Stethoscope with digital frequency translation for improved audibility

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The performance of an acoustic stethoscope is improved by translating, without loss of fidelity, heart sounds, chest sounds, and intestinal sounds below 50 Hz into a frequency range of 200 Hz, which is easily detectable by the human ear. Such a frequency translation will be of significant benefit to hearing impaired physicians and it will improve the stethoscope performance in a noisy environment. The technique is based on a single sideband suppressed carrier modulation. Stability and bias problems commonly associated with an analog frequency translator are avoided by an all-digital implementation. Real-time audio processing is made possible by approximating a Hilbert transformer with a time delay. The performance of the digital frequency translator was verified with a 16-bit 44.1 Ks/s audio coder/decoder and a 32-bit 72 MHz microcontroller.

1. Introduction: A traditional stethoscope is still the primary diagnostic instrument for an initial assessment of a patient's condition. Interpreting heart sounds, chest sounds, or intestinal sounds with a stethoscope is difficult and requires experience. Although the proposed technique applies equally to lung sounds and intestinal sounds, it will be illustrated for heart sounds. Numerous acoustic recordings of normal and pathological heart sounds can be found on the internet. However, the diagnostic conclusions drawn are influenced by the particular stethoscope design. Different stethoscopes compensate in different ways for the human ear's inability to hear low frequencies [1, 2]. For example, it is well known that changing the tubing length of a traditional stethoscope affects the audibility of heart sounds [3]. Although this change does not affect heart rate measurements, it does change the spectral content of the heart sounds and may alter diagnostic features. This can be illustrated by a simple example mentioned below.

Audible heart sounds are usually represented in graphical form as a phonocardiogram. An example of a single 'normal' heartbeat detected by a stethoscope with very short tubing, $L_1 = 6$ cm, is shown in Fig. 1. The method of recording this phonocardiogram will be described in the following Section. The S1 and S2 pulses exhibit comparable damped sinusoidal responses [4]. Their resonant frequencies have been attributed either to cardiac valve vibrations or to cardiohemetic turbulence [5]. However, stethoscope measurements of those frequencies may not be relied upon for diagnostic purposes.

We considered the effect of lengthening the stethoscope tubing to a more conventional length of $L_2 = 77$ cm. Although the theoretical ¼-wavelength resonant frequency of an equivalent air column would be about 112 Hz, the actual resonant frequency will be lower due to the elasticity of the stethoscope tubing. A phonocardiogram with the longer tubing is shown in Fig. 2, and a comparison of the frequency spectra is shown in Fig. 3. Apparently, lengthening the tubing shifted the alleged heart valve vibrations from a nearly inaudible 42 Hz to a more audible 91 Hz. This frequency shift had to be entirely due to the change in the resonant properties of the stethoscope [6]. In Fig. 3 we also compare the frequency spectra of Figs. 1 and 2 with an A-weighted response. A-weighting is an acoustic standard that recognises the reduced sensitivity of the human ear to low and high frequencies. Fig. 3 illustrates that lengthening the stethoscope tubing has shifted the entire heart sound frequency spectrum by 49 Hz. In other words, the stethoscope output is not the actual sound of the beating heart, but it is the heart sound convolved with the temporal response of the particular stethoscope.

For the above reason, we feel justified in applying any other stethoscope frequency translation technique that shifts the heart sounds perhaps even further into the audible spectrum. This would allow a stethoscope to be used by hearing-impaired medical personnel [7] or in a high-noise environment such as a medical evacuation helicopter [8].

The concept of a stethoscope with electronic frequency translation is not new. A patent was granted in 1980 for an analog quadrature mixer attached to a stethoscope to shift heart sounds by 250 Hz into the audible frequency band [9]. Another implementation, also based on discrete analog components, was described in [10]. The same concept was replicated in 2012 with analog integrated circuits [11]. However, the analog approaches appear to have been abandoned, primarily due to the high circuit complexity, tight component tolerances, and the significant calibration effort required to compensate for the imbalance between the in-phase and quadrature audio channels required by the frequency translation [11].

In this paper, we carry out the frequency translation with a digital approach which does not suffer from the above problems. The technique differs from a commercial 'voice changer' that distorts the sound spectrum on purpose. Here we preserve the spectral characteristics of the audio input signal, but shift them into a more audible region. The frequency translation has no effect on the temporal characteristics of the heart rhythm. An all-digital approach has become feasible by the availability of inexpensive high-fidelity digital audio signal coder/decoders (Codec) and high-performance microprocessors.

2. Methodology: The phonocardiograms in Figs. 1 and 2 were obtained by replacing one earbud of a Sprague-Rappaport style stethoscope with an electret microphone, plugging up the other earbud and adjusting the tubing length. Data were recorded in a 16-bit *.wav format on a Roland-R05 digital audio recorder at 44.1 Ks/s, and processed in Matlab. Phonocardiograms similar to Fig. 1 were the input to the frequency translator.

Frequency translation, or mixing, is a commonly employed technique for translating radio frequency signals to a more manageable intermediate frequency. In hearing aids, it has been used to translate high frequency sounds outside the auditory range into the audible frequency band [12, 13]. Such a frequency translation can be implemented digitally by a fast Fourier transform (FFT), a

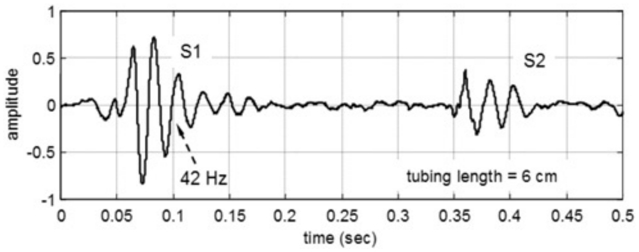

Fig. 1 *Example of a phonocardiogram with short stethoscope tubing*

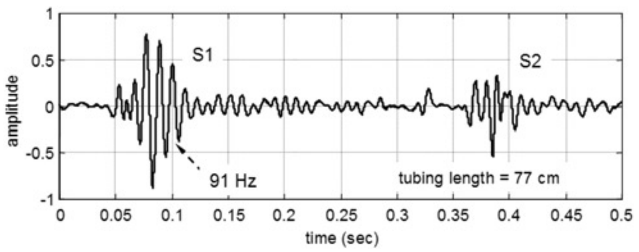

Fig. 2 *Phonocardiogram similar to Fig. 1 but with conventional (longer) stethoscope tubing*

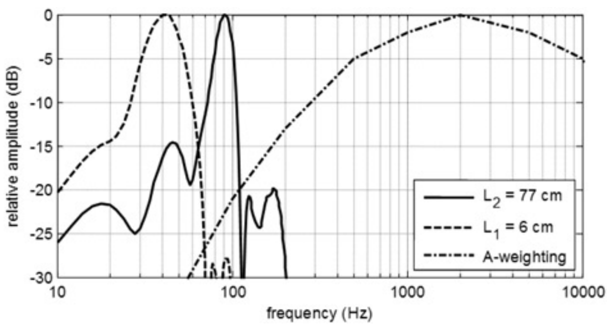

Fig. 3 *Heart sound spectra with different stethoscope tubing lengths compared with the human ear's frequency response*

frequency spectrum shift, followed by an inverse FFT [14]. Although real-time FFT processing is feasible, it is computationally expensive. Therefore, we carried out the frequency translation by a much simpler, single sideband modulation, as illustrated in Fig. 4, where $x(t)$ is the audio input, H is a Hilbert transform, ω_m the modulation frequency and $y(t)$ the audio output.

Up-shifting the entire audible frequency band by a very small amount has been employed to minimise feedback in sound amplification systems [11, 12]. A low frequency, digital Hilbert transformer is difficult to implement. Since the expected frequency range of the S1 or S2 heart sounds is limited to 40–48 Hz [15], the Hilbert transform can be approximated by a time delay [16] that provides a 90-degree phase shift at the resonant frequency. The similarity between a Hilbert transformed S1 pulse and a time-delayed pulse (correlation coefficient 0.93) is illustrated in Fig. 5. The resulting in-phase and quadrature audio signals are multiplied by the sine and cosine of the modulation frequency and summed to produce the frequency shifted audio output.

3. Results: An electronic stethoscope with a digital frequency translator was implemented using a Freescale SGTL5000 audio coder and decoder [17] that requires no additional active components to collect, modify and seamlessly retransmit 16-bit 44.1 Ks/s data. The SGTL5000 was controlled by a 72 MHz 32-bit microprocessor [18]. An Arduino [19] compatible C++

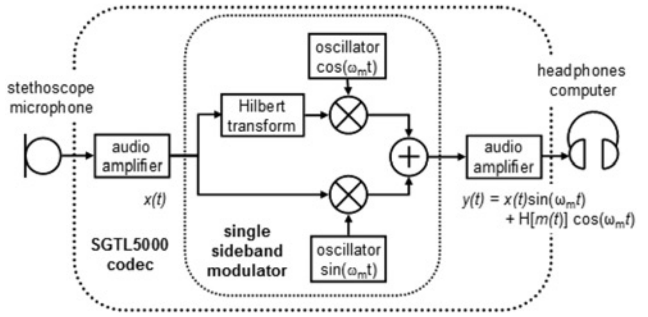

Fig. 4 *Block diagram of an electronic stethoscope with single sideband frequency modulation*

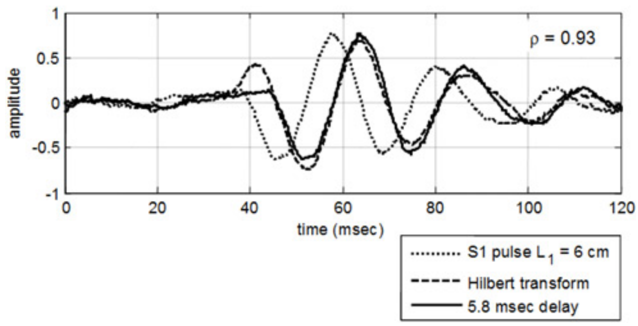

Fig. 5 *S1 pulse with Hilbert transform compared with time delay approximation*

Fig. 6 *Prototype electronic stethoscope with the frequency translator*

audio signal processing library [20] made it very easy to download the functions depicted in Fig. 4 via the microprocessor to the Freescale SGTL5000. A prototype of an electronic stethoscope with a frequency translator is shown in Fig. 6. The specific translation frequency and audio volume can be adjusted by potentiometers to meet the user's preferences.

Two examples will be given to illustrate the performance of this frequency translator:

In the first example, heart sounds picked up by a stethoscope with short tubing (Fig. 7*a*), were shifted by $f_m = 49$ Hz to digitally replicate the effect of lengthening the stethoscope tubing (Fig. 7*b*). Comparisons of the frequency spectra in Fig. 8 illustrates that the translation was carried out without loss of audio fidelity.

The second example is a more practical situation. Again starting with heart sounds from a stethoscope with short tubing, the signal

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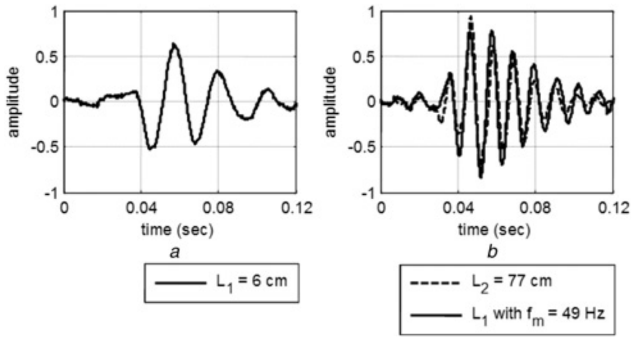

Fig. 7 *S1 pulse with frequency translation to match conventional stethoscope tubing*
a Short tubing input to the frequency translator, $x(t)$
b Output of frequency translator, $y(t)$, compared with a conventional stethoscope tubing length

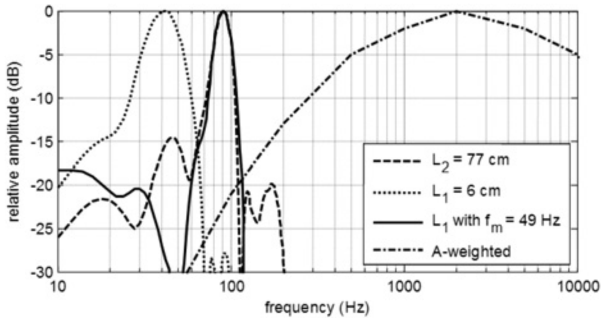

Fig. 8 *Heart sound spectra of frequency translation to match conventional stethoscope tubing length*

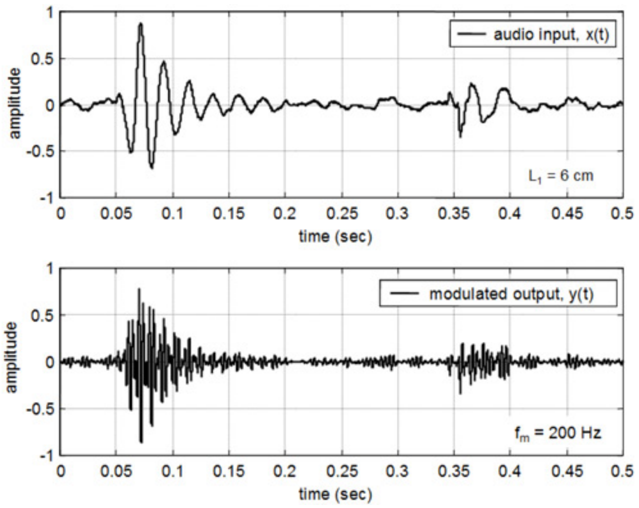

Fig. 9 *Phonocardiogram with digital frequency translation*

was mixed with $f_m = 200$ Hz to translate the heart sounds to an upper sideband at 242 Hz. Raising the translation frequency much higher is not recommended as it would result in sounds that differ too much from expected heart sounds. Furthermore, although the heartbeat rhythm and inter-heartbeat sound envelope are the same, the graphical representation in Fig. 9 no longer resembles a conventional phonocardiogram. However, the heart sound spectrum shown in Fig. 10 falls well within the frequency response of low-cost earbuds or commercial aviation headsets. No new

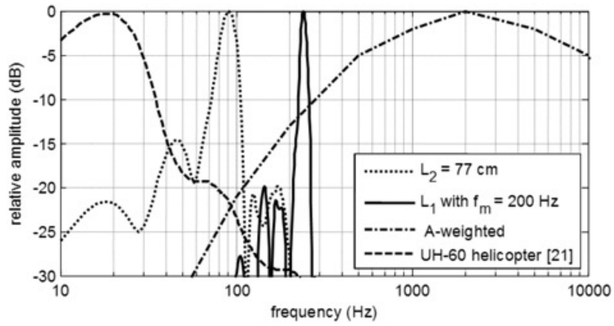

Fig. 10 *Heart sound spectrum with digital frequency translation*

harmonics were introduced. The undesirable lower sideband level is below −20 dB.

Conventional stethoscopes have been found to be nearly useless in a high-noise environment [8]. Fig. 10 compares the relative sound spectrum of a UH-60 medical evacuation helicopter [21] with the heart sound spectrum of a conventional stethoscope and a stethoscope with frequency translation. By shifting the heart spectrum away from low-frequency environmental noise and towards better hearing response, a frequency translation stethoscope would have a significant signal-to-noise ratio advantage.

4. Conclusion: Listening to heart sounds, chest sounds, or intestinal sounds with a stethoscope is a subjective experience. The digital frequency translator described in this paper allows these sounds to be perceived which might otherwise be inaudible. Unlike an analog frequency translator, the digital frequency translator is stable, compact, and low-cost. These qualities make it suitable as a stand-alone stethoscope or as an add-on to an existing electronic stethoscope.

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6 References

[1] Abella M.J., Formolo J.: ‘Comparison of the acoustic properties of six popular stethoscopes’, *J. Acoust. Soc. Am.*, 1992, **91**, pp. 2224–2228
[2] Pinto C., Pereira D., Ferreira-Coimbra J., ET AL.: ‘A comparative study of electronic stethoscopes for cardiac auscultation’. Int. Conf. IEEE Engineering in Medicine and Biology Society, Jeju Island, Republic of Korea, 2017, pp. 2610–2613
[3] Ertl P., Brown R.: ‘Stethoscope acoustics: II. Transmission and filtration process’, *Circulation*, 1966, **34**, pp. 899–908
[4] Chen D., Durand L., Lee H.C.: ‘Time-frequency analysis of first heart sound. Part 1: simulation and analysis’, *Med. Biol. Eng. Comput.*, 1997, **35**, pp. 306–310
[5] Heckman J., Stewart G., Lynch P., ET AL.: ‘Frequency analysis approach to the origin of the first and second heart sounds’, *Am. Heart J.*, 1982, **104**, pp. 1309–1318
[6] Korhonen P., Lukkarinen P., Sepponen S., ET AL.: ‘Frequency response measurements on commercially available stethoscopes’, *Med. Biol. Eng. Comput.*, 1996, **34**, pp. 91–92
[7] Rennert N., Morris F., Barrere C.: ‘How to cope with scopes: stethoscope selection and use with hearing aids and CIs’, *Hearing Rev.*, 2004, pp. 34–38
[8] Houtsma A., Curry I., Sewell J., ET AL.: ‘Dual-mode auscultation in high-noise environments’, *Aviat. Space Environ. Med.*, 2006, **77**, pp. 294–295
[9] Kimball J., Caceres C.: ‘Method and apparatus for discrimination and detection of heart sounds’, U.S. Patent No. 4220160, 1980
[10] Jones M.H.: ‘Frequency shifter for howl suppression’, *Wirel. World*, 1973, pp. 317–322
[11] Amundsen K.: ‘Suppression of acoustic feedback by frequency shifting’, M.S. thesis, University of Oslo, Sweden, 2012
[12] Alexander J.: ‘Enhancing perception of frequency-lowered speech’, US Patent No. 9173041 B2, 2015

[13] Salorio-Corbetto M., Baer T., Moore B.: ‘Evaluation of frequency-lowering algorithms for adults with high-frequency hearing loss’, *Trends. Hear.*, 2017, **21**, pp. 1–23
[14] Eisenberg L.: ‘Electronic stethoscope system and method’, U.S. Patent No. 4792145, 1988
[15] Stein P., Sabbah H., Lakier J., *ET AL.*: ‘Frequency of the first heart sound in the assessment of stiffening of mitral bioprosthetic valves’, *Circulation*, 1981, **63**, pp. 200–203
[16] Hussain Z., Boashash B.: ‘Hilbert transformer and time delay: statistical comparison in the presence of Gaussian noise’, IEEE Trans. Signal Process., 2002, **50**, pp. 501–508
[17] Freescale Semiconductor Inc.: ‘SGTL5000: Ultra-low-power Codec’, available at: https://www.nxp.com/audio/audio/audio-codec, 2013
[18] PJRC.: ‘Teensy USB development board’, PJRC, available at: https://www.pjrc.com/teensy/
[19] Arduino software (IDE).: available at: https://www.arduino.cc/en/Main/Software
[20] Teensy audio system design tool, pjrc.com, available at: http://www.pjrc.com/teensy/gui/index.html
[21] Nelson G., Rajamani R., Erdman A.: ‘Noise control challenges for auscultation on medical evacuation helicopters’, *Appl. Acoust.*, 2014, **80**, pp. 68–78

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