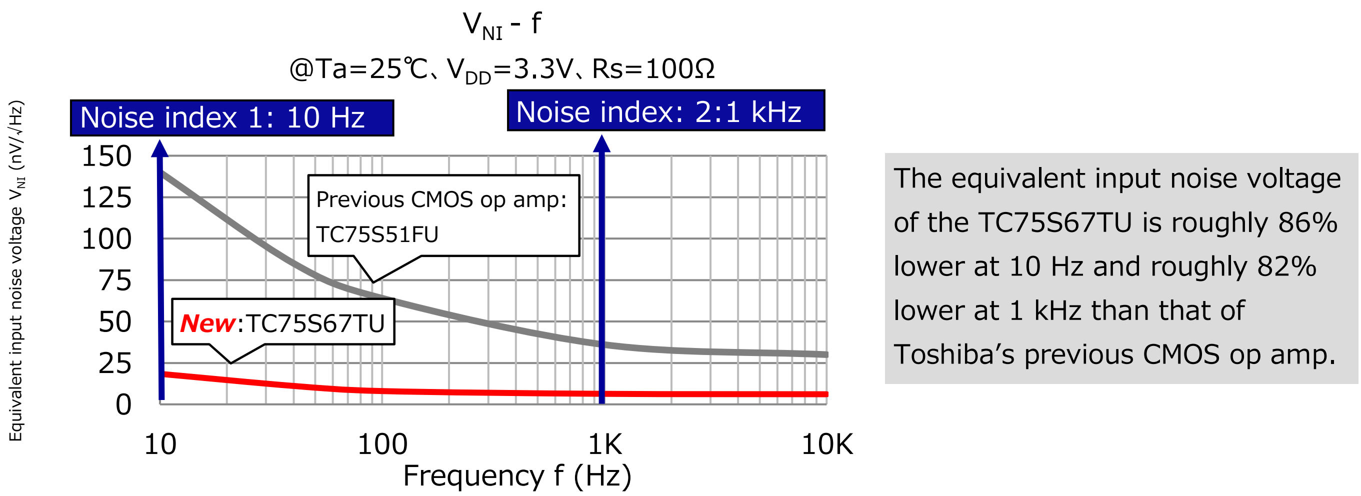


Figure 4.1 Typical equivalent input noise voltage-vs-frequency curve of the TC75S67TU

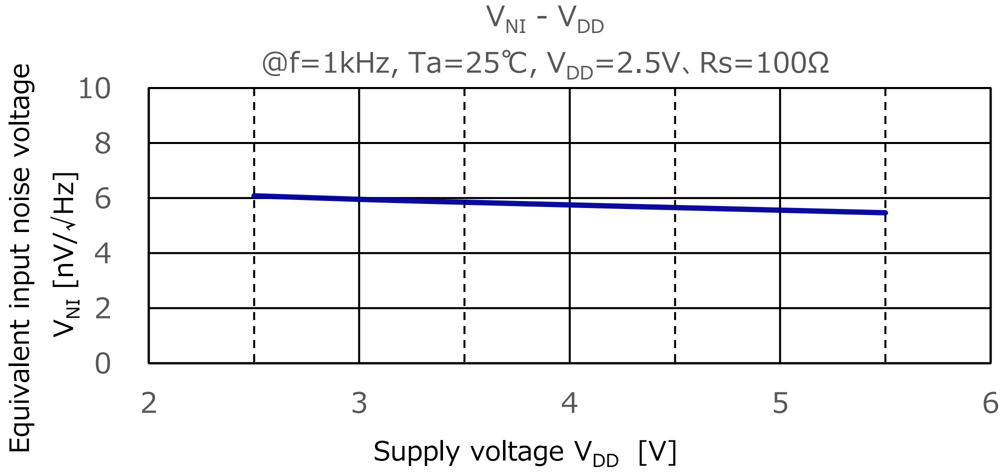


Figure 4.2 Typical equivalent input noise voltage-vs-supply voltage curve of the TC75S67TU

4.2 Selecting external resistors to reduce externally generated noise

An op amp’s external noise is mainly affected by:

(1) External resistor type

Resistors generate 1/f noise caused by flicker noise, which can be reduced by using thin-film chip resistors or metal-film resistors instead of carbon-film resistors or thick-film chip resistors.

(2) Thermal noise

The equations for the inverting amplifier circuit shown in the previous section indicate that thermal noise can be reduced by reducing the R_1 and R_2 values appropriately according to an op amp’s output current without changing their ratio (R_2/R_1). Equivalent input current noise causes the equivalent input noise voltage (R_A) to be multiplied ($1+R_2/R_1$) times by the inverting amplifier circuit. In the case of typical bipolar op amps, resistor R_A helps reduce the input offset voltage generated by the bias current for the input pins, $I_{N(+)}$ and $I_{N(-)}$. However, R_A has little such effect on the TC75S67TU because its input bias current is as small as roughly 1 pA. It is therefore unnecessary to connect R_A to the TC75S67TU to reduce thermal noise. Just for reference, Figure 4.3 shows an equivalent input noise voltage (V_{NI})-vs-signal source resistance (R_A) curve for the circuit shown in Figure 3.1.4.

The thermal noise (V_{NT}) of a resistor is affected by temperature and frequency bandwidth as described in Section 3.1.1. Therefore, thermal noise can be reduced by: 1) reducing the resistor value, 2) minimizing the frequency bandwidth, and 3) reducing a circuit’s operating temperature.

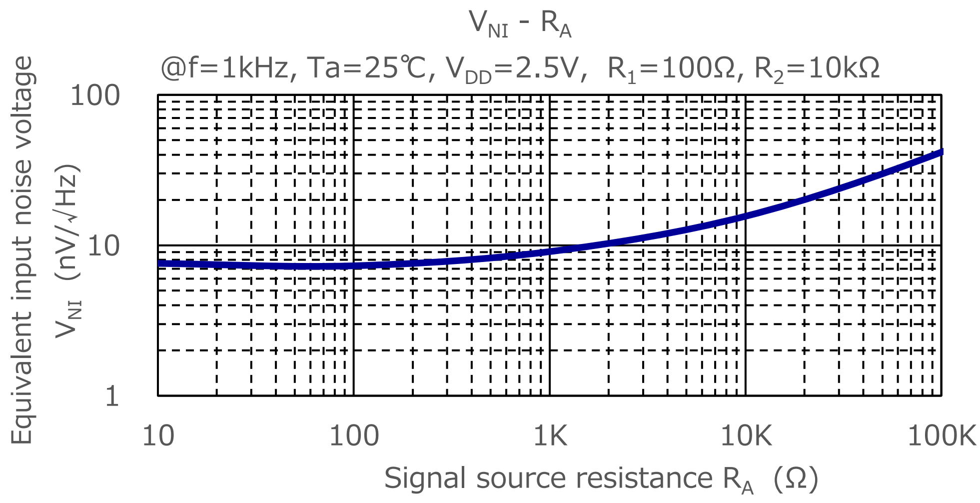


Figure 4.3 Typical equivalent input noise voltage-vs-signal source resistance curve of the TC75S67TU

4.3 CMOS op amp with low input bias current suitable for improving the accuracy of a sensor circuit

As described in the preceding subsection, the input bias current for an op amp could greatly affect the accuracy of a sensor circuit. Fabricated using a CMOS process, the TC75S67TU op amp provides a typical input bias current of 1 pA (at T_a=25°C), several orders of magnitude smaller than that of typical bipolar op amps with an input bias current of a few nanoamperes. Consequently, the TC75S67TU has very little adverse effect on the accuracy of a sensor circuit and is therefore the ideal choice for sensor circuit applications.

5. Summary

IoT and other devices are expected to continue to drive the demand for various sensors. It is necessary to further enhance the accuracy of sensor circuits so as to improve the performance of the applications incorporating them. Toshiba's TC75S67TU CMOS op amp with low noise and low input bias current is designed to amplify a small sensor signal with high precision. The TC75S67TU provides the optimum solution for various sensor signal amplifier circuits. For details of its electrical characteristics, see its datasheet.

Ultra-low-noise op amps:
To download the datasheet for the TC75S67TU→ Click Here

For other op amp circuit designs, see the application note Basic Operational Amplifier and Comparator Circuits.
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