

ISSN 1726-5479

SENSORS & TRANSDUCERS

1 vol. 124
/11



Sensor Instrumentation, DAQ and Virtual Instruments

International Frequency Sensor Association Publishing





Sensors & Transducers

Volume 124, Issue 1,
January 2011

www.sensorsportal.com

ISSN 1726-5479

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Issue 1
January 2011

www.sensorsportal.com

ISSN 1726-5479

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Unspecified Low-Frequency Noise in Chopper Op-Amps

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Received: 31 October 2010 /Accepted: 24 January 2011 /Published: 28 January 2011

Abstract: The low-frequency input noise-voltage of three precision chopper or auto-zero op-amps was measured over the span 0.001 Hz-10 Hz at ambient temperature and at constant temperature. It is seen that temperature should be controlled in order to observe the low-frequency self-noise of precision op-amps. It is then shown that chopper op-amp external network time-constants should be carefully adjusted, or eliminated altogether, in order to avoid degradation of the attainable noise-performance of some chopper or auto-zero op-amps. *Copyright © 2011 IFSA.*

Keywords: Noise, Op-Amps, Low-frequency, Auto-zero, Non-drift, Precision.

1. Introduction

The idea of chopping an analog signal using an on-off switch has been around since 1935 at least. Circa 1950, the first chopper op-amp was introduced. By op-amp (operational amplifier) is meant a DC amplifier having two floating differential inputs. The early 1950 inverting chopper op-amp used a DC op-amp with an additional chopper-circuit and AC amplifier. The chopper-circuit created an AC signal from the DC op-amp inverting (-) input by switching between the (-) input and ground. This switching signal was then processed and applied to the op-amp's non-inverting (+) input, reducing input offset-voltage amplitude and drift.

After the advent of the CMOS analog switch, the chopping principle was applied internally to CMOS integrated-circuits, including op-amps. The goal of the IC chopper operational-amplifier was to create an amplifier which behaved like its' continuous-time linear counterpart, however possessed much lower and more stable input offset-voltage. In the chopper op-amp concept, the reduction of input offset-voltage will naturally produce the suppression of low-frequency noise as well. These new

CMOS devices were described and specified similarly to linear operational amplifiers. Analog design engineers applied standard linear op-amp circuit methods using chopper op-amps.

Today there are approximately 100 unique chopper, auto-zero, and non-drift CMOS operational amplifiers. The inner workings of each of these IC's are likely to be unique and carefully guarded. Many chopper op-amps are protected by patents, although it is not normally possible for the application designer to associate a specific chopper or auto-zero op-amp with a given patent, since few datasheets mention patent numbers. For these reasons, analog application designers who are curious about the inner workings of chopper op-amps are frustrated.

Although chopper op-amps have linear internal components and modules, chopper op-amps are most importantly many tiny embedded analog switches. These analog switches are controlled by an oscillator and a sampling digital controller which operates as a feedback servo-control system to reduce input offset-voltage in both the inverting and non-inverting modes. Chopper op-amp complexity is comparable to a sigma-delta A/D converter, wherein many subtle undesirable offset and noise effects must be compensated for in the switching realm. It is possible for chopper op-amps to have 'override' functions, which override functions interrupt and initialize the normal operation of the sampled digital servo system when out-of-bounds operation occurs.

2. Chopper Op-Amp Interface

A significant difference between a chopper op-amp and an A/D converter is that the inputs and outputs of the A/D converter are specified or recommended, whereas the input and output networks of the chopper op-amp are up to the application designer, who may use classical linear op-amp application circuits using inductors and capacitors, unless these external circuits are forbidden by the chopper op-amp datasheets. (Some chopper op-amp datasheets warn of the use of external capacitors. Other chopper op-amp datasheets conversely *recommend* the use of external capacitors.)

On most chopper op-amp datasheets, the chopper op-amp is typically shown interfaced to some low-impedance resistive source, such as strain-gauge bridges or thermocouples. It is however generally assumed by application designers that chopper op-amps may be applied in similar ways to linear op-amps. This assumption of inter-changeability leads to chopper op-amps being designed into a host of applications which are different than the typical resistive applications which are shown on the chopper op-amp datasheets; such as applications where reactive networks are used to shape the frequency-response of the application circuit. *It is when external reactive networks are used with a chopper op-amp that it is possible for unspecified very-low-frequency noise to arise.*

3. Chopper Op-Amp Input Noise-Voltage Types

Chopper op-amp front ends exhibit several types of voltage noise. One is sampling self-noise, which is the voltage noise-floor of the op-amp front-end under optimum conditions of the sampling servo. (Small sampling noise is the goal of the chopper op-amp design.) Another type of noise is known as 'spike noise', which is a voltage-pulse coupled to the op-amp inputs (or output) from inside the op-amp. These spikes are caused by the CMOS switch drive-signals, which turn the sampling switches on and off, or are caused by the opening and closing of the switches themselves. Spike noise is usually present at frequencies well above 10Hz and therefore not of concern here (except in case of down-conversion).

Another type of voltage noise is 'tilt'. Tilt is used herein to refer to slow-drift of the op-amp offset-voltage (dV/dt) over hundreds or thousands of seconds. The op-amp offset-voltage is sensitive to

temperature, due to imperfections in the manufacturing process or the design of the device. Tilt may show up in the op-amp FFT noise-spectrum at very low frequencies (0.001 Hz). It is difficult to distinguish between tilt-noise and self-noise (such as sampling noise, thermal noise, $1/f$ noise, or unspecified noise) in the FFT plot; therefore tilt should be suppressed in order to observe self-noise.

Thermal, shot, and $1/f$ noise are present in the CMOS input transistors, however these noise sources are not of concern here. The reason is that, below 10 Hz, sampling noise dominates the noise-floor. Without the sampling feedback loop, op-amp $1/f$ self-noise rises sharply below approximately 10 Hz.

Finally, and the subject of this article, there is a new chopper op-amp noise-type designated herein as 'unspecified noise'. *Unspecified noise* refers to non-theoretical noise which may possibly result due to applying a chopper op-amp using external networks having reactive components. These external reactive networks are similar to the networks used for linear op-amp application over the last 40 years of IC op-amp history, wherein reactive networks are attached to the op-amp inputs and/or outputs or as feedback elements.

In the case of the linear op-amp, the final noise resulting from the use of reactive networks can normally be predicted from the mathematical combination of the bode' plot or LaPlace analysis of the op-amp open-loop transfer-function, op-amp noise data from datasheet, and the external reactive network, all taken together. Unspecified noise refers to noise arising from within the chopper op-amp; noise which cannot be predicted or allowed-for by the application designer's use of bode' plots or other linear analysis means; and noise which is not specified in the op-amp datasheet for the purpose of worst-case noise design.

4. Noise Testing

Three CMOS chopper op-amps were selected for noise testing over the frequency span 0.001 Hz-10 Hz, op-amps "001", "002" and "003", using the test circuits of Fig. 1 and Fig. 4. These three op-amps are all chopper or auto-zero op-amps, introduced between 1987 and 2006, having input-offset voltages of 10 μ V or less.

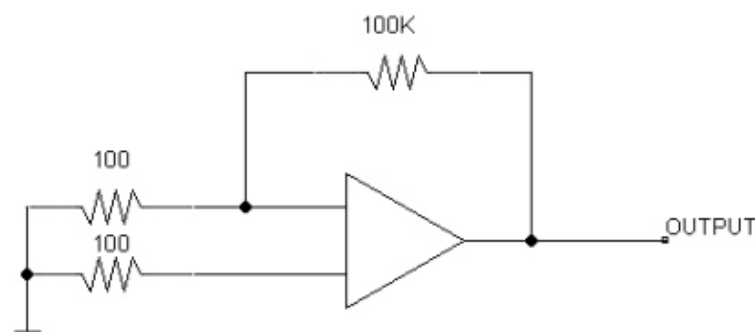


Fig 1. Test circuit used for measuring Op-Amp input noise-voltage for resistive networks.

5. Tilt Controlled by Stabilizing Temperature

Op-amp (002) is tested for input voltage-noise using the circuit of Fig. 1. Fig. 2A shows the input noise-voltage FFT spectrum of op-amp 002 under ambient temperature conditions. The test period is

9,000 sec, with ambient temperature changing approx $\pm 5^{\circ}\text{C}$ over 24 hours in a quasi-sine shape. (24 Hrs = 86,400 sec).

Fig. 2A shows what appears to be a $1/f$ noise component near 0.001 Hz. However, if one inspects the associated time-domain data plot of Fig. 2B, which produced the FFT of Fig. 2A, it is seen that the input offset-voltage is drifting slowly, because the op-amp is not isolated from ambient temperature changes.

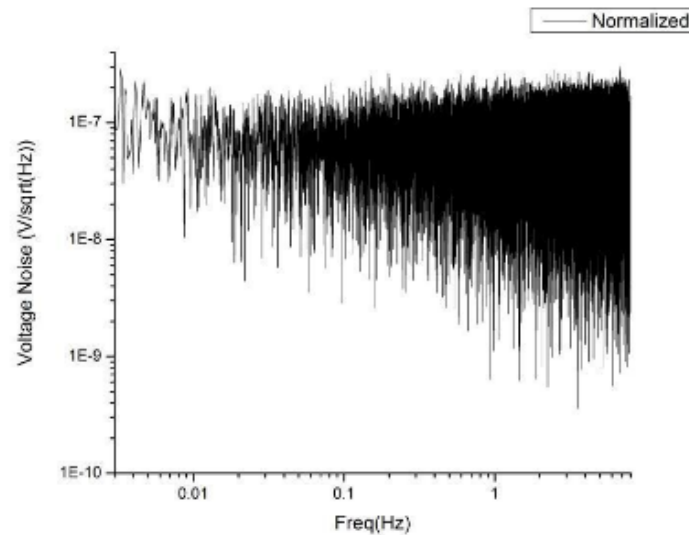


Fig 2A. FFT of Op-Amp 002 input noise-voltage for ambient-temperature conditions.

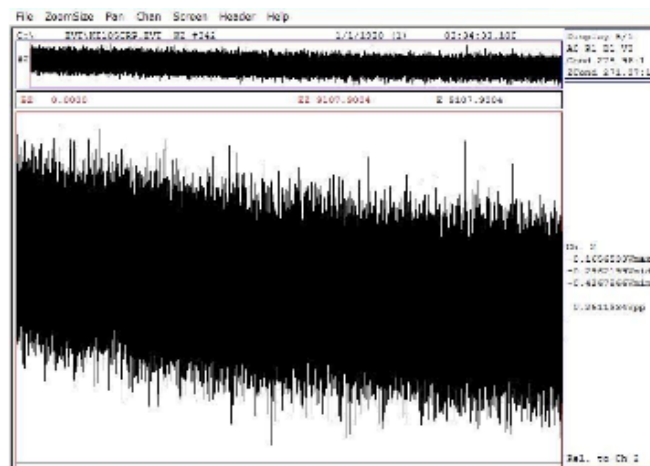


Fig 2B. Time-domain plot of Op-Amp 002 input noise-voltage for ambient-temperature conditions. Signal size is 2.6uV p-p.

Next, temperature drift is suppressed by using an environmental chamber [5]. For the FFT of Fig. 3A, the temperature-drift of 002 has been reduced to approx ± 0.05 °C over 14,000 sec. Under said temperature control, the FFT of Fig. 3A shows no '1/f' noise; instead noise-voltage of 002 now decreases monotonically below 10 Hz. This FFT feature is characteristic of all chopper op-amps tested so far using temperature control.

The time domain data for the FFT of Fig. 3A is shown in Fig. 3B. The time-domain tilt of Fig. 2B is seen to be suppressed in Fig. 3B by temperature control. Note that the magnitude of tilt being suppressed is only several hundred nV over thousands of seconds, which is however sufficient to alter the monotonic appearance of the FFT near 0.001 Hz.

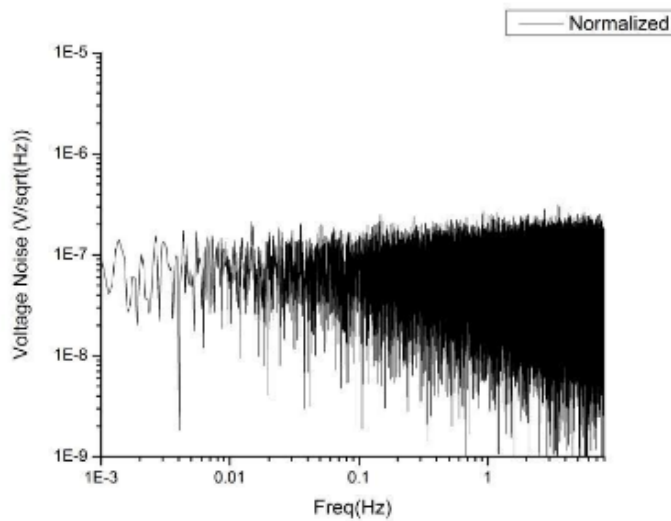


Fig 3A. FFT of Op-Amp 002 input noise-voltage for constant temperature condition

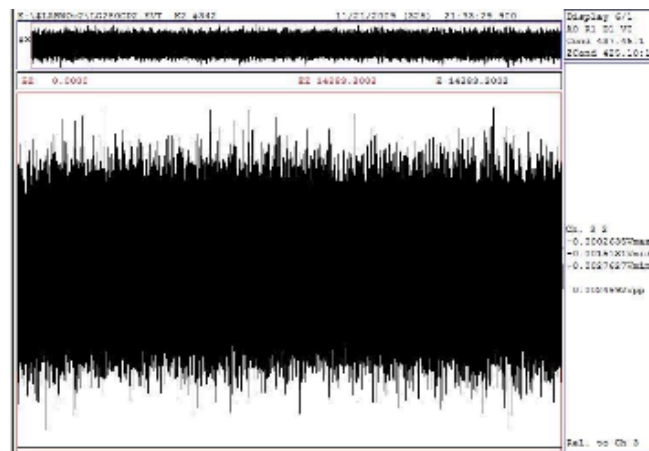


Fig 3B. Time-domain plot of data used for FFT of Fig 3A.
Signal-size at input is approx 2uV p-p.

Not as easily seen as tilt is in the time-domain data is any $1/f$ noise arising from chaotic air convection-currents. This source of noise is reduced by controlling the temperature of the DUT (device-under-test) by using an optical heat-source and a contact thermometer. This arrangement bypasses the air as a medium of heat delivery, improving temperature-control bandwidth by approximately 100:1.

Another $1/f$ noise-source is ambient infrared heat sources, including the human head (30 W), which infrared sources may radiate $1/f$ noise directly into the device-under-test. Unwanted infrared heat is managed by placing the test op-amp under a 1/4" glass cover, which blocks most infrared.

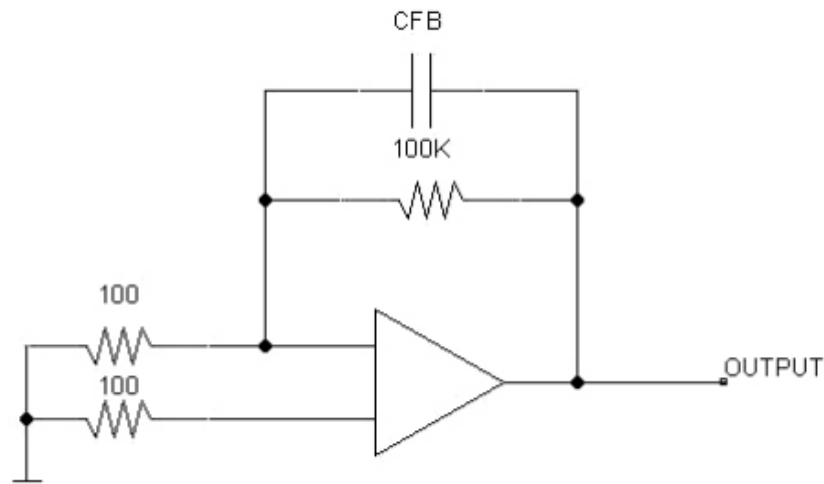


Fig 4. Test circuit used for measuring unspecified-noise. A feedback capacitor Cfb is present.

Much of the test fixture noise, such as wiring thermocouples, contact tension of sliding contacts, and power-supply noise is reduced by placing support electronics inside the environmental chamber. Due to all of these methods, the data of Fig. 3A is believed to be close to the true self-noise of chopper op-amp 002. This belief is supported by the consistency of many data sets obtained over 1 year's time.

For the remaining data in this paper, DUT temperature-control is used which maintains temperature constant at approximately 50 °C within ± 0.05 °C, eliminating tilt-noise as a factor in the op-amp input noise-voltage FFT. With temperature control, *chopper op-amp input noise-voltage below 10Hz is assumed to consist primarily of op-amp sampling noise and unspecified noise*. For information regarding methods of testing of very low-frequency semiconductor noise, see [1-4].

6. Unspecified Chopper Op-Amp Noise

Three op-amps are tested for input noise-voltage using first the circuit of Fig. 1 and next the circuit of Fig. 4, at constant temperature. Fig. 4 is similar to Fig. 1 except that Fig. 4 contains a feedback capacitor Cfb; the circuit of Fig. 4 being used to test for unspecified noise. Capacitor sizes used were 1 nF (op-amp 001), 30 nF (op-amp 002), and 100 nF (op-amp 003). The DUT closed-loop gain was 1 K V/V and the total test fixture gain was 100 K V/V, as measured from the DUT inputs. $R_{in} = 100$ Ohms.

6.1. Op-Amp 001

Fig. 5A shows the input noise-voltage FFT of op-amp 001 for the circuit of Fig. 1. Fig. 5B shows the input noise-voltage FFT of op-amp 001 for the circuit of Fig. 4, where an external resistor/capacitor feedback network is used. In Fig. 5B, op-amp 001 shows good noise immunity to the external network of 100 K ohms || 1nF. The noise-density at 0.001 Hz increases from 30 nV/Rt-Hz for the circuit of Fig. 1, to 60 nV/Rt-Hz for the circuit of Fig. 4; 60 nV/Rt-Hz being a relatively low noise level for any op-amp at 0.001 Hz.

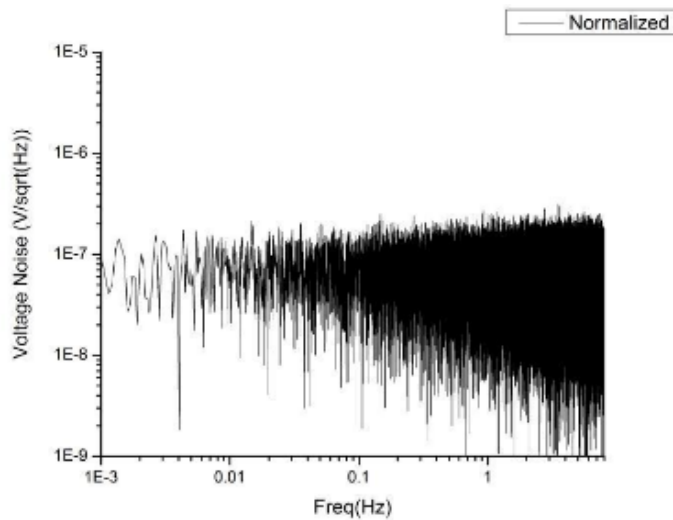


Fig 5A. FFT of Op-Amp 001 input noise-voltage for resistive external network.

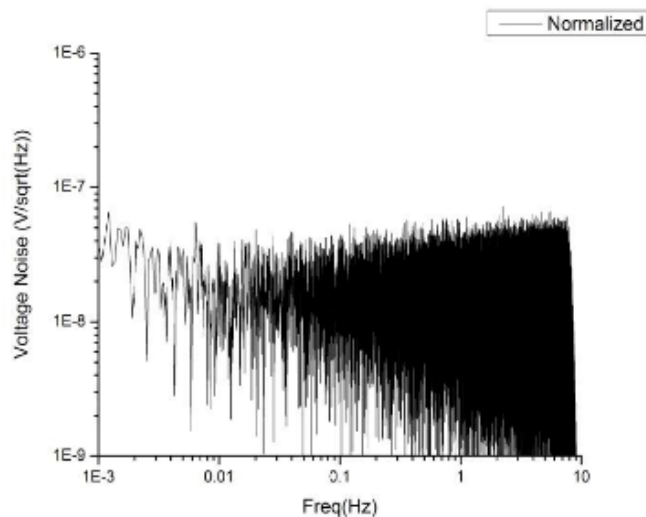


Fig 5B. FFT of Op-Amp 001 input noise-voltage for Cfb in feedback network.

6.2. Op-Amp 002

When op-amp 002 was tested using Fig. 4, 002 appeared to produce large unspecified noise. However, to be certain that any excess or unspecified noise was being evoked by the external feedback capacitor, the following procedure was used:

Fig. 6: At the start of a 30,000 sec noise test, $C_{fb} = 30$ nF. Halfway through the test, the 30 nF capacitor was removed. Unspecified noise is apparent during the first 15,000 sec of the time data of Fig. 6, which is the period during which the capacitor C_{fb} was present.

Fig. 7: At the start of a second 30,000 sec noise test, $C_{fb} = 0$. Halfway through the test, the 30 nF capacitor was inserted for C_{fb} . Unspecified noise is apparent during the last 15,000 sec of the time data of Fig. 7, which is the period during which the capacitor was present.

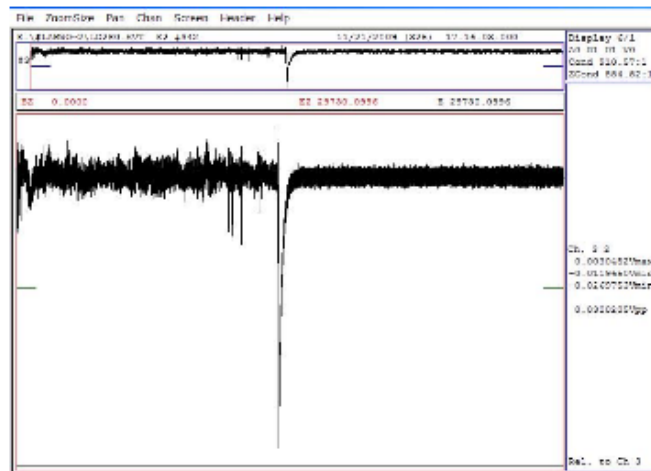


Fig 6. Time-domain plot of Op-Amp 002 input noise-voltage.
For first-half of data, $C_{fb} = 30\text{nF}$; second half, $C_{fb} = 0$.

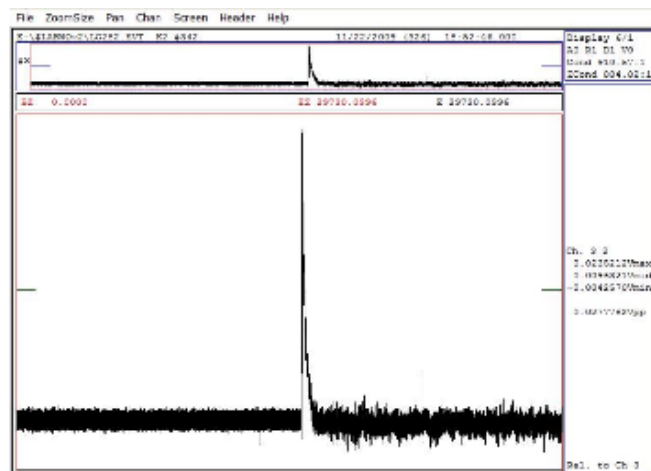


Fig 7. Time-domain plot of Op-Amp 002 input noise-voltage.
For the first-half of data, $C_{fb} = 0$; second half, $C_{fb} = 30\text{nF}$.

Comparison of Fig. 6 and Fig. 7 seems to support the conclusion that a 30 nF feedback capacitor in parallel with a 100 K feedback resistor is evoking unspecified noise from chopper op-amp 002. The excess noise is also seen in the FFT's. Fig. 8 shows the FFT of the 0-15,000 sec time data of Fig. 7 ($C_{fb} = 0$), and Fig. 9 shows the FFT of the 15,000 sec-30,000 sec time data of Fig. 7 ($C_{fb} = 30\text{ nF}$).

In Fig. 8 the input noise-voltage decreases monotonically with frequency from 10 Hz to 0.001 Hz. In Fig. 9, with the feedback capacitor present, the input noise-voltage begins to increase below 1 Hz and continues to increase to a level of $2\mu\text{V}/\text{Rt-Hz}$ at 0.001 Hz.

6.3. Op-Amp 003

Op-amp 003 has the best low-frequency noise of all three of the op-amps tested, for the case of resistive networks. Fig. 10 shows the input noise-voltage FFT for 003 for the circuit of Fig. 1. Note that the noise at 0.001 Hz is only $20\text{ nV}/\text{Rt-Hz}$, for the idealized test condition of DUT temperature drift of less than $\pm 0.05\text{ }^{\circ}\text{C}$.

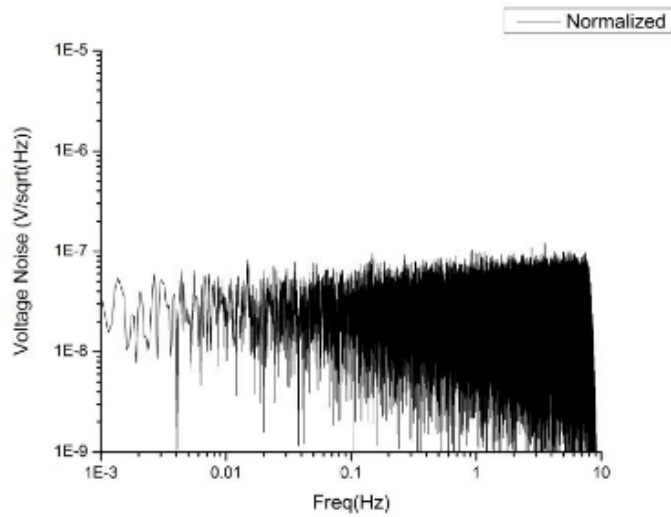


Fig 8. FFT of the input noise-voltage of Op-Amp 002 for $C_{fb} = 0$, i.e. for resistive network.

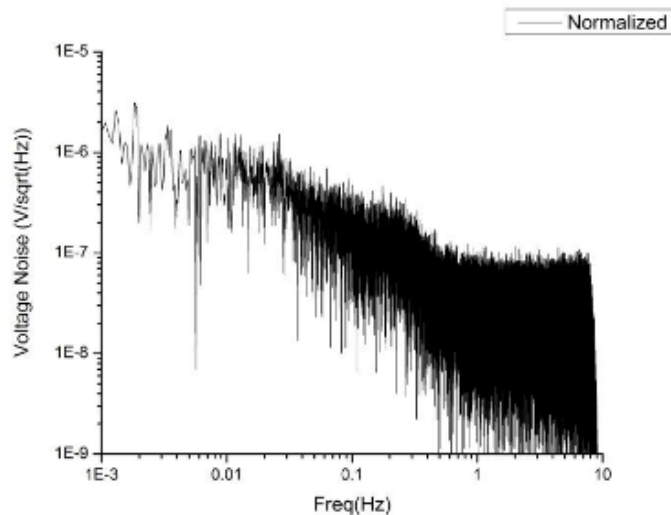


Fig 9. FFT of the input noise-voltage of Op-Amp 002 for $C_{fb} = 30\text{nF}$

Fig. 11 shows an input noise-voltage time-domain data plot for 003 for the test-circuit of Fig. 1. The output noise-voltage of 72 mV p-p for a period of approx 1000 sec is equivalent to an input noise-voltage of 720 nV p-p, after division by a total test-gain of 100 K V/V. This noise decreases to a minimum of about 500 nV p-p for a 10 sec test period.

For the FFT of Fig. 12, a 0.1 μF capacitor (C_{fb}) has been placed across the 100 K feedback resistor as in Fig. 4. Unspecified noise begins to appear below approx 0.1 Hz.

Fig. 13 shows the 22,000 sec time-domain data for the FFT of Fig. 12. Fig. 13 clearly shows unspecified noise having a long period-envelope frequency of $7\text{E-}5$ Hz. However for this part there is also faster unwanted noise evoked by the 0.1 μF feedback capacitor. Fig. 14 shows what appears to be discrete or sampled-data type noise, which may be associated with the sampled-data servo behaving erratically due to C_{fb} .

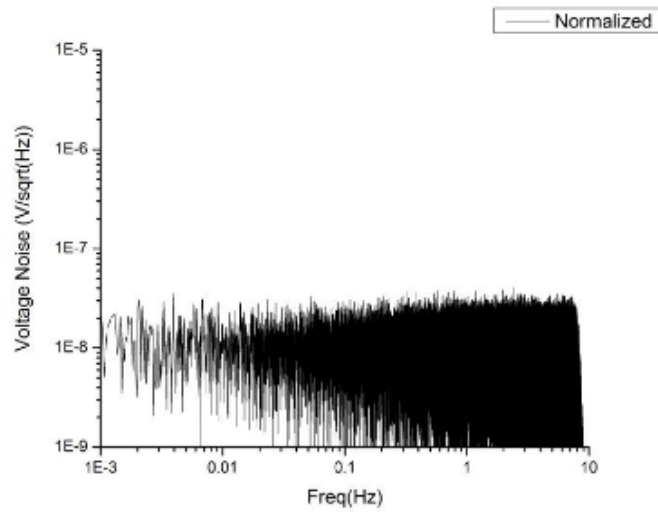


Fig 10. FFT of the input noise-voltage of Op-Amp 003 for resistive networks, $C_{fb} = 0$.

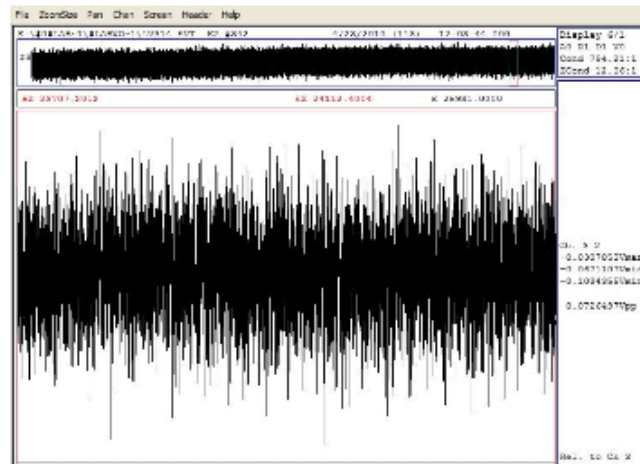


Fig 11. Time-domain plot of the input noise-voltage of Op-Amp 003 for resistive network. Signal-size at Op-Amp input is 720nV p-p.

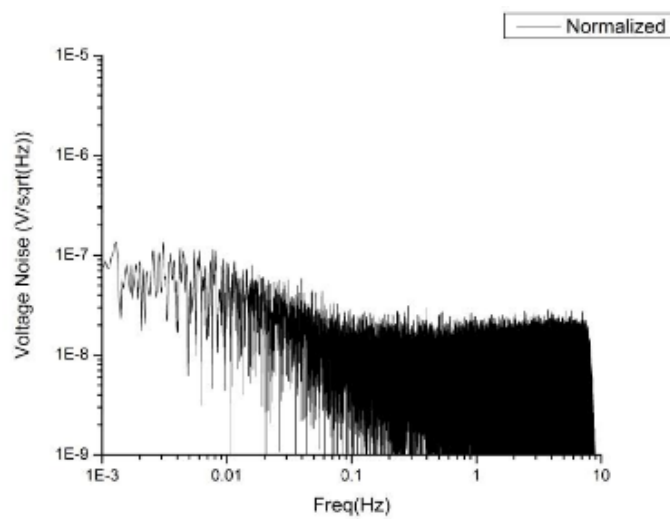


Fig 12. FFT of the input noise-voltage of Op-Amp 003 for $C_{fb} = 0.1\mu F$.

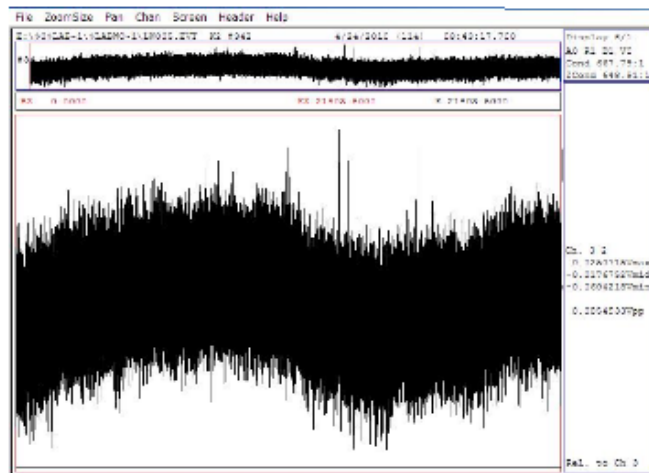


Fig 13. 22.000sec time-domain plot of the input noise-voltage of Op-Amp 003 for $C_{fb} = 0.1\mu F$

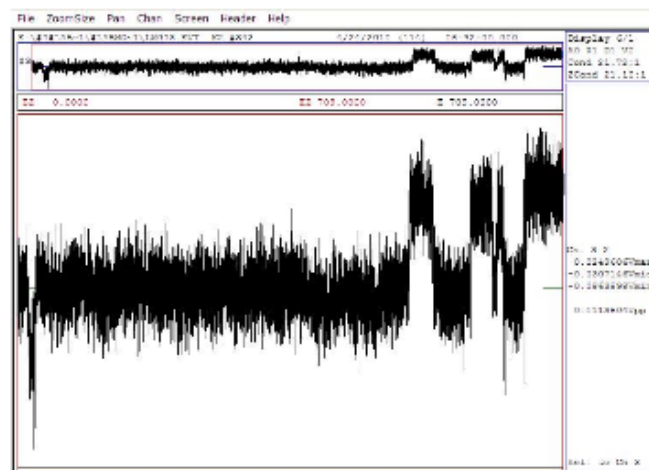


Fig 14. 700sec time-domain plot of the input noise-voltage of Op-Amp 003 for $C_{fb} = 0.1\mu F$

7. Conclusion

Chopper op-amps are capable of remarkable low-frequency input noise-voltage performance, especially when temperature is controlled to prevent drift. However, chopper op-amps are complex sampled-data feedback systems-on-a-chip, whose internal structure and characteristics are unknown to the application designer.

Some chopper op-amps are sensitive to the use of reactive components in their external networks. These reactive networks apparently interfere in some way with the chip's auto-zero sampled data system, evoking unspecified noise at very low frequencies of less than about 10 Hz. The unspecified-noise amplitude for three sample chopper op-amps varies, from a negligible increase to an increase of from 50 nV/Rt-Hz to 2 $\mu V/Rt-Hz$ at 0.001 Hz (40:1). The existence of this unspecified noise may be difficult to observe and prove without tight control of temperature.

In some applications, the appearance of unspecified low-frequency chopper op-amp noise may not trouble a development project. However it is also possible that unspecified low-frequency noise could affect the progress of very sensitive low-frequency research, such as in Earth Sciences.

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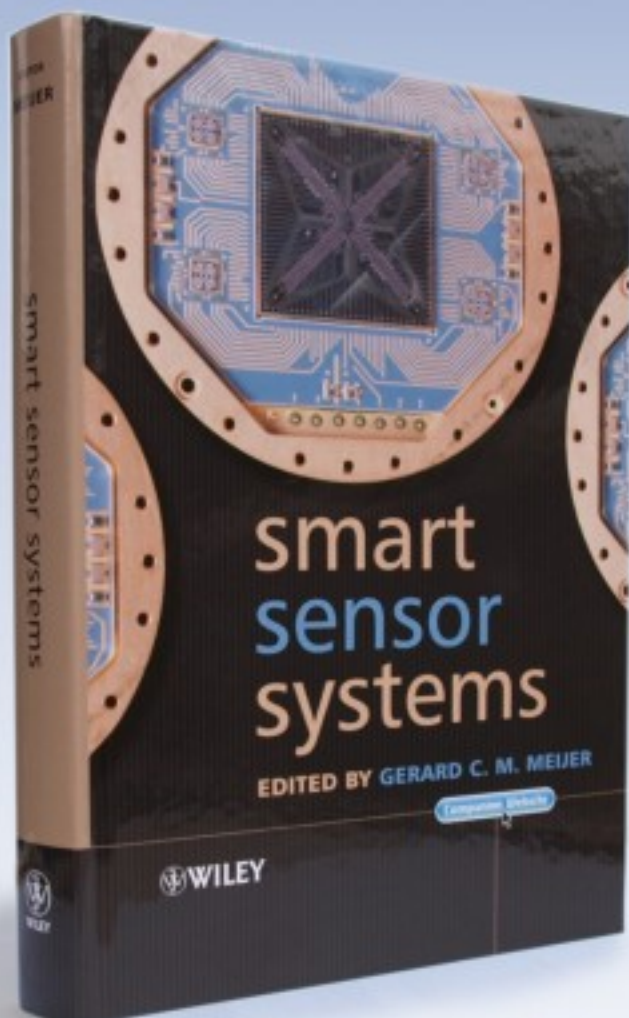
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