High-speed amplifier development for the heat flow sensor

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Abstract. This article describes characteristics of preamplifiers for Atomic Layer Thermopile (ALTP) sensor based on precision operational amplifiers AD8597, ADA4004, ADA4075, ADA4896 and ADA4528. Transfer functions and total output noise values of these preamplifiers were obtained experimentally using an Agilent InfiniiVision 3000 series X oscilloscope. Results of experimental verification of preamplifier characteristics using a high-speed heat source are presented and discussed; the best operational amplifier for the application is determined.

1. Introduction
In a project carried out at Landshut University of Applied Sciences, a heat flow sensor to study combustion processes is being developed. The Atomic Layer Thermopile (ALTP) will be used as a basis for the heat flow sensor. An amplifier must be developed for this project. It must be miniaturized to be placed directly at the measurement site, have minimal noise due to the low output voltage of the sensor, and have sufficient bandwidth to track fast effects during the heat measurement.

This work aims to develop a fast, low-noise, precision amplifier for the ALTP sensor with approximately 1 MHz bandwidth and amplification of about 20 dB. For achieving this goal, samples built around different operational amplifiers were analyzed for their transfer functions and noise parameters. The circuit diagram and the overall view of the test PCBs are presented in Figure 1. Two amplification stages were used for achieving the project requirements in gain and bandwidth. Based on measurement results, the most suitable operational amplifier for the preamplifier with required parameters was identified.
2. Theoretical background

2.1 The Atomic Layer Thermopile Sensor (ALTP)

The ALTP is a novel high-speed sensor for transient heat flow measurement. The sensor’s comprehensive frequency response enables high-resolution thermal flow measurements in the frequency range up to 1 MHz [1]. The ALTP operating principle is based on the transverse Seebeck effect. The output signal is directly proportional to the heat flux density and has a linear characteristic from mW/cm² to kW/m².

Due to the transverse Seebeck effect (TSE), it is possible to create a sensor with a thickness of about 10-100 nm in just one thin-film unit. The foil anisotropy causes TSE in combination with a crystal angle to the normal film surface. Anisotropic foil YBCO (YBa$_2$Cu$_3$O$_x$) consists of copper oxide layers with YBCO layers (Figure 2). Thermoelectric field is directly proportional to the temperature gradient in the foil and is induced towards the foil layer. The temperature gradient generates the resulting thermoelectric voltage $U$ in the YBCO foil. Due to radiation absorption or convective heat exchange thermoelectric voltage is determined by

$$U = \frac{l}{\delta_f} \Delta S \Delta T \sin \frac{2\alpha}{2},$$

where $l$ is the foil length (normal to the layer orientation), $\delta_f$ - the foil thickness, $\Delta T = T_{FFS} - T_{FBS}$ - the temperature difference between the foil front (FFS) and back (FBS) and $\Delta S = S_c - S_{ab}$ - the non-inclined crystal difference in the thermal power (normal and parallel axis c) [1]. The schematic cross-section of a tilted YBCO foil is presented in Figure 2.
2.2 Selection of operational amplifier

The OpAmps AD8597, ADA4004, ADA4075, ADA4896, ADA4528 were selected as candidates for use in the preamplifier. Characteristics of these amplifiers are shown in Table 1.

| OpAmp       | Smallest package | Voltage noise density at 1 kHz, nV/√Hz | Slew Rate, V/µs | Bandwidth, MHz | Supply, V |
|-------------|------------------|----------------------------------------|-----------------|----------------|-----------|
| AD8597      | LFCSP 3x3        | 1.1                                    | 14              | 10             | ±5..±15   |
| ADA4004     | SOT 23-5 3x3     | 1.8                                    | 2.7             | 12             | ±5..±15   |
| ADA4075     | LFCSP 2x2        | 2.8                                    | 12              | 6.5            | ±5..±15   |
| ADA4896     | LFCSP 3x3        | 1                                      | 120             | 230            | +3..+10   |
| ADA4528     | LFCSP 3x3        | 5.6                                    | 0.45            | 6.2            | +2.2..+5  |

All these precision amplifiers can operate in the temperature range from -40°C to +125°C but differ in noise, slew rate and bandwidth. The OpAmps AD8597 and ADA4004 have very low noise values, while the ADA4075 OpAmp has the smallest size. The ADA4896 OpAmp has the highest slew rate, while the ADA4528 OpAmp is equipped with chopping technology which compensates the pink noise. Consequently, this OpAmp has significantly lower dc noise and low frequency compared to standard low-noise amplifiers, sensitive to the 1/f-noise.

3. Proposed algorithm

3.1 Measurement of the transfer function

For obtaining the transfer function of a preamplifier, it was attached to a sinusoidal output of a signal generator with known frequency and amplitude. The amplitude and phase shift at the output of the preamplifier were recorded for many frequencies starting from 10 Hz. The maximum recorded frequency was chosen for every preamplifier separately taking a reduction of the output gain by 30 dB as a criterion. As an example, obtained experimental values for AD8597 OpAmp at an input amplitude of 100 mV and a capacitive load of 100pF are given in Table 2.
Table 2. AD8597 OpAmp Closed-Loop Gain and Phase

| f, Hz  | Gain, dB | φ, °  | Gain Change, dB |
|-------|----------|------|-----------------|
| $10^1$ | 41.7     | 0    | 0               |
| $10^2$ | 41.7     | 0    | 0               |
| $10^3$ | 41.7     | 0.5  | 0               |
| $10^4$ | 41.6     | 1    | 0               |
| $10^5$ | 41.5     | 13   | 0               |
| $4.4 \cdot 10^5$ | 38.7 | 60   | -3              |
| $7.2 \cdot 10^5$ | 35.7 | 85   | -6              |
| $1.06 \cdot 10^6$ | 31.7 | 110  | -10             |
| $1.93 \cdot 10^6$ | 21.7 | 150  | -20             |
| $3.6 \cdot 10^6$ | 11.7 | 190  | -30             |

Figure 3 shows the Closed-Loop Gain and Phase vs Frequency plots for the AD8597 OpAmp.

![Figure 3. AD8597 OpAmp Closed-Loop Gain and Phase vs Frequency graph.](image)

For all other amplifiers, the frequency response was also measured. Figure 4 shows the corresponding graphs.
Figure 4. Amplifier Closed-Loop Gain and Phase vs Frequency graphs: a – ADA4004, b – ADA4075, c – ADA4528, d – ADA4896.

Experimental values for ADA4004 and ADA4075 were obtained with the input amplitude of 100 mV and a capacitive load of 100 pF due to coaxial cable. For ADA4896 and ADA4528, the input amplitude of 30 mV and a capacitive load of 10 pF was used for stability reasons.

3.2 Experimental measurement of noise voltage
The circuit shown in Figure 1 was used for obtaining the total output noise for all the OpAmps under investigation. The noise measurements presented below were carried out with a horizontal resolution of 100 ms/div using the “AC RMS” function of the oscilloscope. In this work output RMS noise voltage was investigated for two sets of feedback resistors with values R2=1 kOhm, R3=100 Ohm and R2=100 Ohm, R3=10 Ohm respectively. In Figure 5 the noise voltage measurement with the AD8597 type OpAmp is shown as an example.

Figure 5. The output noise signal of the preamplifier built with the AD8597OpAmp.
The measurements were conducted for all OpAmps. The experimental results are presented in Table 3.

| OpAmp       | Output RMS noise (mV) | Feedback 1 kΩ/100 Ω | Feedback 100 Ω/10 Ω |
|-------------|-----------------------|----------------------|----------------------|
| AD8597      | 0.34                  | 0.23                 |                      |
| ADA4004     | 0.38                  | -                    |                      |
| ADA4075     | 0.44                  | -                    |                      |
| ADA4896     | 2.00                  | 1.87                 |                      |
| ADA4528     | 1.93                  | 1.65                 |                      |

For the precision amplifier for ALTP sensor, the AD8597 is the most suitable option, as it is the best in noise parameters; the ADA4004 and ADA4075 OpAmps also have good performance in terms of noise characteristics.

3.3 Measurements with ALTP Sensor
For checking the sensor frequency response, a heat source able to change its state quickly is needed. In the laboratory, a white LED with the maximum power of 3.5 W (XPEWHT-L1-R250-00D01) driven by a MOSFET was used for this purpose. The measurements were taken with the peak current of 1.5 A at 4.2 V bias voltage on the LED. A lens was used for focusing the light output on the ALTP sensor situated at a distance of 5 cm; its area amounted to approximately 2 cm².

In order to change the LED state quickly, high currents with significant high-frequency components have to be used. Accordingly, the measuring circuit is exposed to a high electromagnetic interference from the high-frequency currents in the LED driver. Because the signal is rather small, even a small pickup becomes quite significant relative to this signal. As a result, the measured output signal is distorted. In Figure 6, an exemplary measurement is given for a preamplifier built with AD8597. The dark blue trace represents the preamplifier output after an LED pulse. If the heat flow effect on the sensor is excluded, i.e. if a black screen cuts the light, the pickup remains. This pickup signal is shown with a light blue trace in Figure 6 and is used as a reference.
Figure 6. Oscillogram of measured signals. The dark blue line (Ch. 1) is the output signal after an LED pulse, the light blue line (REF2) is the reference signal with heat flow cut, Ch. 2 and Ch. 3 show the drive and the synch signals respectively.

If the reference signal is numerically subtracted from the original output, a pure sensor signal is obtained. The output pulses corrected using this approach are presented in Figure 7 and Figure 8.

Figure 8 shows that the output signals of all preamplifiers except ADA4528 are of the same shape. This result leads us to the conclusion that the observed response is defined by the ALTP sensor itself and not by the preamplifiers using different OpAmps. The rise time of the used ALTP sensor can be determined to be about 2 µs. The ADA4896 has a higher noise signal because of its about 40 times higher bandwidth.

The ADA4528 amplifier has a low-pass filter in its circuitry to compensate for the 200 kHz output noise; it substantially lowers its bandwidth as seen from Figure 8d. The amplifier operation at a lower heat pulse repetition rate of 1 kHz is shown in Figure 9.

4. Conclusion

In this work frequency response of preamplifiers built with AD8597, ADA4004, ADA4075, ADA4896, ADA4528 OpAmps was studied. The AD8597, ADA4004 and ADA4075 OpAmps have good performance for the intended application in terms of noise characteristics; the AD8597 seems to be the most suitable option as it has the best noise and bandwidth parameters. The response time of the ALTP sensor has been measured through a pulsed illumination by a power LED. It was shown that the influence of electromagnetic pickup on the sensor signal could be significantly reduced by numerical processing of the signals.

References

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Figure 7. The output signal of AD8597 amplifier.

Figure 8. Amplifiers output signal: a – ADA4004, b – ADA4075, c – ADA4896, d – ADA4528.

Figure 9. The output signal of ADA4528 amplifier at 1kHz frequency.