A Low-Cost USB-Compatible Electronic Stethoscope Unit for Multi-channel Lung Sound Acquisition

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Abstract. The diagnosis of respiratory diseases relies largely on auscultation. To further improve the diagnosis quality, continuous acoustic multi-channel surveillance of the airways is highly desirable. The application of multiple sensors around the thorax implies size and cost constraints for the sensors. In this article we first report on the design and development of a wearable and low-cost electronic stethoscope which is easy to integrate in a garment. We then analyzed the noise and linearity of the recorded sound signal and benchmarked a prototype with a standard stethoscope which is widely used in clinical practice.

Keywords: Electronic stethoscope · Piezoelectric transducer · Wearables · Lung sounds · Auscultation

1 Introduction

Stethoscope auscultation is a prevalent clinical practice in diagnosing lung related diseases, which make up 5 of the 30 most common causes of death [1]. Despite its widespread use in clinic, digitalization and standardization of this method fall behind [2]. However, an increasing incidence rate of respiratory diseases combined with the need and will to increase the efficiency in medical practice have begun to give a thrust to these belated developments, even with additional expectations such as multi-channel recordings and continuous monitoring, especially at remote settings.

In a clinical examination, a physician typically auscultates a patient's thorax on different points. Taking this approach one step further, we envisage to synchronously record several sound signals from the different auscultation points with electronic stethoscopes to enable computerized multi-channel lung sound analysis. The main challenges in the realization of a system containing multiple sensors which record sound signals in parallel are (1) the sensor size, (2) the sensor synchronization, and (3) the costs, eventually inhibiting the use of commercially available electronic stethoscopes in such a system. Additionally, electronic stethoscopes available in the market are optimized for human hearing and most importantly for physicians' listening habits inherited from acoustic stethoscopes. Built-in filters of these devices impose a limitation on the bandwidth of acquired sound signal, which otherwise could be useful for signal processing algorithms.

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In this work, we propose a low-cost wearable electronic stethoscope unit which can be used as a building block for a wearable multi-channel lung sound acquisition system. The article presents the design of the prototype with an emphasis on electronics development as well as characterization results.

2 Materials and Methods

The core of the presented lung sound acquisition system (Fig. 1) is a piezoelectric transducer which is designed based on the curved-clamped structure presented in [3] to convert the incoming pressure waves to electrical signals. The transducer is realized with a 110 μm-thick PVDF film (TE connectivity, 3-1004346-0) shaped as a square (13×13 mm^2) and curved with 100 mm radius of curvature. This configuration provides 11 mV/Pa sensitivity and a sensor capacitance of 100 pF. The transducer is connected to an impedance converter which drives the input of the analog-to-digital converter (ADC). The data conversion and the USB interface are realized in an audio codec single-chip compliant with USB 2.0 (PCM2912A from Texas Instruments). This off-the-shelf component accelerates the development and provides a plug-and-play solution. The board containing the electronics is equipped with a micro-USB port, thus enabling a standard connection to a computer or a portable device. The open source software Audacity (v2.1.3) is employed to perform the sound recordings. The developed system can perform signal acquisition at sampling rates ranging from 8 ksps to 48 ksps.

The sound acquisition chain begins with the piezoelectric transducer which works as a voltage source whose output amplitude varies as a function of its strain. In the linear region, where the amplitude of the voltage depends linearly on the strain, the sensor is modelled as a voltage source in series with a capacitance (Fig. 1). Consequently any resistive load creates a network with high-pass filter characteristics, while any capacitive load (such as the input capacitance of the impedance converter) behaves like a voltage divider. Hence, it is desired to have a negligible input capacitance to preserve the signal amplitude.

The transducer, modelled as a capacitance, corresponds to a high source impedance at low frequencies where most of the information is located for this application. Thus, the design needs to address the common issues related with high impedance sources: bias current and current noise at the input. In most scenarios, the latter one is overlooked as the contribution of the voltage noise is significantly higher than the one of the current noise, particularly for low and moderate sensor impedance values.

Traditionally JFET input stages have been used to interface with high impedance sensors thanks to their high input impedance and very low (gate) bias currents. Today it continues to be a good option for discrete implementations thanks to their low 1/f noise. Realizing the impedance converter (high impedance of source to a lower impedance) with a single transistor leaves more room for design flexibility on the amplifier stage in terms of selection of components and topologies. Additionally, they enable a slightly easier biasing scheme, which is realized by connecting the gate to the source (or simply to ground for a common-source amplifier), thanks to its negative threshold voltage. In this work, the transducer is interfaced with a common-source JFET amplifier (Fig. 1).

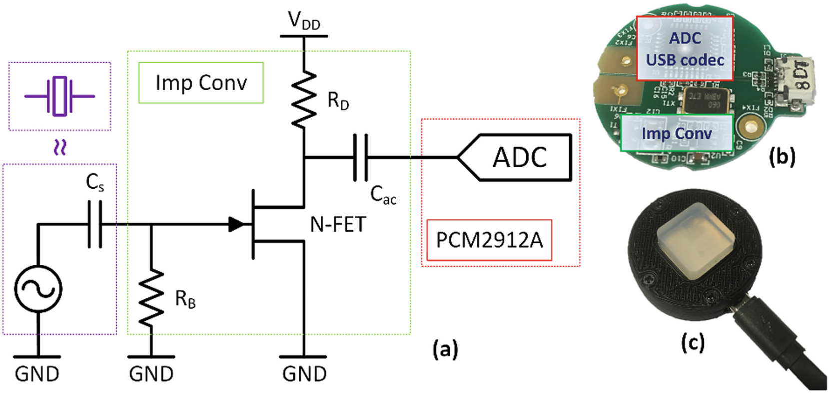

Fig. 1. (a) Simplified schematic of the presented system, (b) fabricated printed circuit board, and (c) assembled prototype (height: 18 mm, diameter: 32 mm) with a USB cable connected to the system

The gain of the impedance converter stage is obtained by multiplying the forward transconductance of the JFET (2SK3666-3 from ON Semiconductor) with the drain resistance. A 1st order high-pass filter (HPF) is created by the sensor capacitance (C_s) and the input resistance of the impedance converter, which is often equal to the gate bias resistor (R_B). Moreover, another HPF is created by the decoupling capacitor (C_{ac}) and the drain resistor (R_D) (Fig. 1). A 3 dB bandwidth of the output signal is limited to 0.454×8 kHz = 3632 Hz by the digital low-pass filter of the ADC [4].

The energy supply for the board is provided via USB which powers the audio codec directly and the impedance converter via a low drop-out (LDO) voltage regulator (3.0 V). The PCM2912A chip incorporates internal LDOs to regulate its analog and digital supply voltages (3.3 V). The overall current demand of the board is dominated by the audio codec and USB interface (85 mA). Given that it is not designed to be an autonomous device at this phase, USB 2.0 is quite sufficient to power the system with its rated current at 500 mA.

3 Results

First, we characterized the noise and linearity performance of the signal acquisition chain (Fig. 1) in the absence of the sensor. A full-scale (FS) input measurement was conducted to quantify the noise floor and the non-linearity of the acquisition chain. The signal generator was connected in series with a 100 pF capacitance, which is equivalent to the sensor capacitance, and the input signal was set to 160 $mV_{p\text{-}p}$ at 1 kHz. Figure 2 shows the spectrum of the full-scale signal. 2nd and 3rd harmonics of the signal are located 48 dB and 56 dB below the fundamental tone, respectively. The noise floor lies around −90 dB.

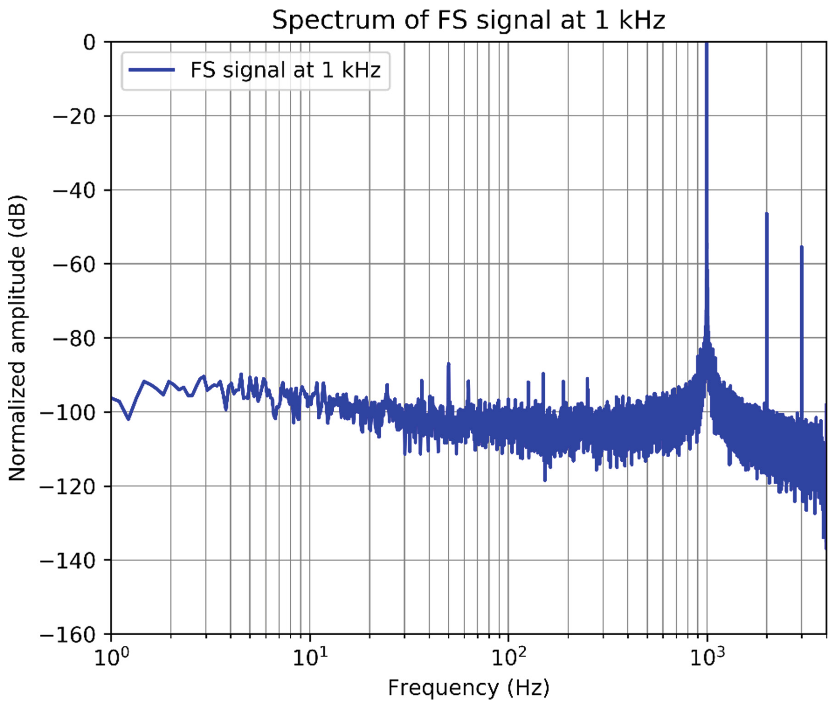

Fig. 2. Spectrum of full-scale signal at 1 kHz

Following the characterization of the system, a comparative study was conducted with a reference electronic stethoscope. The Littmann® 3200 from 3 M is one of the most often used electronic stethoscope in the clinical environment and is capable of transmitting the recorded signals to a computer via Bluetooth. This feature provides a means to compare the signals acquired by our device and the one of Littmann 3200 in the time and frequency domains. Both devices were placed below the right middle lobe next to each other and both were held in place by a chest strap in order to minimize the secondary effects such as hand tremor and contact pressure. A synchronous 10-second lung sound recording has been performed. Figure 3 presents the spectral comparison of the lung sounds acquired by our device and the Littmann 3200 stethoscope in extended mode. As the Littmann 3200 stethoscope is optimized for human hearing, it can be suggested that a high-pass filter around 50 Hz, which creates the deviation between two spectra, is implemented [5]. Peaks observed around 550 Hz and 800 Hz with an anti-resonance dip in between have also been reported in [6] for extended mode. For the rest of the spectrum, a good match is observed. Similar results were obtained from a second run with the positions of the two devices swapped. This shows that the distance between two devices is short enough not to have an effect on the results.

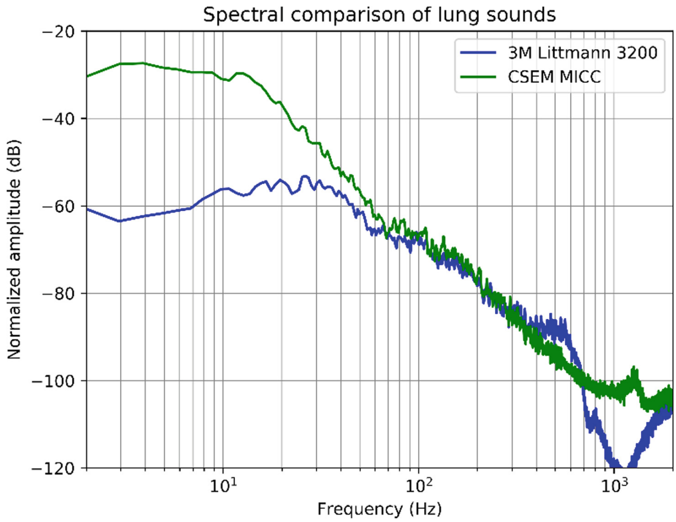

Fig. 3. Spectral comparison of lung sounds acquired by our device (CSEM MICC) and Littmann 3200 stethoscope

4 Discussion and Conclusion

We have designed and developed a low-cost, USB-powered electronic stethoscope prototype as a precursor of a wearable multi-channel lung sound recording system. The system exhibits promising results in terms of signal-to-noise ratio and linearity. Benchmarking results with a clinically-accepted electronic stethoscope showed equivalent signal qualities. It is envisaged to further miniaturize the system by means of integrated circuit technology to facilitate the integration onto garments.

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