

Signal to noise ratio improvement by power supply voltage switching

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Abstract – AC excitation followed by synchronous demodulation is an effective noise-reduction method for signal conditioning in modulating sensors. However, it cannot be applied to self-generating sensors such as thermocouples or piezoelectric films. Switching on and off the power supply voltage of an amplifier yields a modulated output signal and allows for synchronous demodulation. Hence, this method improves the signal-to-noise ratio (SNR) by reducing $1/f$ noise and also reduces power consumption. Furthermore, it can be applied to self-generating sensors. A prototype system based on this method has been applied to a thermocouple signal conditioner whose power supply voltage was switched at 1 kHz. The nonlinearity error obtained was below 0.01 FSR (Full Scale Range) and the SNR was 90 dB for a 1.5 Hz noise bandwidth.

I. Introduction

Signal modulation is a common solution to reduce noise when amplifying dc signals. Noise in operational amplifiers (op amps), and other analogue integrated circuits, arises from thermal, shot and flicker noise, whose overall effect depends on the signal bandwidth. Flicker ($1/f$) noise is a particular nuisance for very low-frequency (“dc”) signals such as those from many sensors. Modulating sensors excited by ac voltage or current avoid this problem because their information is up-translated to a frequency band where it can be amplified by an ac amplifier, and then they are synchronously demodulated and low-pass filtered to recover the low-frequency signal [1].

Integrated circuit design techniques such as chopping [2] and switched biasing [3] reduce the effect of $1/f$ noise in low-frequency amplifiers. Chopper modulation, in particular, has been long used for precision dc amplifier design based on common integrated circuits (Fig. 1) [1]. A repetitive switch alternately connects the input of an ac amplifier to the (very low frequency) input signal or to a reference voltage, usually signal ground. The resulting square wave is amplified without being affected by the amplifier offset and drift because the input signal has been up-translated to a frequency band centred on the switching frequency. The amplified output signal is then synchronously demodulated to down-translate the frequency band back to base band, and low-pass filtered to reduce any residual ripple due to the oscillator frequency and its harmonics. The output is the amplified dc component of the input signal. The input signal bandwidth must be smaller than half the switching frequency, which in IC chopper amplifiers is fixed.

We propose a new modulation technique that is based on switching on and off the power supply voltage of the amplifier (Fig. 2), and that can be applied also to self-generating sensors. Instead of chopping the input signal, we “chop” the amplifier gain via the power supply voltage. As opposed to IC chopper amplifiers, the switching frequency can here be tailored to the application.

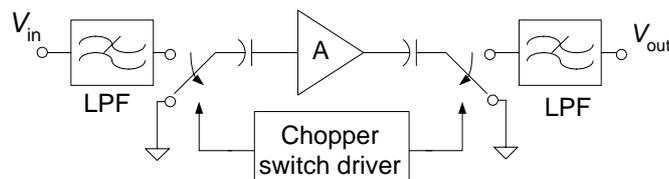


Figure 1. Operation principle of a chopper-based dc amplifier

II. Theoretical analysis

The power supply voltage $V_p(t)$ in the proposed signal modulation technique is a rectangular wave whose value alternates between V_{cc} and signal ground (0 V). The Fourier series of this signal is

$$V_p(t) = V_{cc}D + \frac{2V_{cc}}{\pi} \sum_{n=1}^{\infty} \frac{\sin(n\pi D)}{n} \cos \frac{2n\pi t}{T} \quad (1)$$

where D is the duty cycle of the signal (t_H/T) and f_p is the switching frequency ($1/T$) (Fig. 3a). The amplifier output signal will be the product of the input signal times the system gain, which in a first-approach analysis can be assumed to be proportional to the power supply voltage above ($G = k_v V_s$). The power spectral density (PSD) of the op amp input voltage noise is

$$S_e(f) = e_n^2 \left(1 + \frac{f_{ce}}{f} \right) \quad (2)$$

where e_n^2 is the noise power spectral density at high frequencies and f_{ce} is the (corner) frequency at which $1/f$ noise is as relevant as high-frequency noise. The power spectral density of the noise at the output of the demodulator will be the convolution of $S_e(f)$ and the spectrum of the signal gain (Fig. 3b). After low-pass filtering that noise, we obtain the base-band output noise,

$$S_o(f) = e_n^2 \left(1 + \frac{f_{ce}}{f} \right) k_v^2 \left[V_{cc}^2 D^2 + \frac{4V_{cc}^2}{\pi^2} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi D)}{n^2} \right] \quad (3)$$

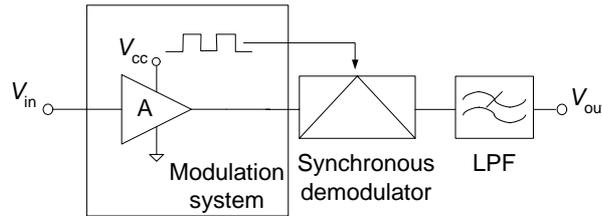


Figure 2. Power supply voltage switching as a signal modulation and demodulation technique

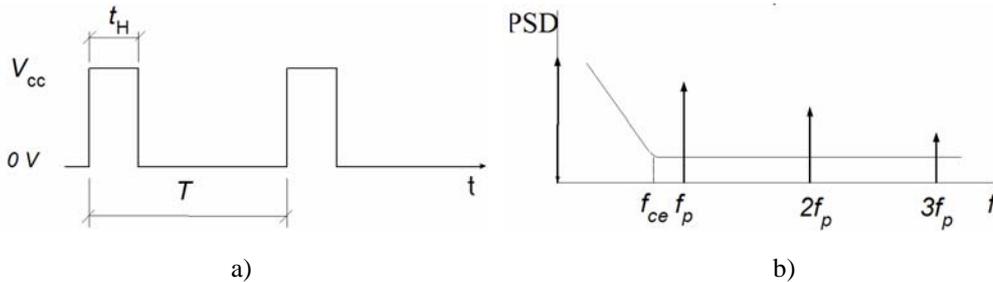


Figure 3. a) Rectangular-wave shaped power supply voltage with arbitrary duty cycle t_H/T . b) Power spectral density of the op amp $1/f$ noise and frequency spectrum of the switched power supply voltage

To reduce the contribution of $1/f$ noise, amplification must concentrate most of its power in frequency bands above f_{ce} and the amplified signal must then be synchronously demodulated and low-pass filtered. It can be shown that if $f_p > f_{ce}$ the signal-to-noise ratio of an amplifier with switched supply voltage $(SNR)_s$ increases with respect to that of an amplifier with a continuous supply voltage $(SNR)_c$ by a noise ratio FI (noise factor improvement) equal to

$$FI = \frac{(SNR)_C - (SNR)_S}{(SNR)_C} = \frac{(1-A)f_{ce} \ln \frac{f_H}{f_L} - A(f_H - f_L)}{A f_{ce} \ln \frac{f_H}{f_L} + A(f_H - f_L)} \quad (4)$$

where

$$A = \left[D^2 + \frac{4}{\pi^2} \sum_{n=1}^{\infty} \frac{\sin^2(n\pi D)}{n^2} \right]$$

and f_H and f_L are the end frequencies of the system bandwidth. FI increases for small A values. This means that the signal-to-noise ratio of the amplifier with switched supply voltage can be increased by reducing the duty cycle of the switching signal. This improvement can be seen as the result of “spreading” the amplifier gain along a broad frequency range instead concentrating it at “dc” as happens for an amplifier with “continuous” gain.

The modulation-demodulation model described assumes an ideal response for the switched amplifier. However, it has been shown in [4] that the op amp output voltage is non-linear during the transient caused by switching on its power supply voltage while the input signal is present, because the internal transistors in the amplifier do not reach their dc operating points before a settling time t_b . Once bias voltages have settled, the output voltage reaches its final value in a time (t_d) that depends on the amplifier gain. Therefore, the overall settling time (t_c) after switching the supply voltage will be

$$t_c = t_b + t_d \quad (5)$$

and will depend on the particular type of op amp, the power supply voltage levels and the input signal amplitude. Hence, the demodulator must wait until this transient stage has finished.

III. Experimental techniques

We have implemented the modulation technique described to a very-low-power op amp (LT1491N, $e_n = 50 \text{ nV}/\sqrt{\text{Hz}}$, $f_{ce} = 20 \text{ Hz}$, GBW = 200 kHz from Linear Technology) on single-supply operation (5 V). The transient behaviour of this op amp was first studied for the (single-ended) inverting amplifier in Figure 4, as the settling time determines the minimal duty cycle for power supply voltage switching.

Then we tested the signal conditioning system in Figure 5a. The modulator was the fully-differential amplifier in Figure 5b, designed with a nominal gain of 19. We experimentally checked that the transient behaviour of this differential amplifier did not radically differ from that of the single-ended amplifier. The circuit was built using resistors with 5 % tolerance. A function generator (Agilent 33220 A, 50 Ω output resistance) supplied a 0-5 V rectangular waveform that simulated the on-off switching of a power supply. The $V_{cc}/2$ reference voltage needed to operate op amps with a single supply was obtained from the same function generator output. The demodulator was a synchronous sampler based on switched capacitors as proposed in [6]. It was implemented with CD4053 switches and a programmable sampling signal generated by a SN74LS123N digital monostable. A passive first-order low-pass filter with 1.5 Hz corner frequency followed the demodulator. The output voltage was acquired with a PC via GPIB by a 6 1/2 digit digital multimeter (HP3478A, integration time of 1 power-line cycle). The average value and standard deviation of 300 readings for each of four different input voltages was measured for the synchronous demodulator. Linearity was evaluated from the best straight-line fit of the averages. The non-linearity was estimated by the average of the differences between the experimental results and the linear fit, and expressed as a percentage of the full-scale range (FSR).

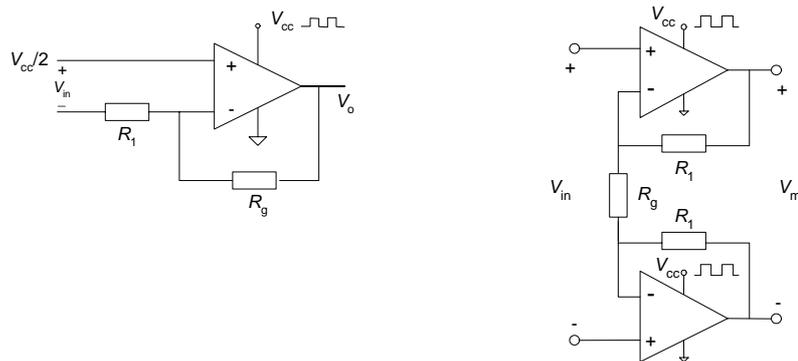


Figure 4. Measurement set-up used to test the transient behaviour of the op amp used as modulator by switching its power supply voltage

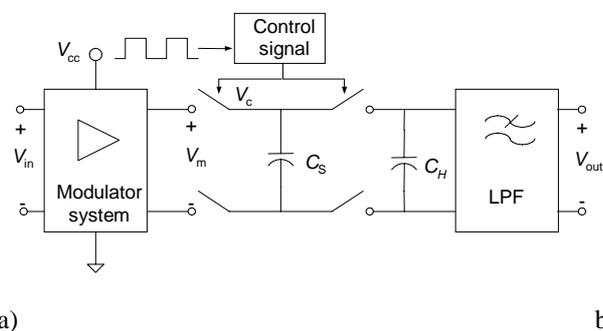


Figure 5: a) Experimental system including the input modulator and the synchronous demodulator. b) Modulator system with switched power supply voltage

The self-generating sensor selected was a J-type thermocouple. Figure 6 shows the front-end of the signal conditioner, that includes an RTD (PT1000, $\alpha_0 = 0.00385 \text{ K}^{-1}$, $R_0 = 1 \text{ k}\Omega$) for cold-junction-compensation. A portable climatic chamber (Hart Scientific, 9102S) provided known temperatures from $0 \text{ }^\circ\text{C}$ to $100 \text{ }^\circ\text{C}$.

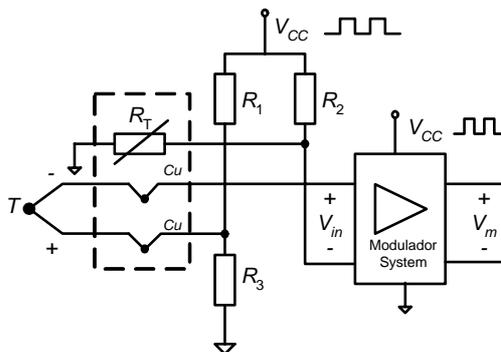


Figure 6: Thermocouple signal conditioning

IV. Experimental results and discussion

Figure 7 shows the transient response of the amplifier in Figure 4 for different input signal amplitudes (the reference voltage was $V_{cc}/2$), when the supply voltage was switched at 1 kHz and the nominal gain was 10. The experimental settling time (t_c) was about $100 \mu\text{s}$ for this op amp, regardless of the amplitude of the dc input signal. This time determines both the maximal switching frequency f_p (to less than 10 kHz for this amplifier) and the best time to synchronously demodulate the amplified signal after the switching signal has been turned on.

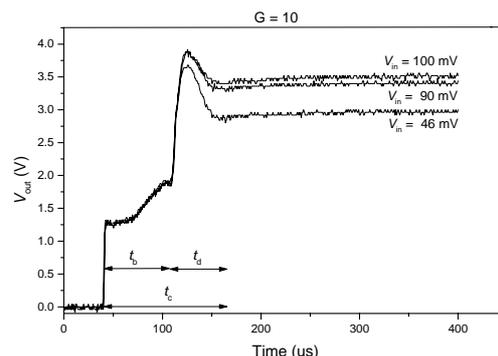


Figure 7 Transient response for the amplifier in Fig. 4 with switched supply voltage for different input (dc) signal amplitudes and nominal gain 10

The demodulator nonlinearity for different input voltage amplitudes estimated by the average of the differences between the experimental data and the linear fit was below 0.01 FSR. The standard deviation ($n = 100$) provided an estimate of the signal-to-noise ratio (SNR), which was better than 90 dB.

Table 1 summarizes the results when applying the proposed technique to a J thermocouple system, which we calibrated at 40 °C and 70 °C. There is a good agreement in spite of the low-gain for the amplifier, which was limited by its reduced bandwidth. Furthermore, the uncertainty in the measured temperature (coverage factor 1) was better than the resolution specified for the climatic chamber. Therefore, circuit noise was not the limiting factor. Additional measurements are needed to show that the proposed technique effectively reduces noise below that resulting for an amplifier working at base band.

T_c (°C)	T (°C)	$U(T)$ (°C)
0	0.2	0.15
10	10.5	0.20
20	20.2	0.12
30	30.1	0.12
40	40.0	0.12
50	50.7	0.13
60	60.9	0.12
70	70.0	0.14
80	80.7	0.12
90	90.4	0.13
100	99.7	0.14

Table 1. Experimental results for a J thermocouple system. T_c : actual temperature in the climatic chamber; T measured temperature and $U(T)$ uncertainty in the measured temperature

V. Conclusions

Switching the power supply voltage of a single-supply amplifier is equivalent to switching its gain. This yields a rectangular signal whose amplitude is modulated by the input signal, and that can be subsequently demodulated by using the same switching signal as the reference signal for the demodulator. This procedure reduces not only energy consumption but also $1/f$ noise. Transient effects because of both amplifier unbiased internal stages and finite bandwidth, limit the maximal switching frequency and determine the optimal time for output demodulation. To reduce $1/f$ noise, the switching frequency must be higher than the corner frequency of the amplifier input noise power spectral density. Experimental results using a 1 kHz, 0 V to 5 V rectangular waveform as power supply voltage for a fully differential amplifier and a synchronous sampling demodulator, have yielded a 0.01 FSR nonlinearity and SNR > 90 dB. The application of the technique to a signal conditioner for a thermocouple has shown that the temperature resolution is better than that of the reference temperature available (± 0.2 °C). This method can be applied to other self-generating sensors and, unlike IC chopper

amplifiers, permits us to select the desired chopping frequency. Additional measurements are needed to show that the technique effectively reduces system noise as compared with an amplifier working at base band.

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