Acoustic readout circuit system without highpass filter for hearing aid

H.-Y. Lee and C.-H. Luo

A readout circuit system is designed for a hearing aid without a highpass filter. The system achieved an SNR of 42.3 dB and a third-order harmonic distortion ratio of 58 dB when the input voltage was 60 μV to attain output of 0.48 V. For 57.9 and 74.8 dB gains, the bandwidths were 60 Hz–106 kHz and 100 Hz–20 kHz, respectively. The 1.65 mm² system chip consumes 222 μW in 0.35 μm CMOS process.

Introduction: Hearing instruments used by those who are hard of hearing tend to be bulky, modestly expensive, and require large power consumption. A need, therefore, exists for an instrument that is smaller, more affordable, and with lower power consumption requirements. In modern hearing instruments, the charge amplifier is the most widely used component within a readout circuit. Chip filters, which are also important components within readout circuits, are regularly used to suppress out of band signals that fall outside the normal range of acoustic frequency (20 Hz to 20 kHz). However, the critical problem for chip filters is their high cost and high power consumption requirement. Industrial specification requires the implementation of a highpass filter [1] to remove the offset and attenuate the 60 Hz noise. This Letter advances the idea of improving the readout circuit system by replacing the highpass filter with an on-chip integrated circuit which would achieve the benefits of low complexity, low power consumption and low cost.

System design: This readout circuit system is intended for capacitor microphone sensors in acoustic applications, which are applied to many unusual cases such as bone anchored hearing aids (BAHAs), or throat-vibrated hands-free hearing aids. The proposed readout system is shown in Fig. 1. The system consists of three parts: the charge amplifier (CA), the program gain amplifier (PGA), and the lowpass filter (LPF). From the viewpoint of feedback, the charge amplifier can be modelled as shown in Fig. 1 where \( G_m, C_2, \) and \( g_n \) are the transconductance, output capacitor and output resistor of the operational transconductance amplifier (OTA), respectively. In addition, \( L_n \) is the input current source (the sensor is similar to a charge generator), \( C_1 \) is the sensor capacitor, \( C_2 \) is the amplified capacitor, and \( R_1, R_2 \) are the equivalent resistances of the subthreshold region-resistor. The transfer function of the proposed charge amplifier is

\[
A_{\text{open}}(s) = \frac{(s/ω_C + 1)}{(s/ω_C + 1) + \frac{G_m V_n}{E(s)}}
\]

where \( ω_C = 1/R_C, \) \( ω_C = g_n/C_2 \) and \( ω_C = g_n/C_L \) are the dominant pole, second pole and gain-bandwidth (GBW) of the OTA, respectively, and \( A_{\text{open}}(s) = G_m/sC_2 \) is the open loop gain, \( E(s) \) is the ideal closed loop gain which is set by the ratio of \( C_1 \) to \( C_2 \), and \( E(s) \) is the error factor.

The CA has large input impedance to catch the signal from the sensor; the PGA extends the input dynamic range of the system; and the LPF removes undesired out-band high frequency noise. The noise voltage contributed by an amplifier is dependent on the magnitude of source coupled with noise. In the cascade amplifier (CA and PGA), the noise signal referred to input is shown as follows [2]:

\[
V_N = V_{n1} + \frac{V_{n2} - 1}{G_1} + \frac{V_{n3} - 1}{G_1 G_2} + \cdots + \frac{V_{mn} - 1}{G_1 G_2 \cdots G_n}(2)
\]

where \( V_{n1} \) is the overall noise referred to input, \( V_{n2} \) is the noise in the first stage, \( V_{n3} \) is the noise in the second stage, \( G_1 \) is the gain of the first stage and \( G_n \) is the gain of the \( n \)th stage. In (2), the noise in the overall system is dominated by the noise contribution of the first stage. Moreover, the high voltage gained by CA and PGA can be used to further suppress the unwanted noise in the amplifier circuit.

In modern communication systems, the received signal is usually digitised into the digital domain with complex signal processing. Therefore, an analogue-to-digital converter (ADC) plays an important role as an interface. To maximise the dynamic range of the ADC, a PGA is usually placed in front of the ADC. The digitally programmable gain amplifier is controlled by the feedback signal to obtain a suitable signal range for processing. It can enlarge the measurable range of the acoustic or biomedical signal, and the dynamic range in biomedical applications. In the proposed PGA, the circuit design is deliberately chosen to be similar to that of the CA. Unlike the conventional PGA, which solely provides the programming gain, the proposed circuit design also provides a one-order pole. By combining the one-order CA pole with the one-order PGA gain, the effect of a highpass filter can
be created, thereby reducing power consumption. Fig. 2a shows the creation of the two-order highpass filter. As to the LPF, the topology of the filter is referenced to [3] and the transfer function is

\[
H(s) = \frac{1}{s^2 + \left(\frac{C_2}{g_{m_2}}\right) + \left(\frac{g_{m_1}g_{o_1}}{g_{o_2}}\right) + \frac{g_{o_1}}{A_0}}
\]

(3)

The equation shows that the two poles of the filter are at the same frequency, \(g_{m_1}/C_1\), where \(A_0\) is the DC gain of the OTA, \(C\) is the external capacitor, and \(g_{o_1}\) and \(g_{o_2}\) are the finite output resistance of \(g_{m_1}\) and \(g_{m_2}\), respectively. Since the PGA has the ability of tuning poles, an equivalent fourth-order LPF can be obtained by aligning the second pole of the PGA to the second pole of the CA and the two poles of the LPF. The two-fold result of this combination is a two-order highpass filter and a four-order lowpass filter, as shown in Fig. 2b.

**Results and conclusion:** The readout circuit system occupies 1.65 mm² in 0.35 µm CMOS process and consumes 222 µW. All blocks use a 1.4 V supply for the hearing aid instrument zinc–air battery. The input signal range is 60–400 mV. At the 57.9 and 74.8 dB gain levels, the bandwidths are 60 Hz–106 kHz and 100 Hz–20 kHz, respectively. As shown in Fig. 3, the signal-to-noise ratio (SNR) is 42.3 dB and the third-order harmonic distortion ratio (HD3) is 58 dB when the input voltage is 60 µV. In this case, the maximum output is 0.48 V. Table 1 gives a comparison with previous work. In this Letter, we have proposed a bandpass filter that is equivalent to a two-order HPF and a four-order LPF. This is achieved by combining the poles of the CA, the PGA and the LPF. Thus, a regular two-order highpass filter can be removed from the readout circuit system, lessening overall circuit complexity and significantly reducing power consumption.

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<td>Process</td>
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H.-Y. Lee and C.-H. Luo (Department of Electrical Engineering, National Cheng Kung University, Tainan 701, Taiwan, Republic of China)
E-mail: robinluo@mail.ncku.edu.tw

**References**