Fibre-Optic Interferometry as a Means for the First Heart Sound Detection

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Abstract: - Ambient-assisted living, in particular for the elderly and people with disabilities, call for sensors being capable of detecting several vital sign at a time. We introduce a new healthcare monitoring technology based on fibre-optic interferometry which detects sub-micron changes of optical fibre length. The human heart activity causes fibre-optic changes of a few microns. These can be extracted by analysing the acquired intereferometric signal. We applied modified continuous wavelet transform whose multiresolution properties can sort out different signal components.

Our main finding is that Morlet-wavelet-based transform of fibre-optic interferometric signal can detect the first heart sound with considerable reliability. To confirm the locations of extracted signal components are representative, we compute their delays after referential R waves and compare their inter-beat intervals to referential RR intervals. Estimated delays of 48.91±21.48 ms fall within the expected physiological limits for the first heart sound. Also the inter-beat intervals are aligned with high precision, yielding P_{90} error below 10%.

Key-Words: fibre-optic interferometry, human vital signs detection, continuous wavelet transform, phonocardiography, first heart sound

1 Introduction

Recent demographic studies underline a rapid growth of percentage of elderly people. In a few decades, the biggest societal problems will be related to prolonging the time of independent and healthy living of the elderly and people with special needs. Home and continuous health care is expected to facilitate savings of considerable amounts of health-system finances.

Several sensors and systems have been developed that serve the monitoring of people's healthcare status. They mainly detect the different human vital signs, such as heart rate, electrocardiograms (ECG), respiration, motion, electromyograms (EMG), etc. Focusing on heart activity only, a lot of methods are available for monitoring [1], such as ECG used as the gold standard, ballistocardiography, phonocardiography, plethysmography, etc. However, such principles involve placement of electrodes and other sensors on the patient's body and require specific skills and knowledge. Additional problem is the amount of sensors that are also fragile and due to many reasons (placement, wires) can be obtrusive.

Sensors for ambient-assisted living are required to be unobtrusive and suitable for automated, uncontrolled operation. In particular, the group of sensors for detecting the electrical, acoustic, or mechanical activity of the heart is under intensive investigations. Unobtrusive sensors operating with no direct contact with a person's body are most desirable. Such advanced sensors receive signals generated by the heart through transmitting medium, e.g. the bed or clothes [6]. Heart activity is detected indirectly, conveyed thorough the medium, and in entirely unobtrusive way. Important solutions have been proposed in this field lately (a short survey is given in [2]).

An example of a flexible and very sensitive sensor for measuring mechanical, acoustic, and temperature impacts at the same time, is optical fibre. Feasibility of measuring heart rate by using fibre-optic interferometer has already been examined in [2] and [3]. When mechanical forces produced by heartbeats perturb optical fibres, this affects fibre-optic interferometric signal. First method for detecting heartbeats from the interferometric signals calculated the signal zero-crossings and filter banks tuned to possible heartbeat frequencies [2]. Another approach was built with time-frequency representation by using pseudo Wigner-Ville distribution [3].

The different heart-activity features, respiration and, in part, also movement spread through disjoint frequency bands. It is well known that wavelet transform allows for multiresolutional analysis by applying a scheme of scaled wavelets whose frequency-domain characteristics correspond to band-pass filters. Hence, the output of wavelet transform yields time-scale representation separating the features that do not overlap in the frequency or time domain.

In this paper, we study the discrimination power of time-scale approach when the first heart sound is of interest. We base it on fibre-optic signal transformed by the Hilbert transform and analysed by using Morlet wavelets.

2 Methodology

Our heartbeat detection method relies on a fibre-optic Michelson interferometer [7], [8]. This consists of laser diode (in our case telecom distributed feedback laser diode – DFB), sensing fibre, reference fibre, optical coupler, optical detector, and electronic converter (Fig. 1). Reference fibre is shielded mechanically by placing it in a loss tube, while the sensor fibre is put in a good contact either with the observed person's body directly or a transferring medium and the body indirectly. The optical coupler connects the laser diode and optical detector on one side with sensing and reference fibres on the other side. Unconnected fibre ends are covered by thin silver layer to enhance back reflection of the light waves. The coupler then functions as a splitter and combiner of back reflected light waves. These are added-up and interfere in the coupler. Minute changes in sensing fibre length thus cause significant changes in the phases of reflected light. This further means changes of the optical power that is detected by optical detector. The device has a cosine transfer characteristic. One period corresponds to a fibre length change that is equivalent to the half wavelength of the used optical source, which is 0.65 μm in our particular case (we used 1300 nm telecom DFB diode). Detected optical power is sampled at 2 kHz and outputted as interferometric signal $i(n)$, Eq. (1).

The relationship between the external stimuli that stretch and shrink optical fibre and interferometric signal $i(n)$ is highly nonlinear. In order to derive the signal that represents such shortening and stretching of optical fibre, $i(n)$ must be transformed by phase demodulation.

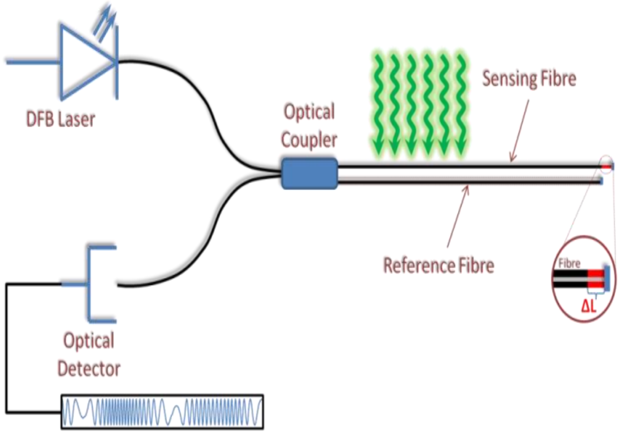


Fig. 1: Fibre-optic interferometer

Signal i(n) is modelled as follows:

$$i(n) = A(n)\cos[s(n)] \tag{1}$$

where $A(n)$ stands for the interferometric signal amplitudes and $s(n)$ for a superimposition of all the stimuli interfering with the optical fibre. Analytic representation of such a signal can be derived by using the Hilbert transform:

$$\begin{aligned} y(n) &= i(n) + j \cdot H[i(n)] \\ &= A(n)\{\cos[s(n)] + j \cdot \sin[s(n)]\} \end{aligned} \tag{2}$$

with j meaning the imaginary unit. Phase angle can be expressed as

$$\tan\phi(n) = \frac{\sin[s(n)]}{\cos[s(n)]} = \tan[s(n)] \tag{3}$$

By combining Eqs. (2) and (3), the phase of the analytic signal, $y(n)$, is computed:

$$\phi(n) = \tan^{-1}[y(n)] \tag{4}$$

The phase in Eq. (4) is wrapped due to the operation of arctangent function, $\tan^{-1}$. This means that a step with unwrapping must follow:

$$s(n) = unwrap[\phi(n)] \tag{5}$$

Consider now the derived external fibre-optic influences, $s(n)$, can be seen as a superimposition:

$$s(n) = s_{BR}(n) s_{HB}(n) + s_{MV}(n) + r(n) \tag{6}$$

where $s_{HB}(n)$ stands for the contribution of heartbeats, $s_{BR}(n)$ for the contribution of breathing, $s_{MV}(n)$ for the contribution of movement, and $r(n)$ for a residue whose main contents come from the ambiguity of unwrapped interferometric signal phase. It is caused by disability of locating time instants when optical fibre reverts from stretching to shrinking and vice versa. Therefore, such reversals are inherently neglected during unwrapping, which means that $s(n)$ behaves as the optical fibre were only stretching all the time. For the same reason, the

ISBN: 978-1-61804-113-5

amplitudes of contributions of vital signs, $s_{HB}(n)$, $s_{BR}(n)$, and $s_{MV}(n)$, increase steadily, instead of increasing in the initial and decreasing in the termination phase of any heartbeat, inhalation or exhalation, and motion. Nevertheless, the contributions of different vital signs still remain unique and can be discerned.

Residue $r(n)$ includes also a superimposition of all disturbances, i.e. temperature noise, high-frequency random noise, and other environment influences (sounds and uncontrolled vibrations). It should be emphasised that the respiration modulates the amplitudes of heartbeat contributions in model (6).

2.1 Multiresolutional separation of interferometric signal components

Fibre-optic interferometric measurement acquires a compound signal whose components occupy partially non-overlapped frequency bands. This alludes one of possible discrimination approaches can be based on multiresolutional scheme of the wavelet transform [4].

The signal $s(n)$ can be transformed to time-scale representation W by using slightly modified version of continuous wavelet transform:

$$W(a,b) = \frac{1}{\sqrt{a}} \sum_{n=-\infty}^{\infty} \left[s(n) - \hat{s}_{a,b}(n) \right] \cdot \psi\left(\frac{n-b}{a} \right) \quad (7)$$

where a stands for scale, b for time lag, $\psi(n)$ for mother wavelet, and $\hat{s}_{a,b}(n)$ represents a local trend line in signal $s(n)$. The latter removes a linear trend from $s(n)$, according to current scale a and time lag b. The signal segment covered by mother wavelet at scale a and time lag b is detrended prior to continuous wavelet transform, so that the signal sample values are decreased linearly between the wavelet onset and termination. This step is necessary due to monotonically increasing signal $s(n)$, as we explained in the previous subsection.

Morlet mother wavelet is used in our approach due to its compact time and frequency localization [5].

3 Experiment and results

Our experimental protocol supported a search for audible effects of cardiac activity by fibre-optic interferometer. Nine males and one female of age 31.30±10.45 years, height 177.50±7.04 cm, and weight 79.00±14.55 kg participated in the experiment. They were connected to a standard Schiller ECG device in order to acquire referential ECG signal in parallel with interferometric signals. We applied 4 electrodes on the extremities and lead II was taken as the referential one. Both the referential and interferometric signals were acquired by our own four-channel sampling device at 2000 Hz sampling rate. Hardware signal synchronization was applied.

After ECG referential electrodes mounted, participants were asked to reach their submaximal heart rate by cycling an ergometer [9]. Following, they immediately lied back down on the mattress and the interferometric and referential signal acquisition began simultaneously. Optical fibre was spirally bent on the stretchable (flexible) bed mattress and overlaid by a thin layer of foam. Subjects had to lie still and breathe normally through their nostrils. Interferometric and referential signals were acquired for 5 minutes. During this time, heart and respiration rate both decreased significantly. This kind of experimental protocol allowed for the dynamic changes of cardiac activity and, consequently, different mechanical and acoustic influences on optical fibre.

3.1 Multiscale analysis

Established clinical examinations focus on four different heart sounds as a consequence of audible cardiac activity, the so called phonocardiography.

We applied wavelet transform to fibre-optic interferometic signals and searched for the frequency components that belong to the most important, the first heart sound. The corresponding multiresolutional scheme depends on the scales involved in the computation of wavelets. Wavelets exhibit pass-band frequency characteristics.

Phonocardiographic frequencies are not defined uniquely in the literature. Most definitions say the first heart sound (S1) extends from 10 Hz to 140 Hz [10]. Our intention was to verify whether this sound can be detected within fibre-optic interferometric signal or not. We centered the wavelet frequency band at 44 Hz, which corresponds to scale 44 for the Morlet wavelets.

3.2 Evaluation of results

Extensive studies have proved that heart sounds appear within well-defined time intervals after most intensive electrical heart activity, i.e. the R wave [10]. As our main goal was to find out whether or not cardiac acoustic activity can be detected by fibre-optic interferometry, we measured delays from R waves to the highest amplitudes (energy) within the signal components filtered out by the wavelet transform at scale 44.

Therefore, the first step was to locate the R waves in referential ECG recordings. This task was completed by using Pan-Tompkins QRS detection algorithm [11]. All false detected or undetected R waves were corrected manually. After that, the acquired fibre-optic interferometric signals were phase unwrapped and the obtained compound signals were analysed by the wavelet transform (Section 2). A short segment of the interferometric signal illustrates the principle in Fig. 2. The extracted first heart sound S1 (in blue) is aligned with the referential ECG (in red). Heart sounds were further processed by the Hilbert transform, which encapsulated the signal components into their envelopes. Signal energy maxima were located by the envelope extremes and every maximum was aligned with its nearest preceding R wave as found in the referential ECG. Distances from the R waves to the energy maxima were measured for each detected cardiac sound.

Time delays between estimated energy maxima and the corresponding R waves were statistically evaluated by means and standard deviations, yielding 48.91±21.48 ms for the first heart sound (S1) components. Detailed results for all tested subjects are collected in Fig. 3.

Distances between successive detections were also compared to referential RR intervals. Mean and median relative errors were computed. For each of the calculated errors, dispersion was assessed by using 90th percentile P_{90}, yielding the value with 90% of errors below it. The results are depicted in Fig. 4.

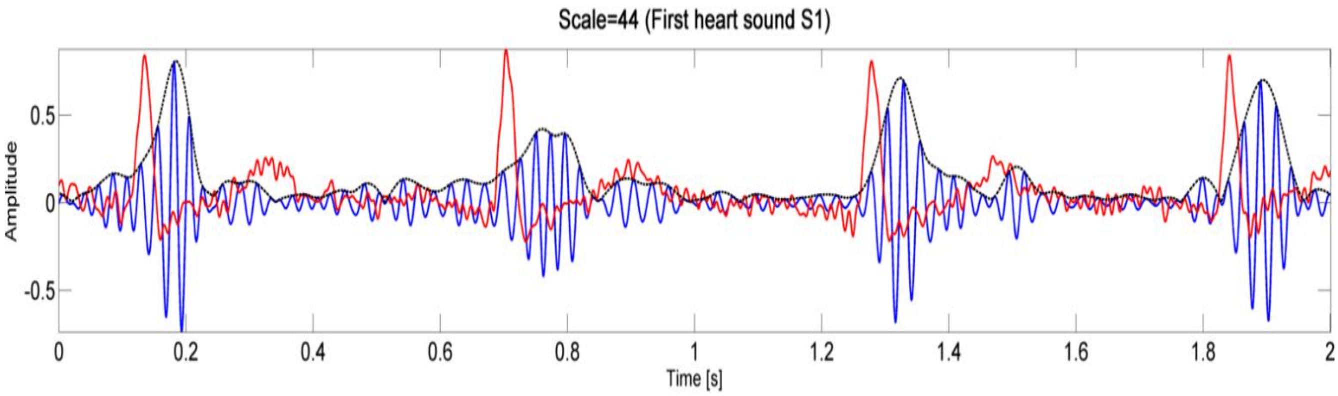


Fig. 2: A segment of wavelet transform of interferometric signal $i(n)$ illustrates the extracted first heart sound contributions (S1): it is depicted in blue and encapsulated in black envelopes, while the referential ECG appears in red.

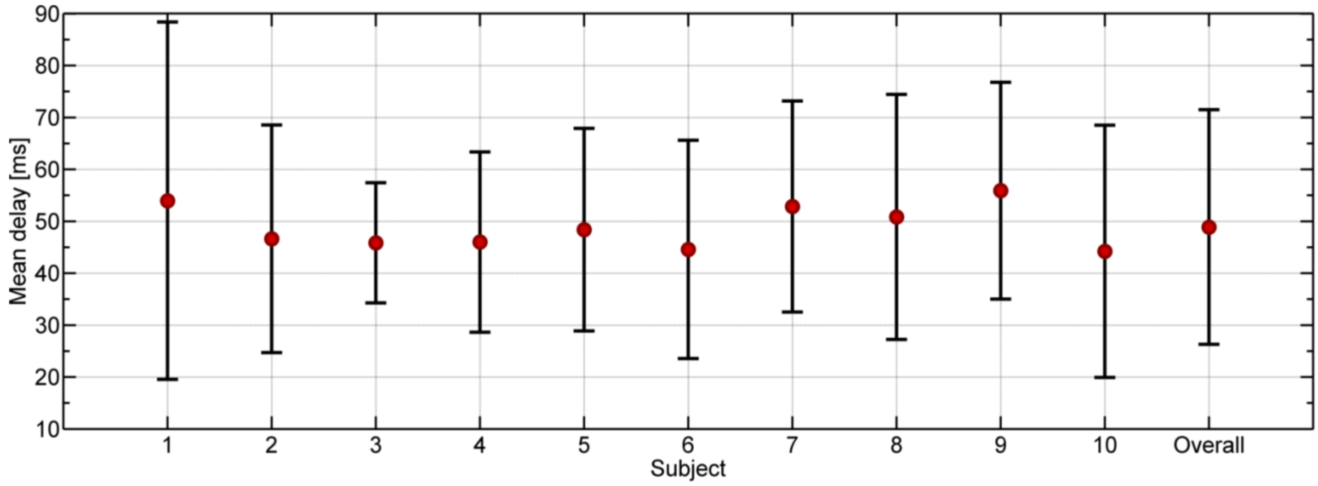
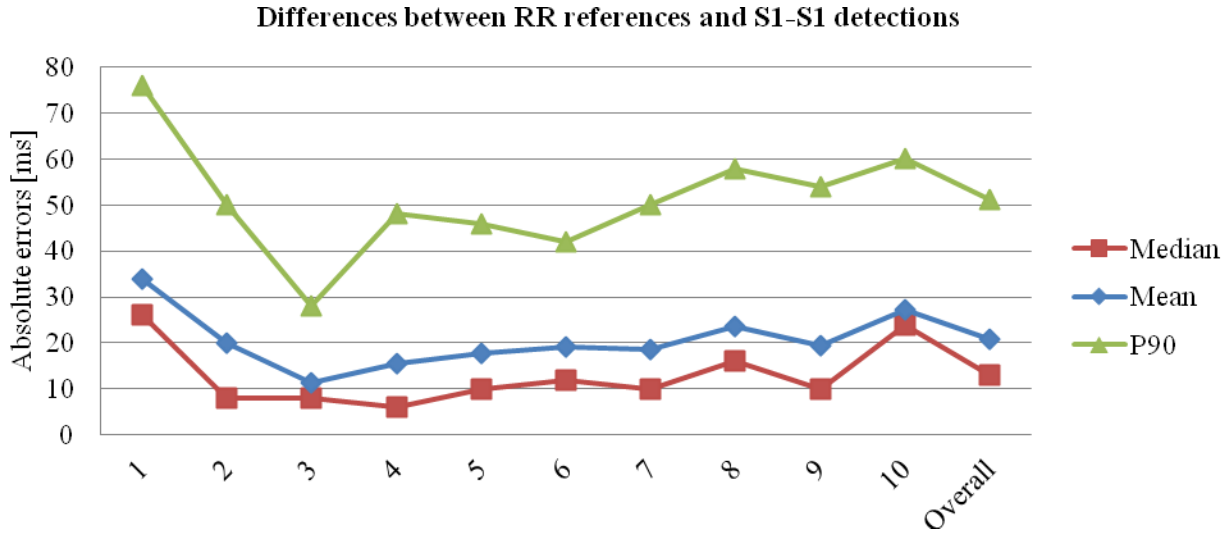


Fig. 3: Delays between R waves and the energy maxima in the first heart sound, S1, as detected in scale 44 by the wavelet transform of interferometric signals: means depicted by red spots, standard deviations by upright lines.



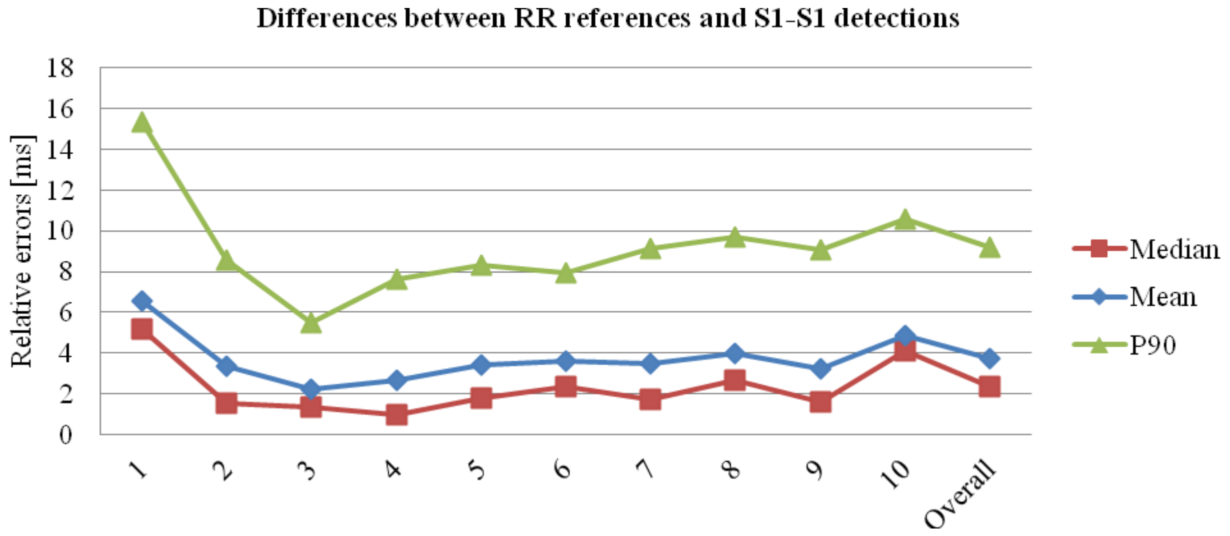


Fig. 4: Mean errors (in blue), median errors (in red), and dispersion of mean errors determined by P_{90} (in green) are measured between the intervals of detected maxima in the first heart sounds and corresponding referential RR intervals: absolute errors (upper panel); relative errors (lower panel).

4 Discussion and conclusions

Our experiments prove that fibre-optic interferometry is sensitive enough to react to even weak acoustic perturbations caused by human vital signs. Due to non-overlapping frequency contents of the different cardiac contributions, we successfully extracted first heart sounds by applying the Morlet wavelet.

The frequency band 10-140 Hz is recommended for observing the first heart sound [10]. We focused on the frequency where, at least to our experience, the vast majority of energy may be expected, i.e. around 44 Hz, and the corresponding scale was set to 44.

Our most important goal was to verify whether or not the applied wavelet signal decomposition is representative, meaning that the obtained signal components show the properties that actually characterize phonocardiographic recordings. As we limited our detection to preselected frequency band that certainly contains the observed phenomenon, detections had to be confirmed by different evidence. We decided to estimate the delays of the detected energy maxima after the referential R waves (Figs. 3). Previous studies claim the first heart sound, S1, must appear 10-50 ms after the R wave and its duration is about 100-160 ms [10].

The overall estimations according to our experiments yield the average locations at 48.91±21.48 ms after referential R waves. This figure coincides well with physiological expectations.

ISBN: 978-1-61804-113-5

We also compared the inter-beat distances, as detected by phonocardiographic energy maxima, to the referential RR intervals. Fig. 4 shows the mean relative errors are 3.74±1.22% for the first heart sound. Two conclusions can be drawn upon this statistics. Firstly, the regularity and stability of the detected signal components when compared to referential RR intervals reinforce the belief that the detections can be considered reliable and, therefore, represent the actual physiological phenomena. And secondly, the first heart sound location is very stable.

Finally, we believe the proposed wavelet analysis of fibre-optic interferometric signals can extract phonocardiographic contributions of cardiac activity with high reliability.

Acknowledgement

All persons signed an informed consent to participate in our experimental protocols that were approved by the National Medical Ethics Committee of the Republic of Slovenia (no. 81/10/10). We also acknowledge partial financial support of the Slovenian Ministry of Education, Science, Culture, and Sport (contract no. 3211-10-000464 for the Competence Centre of Biomedical Engineering).

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