Noninvasive Fetal Heart Rate Monitoring: Validation of Phonocardiography-Based Fiber-Optic Sensing and Adaptive Filtering Using the NLMS Algorithm

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Abstract. *Here we present the evaluation results of our novel noninvasive phonocardiographic-based fiber-optic sensor for fetal Heart Rate (fHR) detection using adaptive filtering and the NLMS Algorithm. The sensor uses two interferometric probes encapsulated inside a PolyDiMethylSiloxane (PDMS) polymer. Based on real data acquired from pregnant women in a suitable research laboratory environment, once they had given their written informed consents, we created a simplified dynamic signal model of the distribution of maternal and fetal heart sounds inside the maternal body. Building upon this signal model, we verified the functionality of our novel fiber-optic sensor and its associated adaptive filtering system using the NLMS Algorithm. The main reason why we chose this technology to develop our system was that it allows monitoring the fHR without exposing the fetus to any external energies or radiation (in contrast to the ultrasound-based Cardiotocography Method). We used objective criteria such as: Signal to Noise Ratios:* SNR_{in}, SNR_{out} *and Percentage Root-mean-square Difference (PRD) for our evaluations.*

Keywords

ElectroMagnetic Interference (EMI), fetal Heart Rate (fHR), fetal PhonoCardioGraphy (fPCG), Fiber-optic sensor, maternal PhonoCardioGraphy (mPCG), Normalized Least Mean Square (NLMS) algorithm, PolyDiMethylSiloxane (PDMS).

1. Introduction

In this article, we report on the evaluation of a noninvasive method for fetal Heart Rate (fHR) detection and monitoring during gestation, labor, and delivery based on fetal PhonoCardioGraphy (fPCG). Our proposed method relies on the combined capabilities of fiber-optic sensing and adaptive filtering (implementing the Normalized Least Mean Square - NLMS - Algorithm). In our recent work reported elsewhere [1] and [2], we developed an adaptive system, which enabled us to measure the fetal Heart Rate (fHR) by means of fPCG signal peak detection using the maternal abdominal PhonoCardioGrams (aPCGs). We observed that diagnostic-quality fPCG signals required for accurate fHR detection are contaminated by an unwanted maternal component (the mPCG signals) in addition to other technical and biological interferences. We showed that as the spectral contents of the fPCG and mPCG signals overlap in the frequency domain, common filtering methods such as signal subtraction, linear filtering, and others are ineffective in extracting reliable fHR information and therefore cannot be used.

Our recent research as well as others have also indicated that Fiber-optic technologies such as Fiber Bragg Gratings (FBGs) or interferometers are used increasingly in many biomedical applications; see articles [3], [4], [5], [6], [7], [8], [9], [10] and [11]. Building upon these advancements, we developed our novel sensor that uses two non-invasive interferometric probes encapsulated in a PolyDiMethylSiloxane (PDMS) polymer with the designation Sylgard 184.

The well-established conventional Phonocardiography is based on the scanning of acoustic signals by means of a microphone placed on the thorax. As for fetal Phonocardiography, the microphone is placed on the maternal abdomen [12], [13] and [14].

Our solution described here is based on the scanning of acoustic signals by means of two Mach-Zehnder interferometric fiber-optic probes. The advantages of these interferometers are their immunity to Electro-Magnetic Interferences (EMI), and their ability to measure any changes in the optical path length (such as the core refraction index, fiber length and the wavelength used). Therefore, the smallest measurable frequency due to any phenomena resulting in the change of the above-mentioned physical properties is theoretically unlimited [15] and [16].

To perform our system evaluations, we needed to use synthetic data. For generating suitable synthetic signals, we conducted a set of measurements on pregnant women in a suitable research laboratory environment after obtaining their written consents. We then created a simplified dynamic signal model for the distribution of maternal and fetal heart sounds inside the maternal body. Based upon this signal model, we generated synthetic data with properties as close as possible to the real data. The necessity to use synthetic data at this stage of our research was further justified by considering the fact that our patent-pending interferometric sensors have yet to be legislatively approved for clinical testing on pregnant women. It is important to emphasize that legislative regulations for use of new technology on pregnant women are extremely strict (as an unborn fetus is critically sensitive to external energies such as mechanical pressure, electromagnetic radiation, change in temperature, and so on).

In current clinical practice, clinicians use either ultrasound-based methods such as CardioTocoGraphy (CTG), which measures the fetal heart rate along with maternal uterine contractions, or fetal Echocardiography (fECHO) to diagnose fetal congenital heart defects from the 20^{th} to the 23^{rd} week of pregnancy [17] and [18]. These sophisticated technologies are now integral parts of routine modern obstetrics. It is important to emphasize that the CTG technology has helped clinicians reduce the mortality rate of newborn babies during delivery. In spite of this considerable impact, it is generally recognized that this technology has some disadvantages such as high sensitivity to noise caused by maternal movements and the need to frequently reposition the ultrasound transducers. Also, this method is not suitable for long-term continuous fetal heart rate monitoring due to the potentially harmful influence of ultrasonic radiation on the fetus.

Our method and system, once statistically and clinically proven and validated, offer a number of advantages (in contrast to the currently used ultrasound-based CTG and other conventional methods), including their applicability to continuous long-term fHR monitoring without exposing the fetus to any radiation as well as their compatibility with Magnetic Resonance Imaging (MRI) environments. The continuous long-term monitoring capability of our system is highly desirable, especially in those cases in which the pregnant woman faces a dangerous situation (such as after an accident), and it becomes absolutely essential to perform a time consuming MRI examination to ensure that the unborn child is intact and safe. The other specific advantage of our technology is that it can be used in water deliveries.

2. Methods

2.1. Fetal Phonocardiography

Fetal PhonoCardioGraphy (fPCG) was discovered during the 17^{th} century by Kergardec, Marsac, and Kennedy [19]. Although fPCG was discovered a very long time ago, interest in this research area has only grown over the past few years. This figure shows the number of peer-reviewed articles that appear in the Science Direct, the Institute of Electrical and Electronics Engineers (IEEE) and the National Institute of Health (PubMed) databases.

The PCG signal is composed of two main acoustic components (the first heart sound S1 and second heart sound S2), see Fig. 1, and two additional heart sounds (S3 and S4). S1 is systolic and is connected with the closure of bicuspid and tricuspid valves at the beginning of ventricular contraction. S2 is diastolic and is produced by the closure of semilunar valves. The third heart sound (S3) is pro-diastolic and appears when a valve muscle quivers during the fast phase of blood flow into the valve. The fourth heart sound (S4) is presystolic and is a sign of the quivering of valve muscle during systole in the atrium. The last two mentioned heart sounds (S3 and S4) are not common for adults, and their presence is a sign of cardiac insufficiency [20].

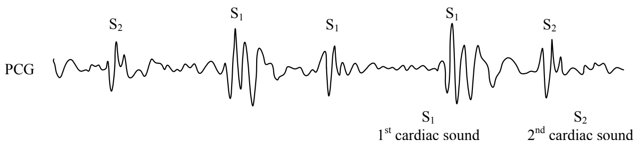

Fig. 1: Basic components of PCG signals.

2.2. PCG-Based Fibre-Optic Sensor

Our fiber-optic sensor is encapsulated inside polydimethylsiloxane [21], [22] and [23] and is comprised of two Mach-Zehnder interferometric components formed by 1×2 and 3×3 power couplers with an even split ratio; see Fig. 2.

Fig. 2: Our noninvasive fiber-optic measurement probe.

The reference fiber is stored in a stable environment. The output beams are recombined at a second 3×3 coupler. The output signal is detected by photodetectors. The resultant optical intensity after 3×3 coupler can be described by the following Eq. (1).

$$I_n = A_n + B_n \cos\left[\phi(t) + \phi_{drift}(t) + (n-1)\frac{2\pi}{3}\right], \quad (1)$$

where n represents the coupler output index with a value of 1, 2 or 3. The symbol A_n represents the mean value of optical intensity (DC component). Symbol B_n represents the optical intensity variation amplitude depending on fringe visibility, $\phi(t)$ represents the signal of interest, and $\phi_{drift}(t)$ is a quasi-static phase shift due to coupler properties. For the extraction of the proper signal, it is necessary to use a demodulation algorithm [24].

2.3. Implementation of the Adaptive NLMS Algorithm

The measurands sensed by our interferometric sensors generated the fetal heart rate information, which was then fed into an adaptive stochastic system using the Root Mean Square Error (RMSE) criterion. This stochastic approach required a large number of measurements to produce powerful statistics. This consideration led to the utilization of the Normalized Least Mean Square (NLMS) Algorithm, which is a representative of basic stochastic gradient-based adaptation methods; see articles [25] and [26].

The Normalized Least Mean Square (NLMS) Algorithm is a variant of the Least Mean Square Algorithm. The former is able to accelerate the convergence speed with a reasonable computational cost and selects a normalized step-size μ_n, which results in both a stable and fast converging adaptation algorithm, see [27] and [28]. Implementation of the NLMS Algorithm can be summarized as follows:

```
BEGIN w⃗(n=0)=0⃗
FOR (n=1,2,...,N):
y(n)=w⃗^T(n)·x⃗(n)
e(n)=d(n)−y(n)
w⃗(n+1)=w⃗(n)+μ(n)·e(n)·x⃗(n).
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The step-size μ_n can be described as follows Eq. (2).

$$\mu(n) = \frac{\mu}{\delta + \vec{x}^T(n)\cdot\vec{x}(n)}. \quad (2)$$

Finally, we obtain the following Eq. (3).

$$\vec{w}(n) = \vec{w}(n-1) + \mu\frac{e(n)\cdot\vec{x}(n)}{\delta + \vec{x}^T(n)\cdot\vec{x}(n)}, \quad (3)$$

where $\mu \in (0,2]$ and $\delta > 0$. Parameter δ representsthe regularization parameter (prevents the denominator of Eq. (4) becoming zero).

3. Results

Our measurement system comprised of a novel fiber-optic sensor and its associated adaptive filtering system for fetal Heart Rate (fHR) monitoring is shown in Fig. 3. The adaptive system consists of two measurement sensors (FC/APC type) which were placed on the chest and abdomen, optical interrogator and DSP (Digital Signal Processing) unit for the recording, amplification, digitalization, demodulation and filtering the measured signals. Optical interrogator consists of DFB (Distributed Feedback Laser) laser with wavelength 1549.5 nm and output power of 3 mW and three InGaAs Amplified Photodetectors (Indium Gallium Arsenide). Signal was digitalized by National Instruments card NI-USB 6210 with the sampling frequency of 250 kHz and analyzed by software application written in the LabView (2015, National Instruments, Austin, Texas, USA) [29] and [30].

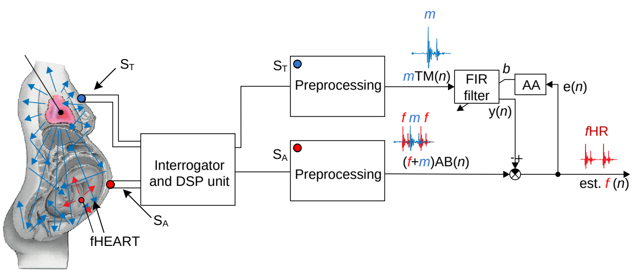

Fig. 3: Basic scheme of our sensor and its associated NLMS adaptive system for fHR monitoring.

Measurements (Fig. 4) were performed in a suitable research laboratory environment on 8 pregnant women (GA = 36–42 weeks) after obtaining their written informed consents. The test subjects were between the age of 21 and 37, their weight was between 57 kg and 103 kg, and their height was between 156 cm and 196 cm. Based on the obtained results we can state that no significant differences were found in the quality of the collected data based on the subjects' age, weight, and height.

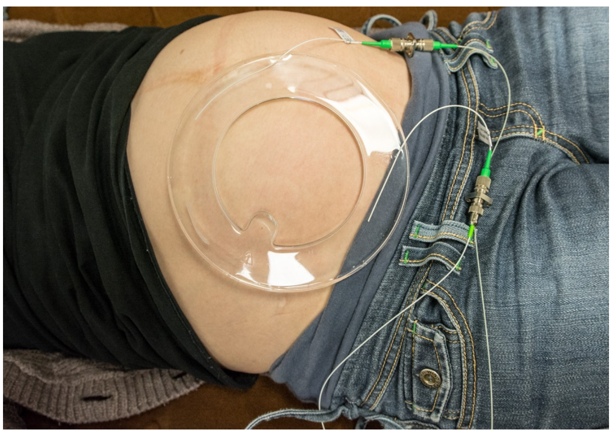

Fig. 4: An example of real data acquisition from a volunteer subject.

Using real data, we created a simplified dynamic model of sound distribution in the human body to generate suitable synthetic signals such as: ST (signals from sensors placed on the chest) and SA signals (from sensors placed on the abdomen). Our PCG signal model was inspired by contributions made by ALMASI et al. [31] and [32], who devoted considerable efforts to generating synthetic PCG signals. In addition, we greatly benefited from our own research in generating realistic synthetic physiological and pathological fECG signals [33] and [34] in order to evaluate the performance of our system.

Figure 5 shows an ideal mPCG signal after removing the mother's breathing artifacts (using a Butterworth second-order band-pass filter with corner frequencies: $f_L = 10$ Hz, and $f_H = 400$ Hz, respectively). This signal served as a reference input for our adaptive system running the NLMS Algorithm. The filtered results enabled us to determine the mHR (by performing mPCG signal peak detection). Maternal first and second heart sounds are denoted as mS_1 and mS_2, respectively, in Fig. 5.

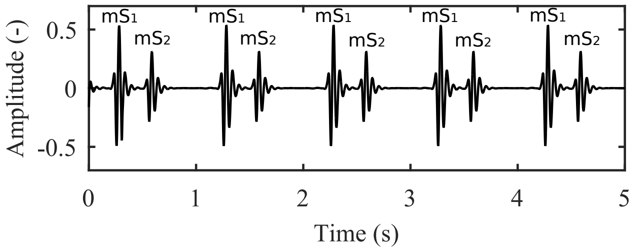

Fig. 5: The reference synthetic mPCG signal based on real measurements made from thoracic (S_T) sensors.

Figure 6 shows an ideal fPCG waveform after preprocessing the maternal signal. We need to emphasize here that the first fetal heart sounds (fS_1) result from the closing of the fetal tricuspid and mitral valves and the second fetal heart sounds (fS_2) are produced by the closure of the fetal pulmonic and aortic valves.

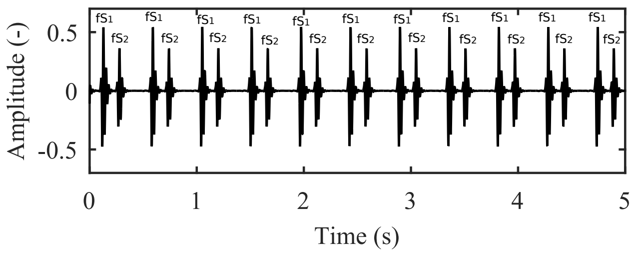

Fig. 6: The reference ideal synthetic fPCG signals based on real measurements from abdominal (S_A) sensors.

Figure 7 shows an example of the primary abdominal PCG (aPCG) synthetic input signal measured by the abdominal sensor. The aPCG signal (made up of the fPCG and mPCG components) is applied to the adaptive NLMS Algorithm. For determination of the fetal Heart Rate (fHR), it is necessary to detect fS1 components in the composite aPCG signals, which is a difficult task without advanced signal processing.

Figure 8 shows an example of the output from our adaptive system using the NLMS Algorithm. Based on these results we can observe that: the mPCG compo-

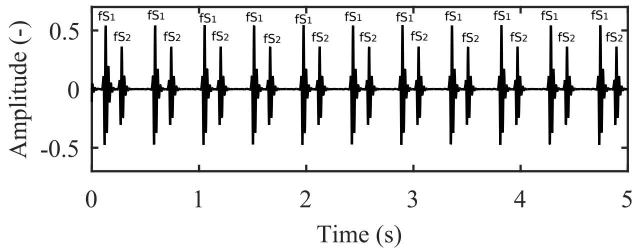

Fig. 7: The reference ideal synthetic fPCG signals based on real measurements from abdominal (S_A) sensors.

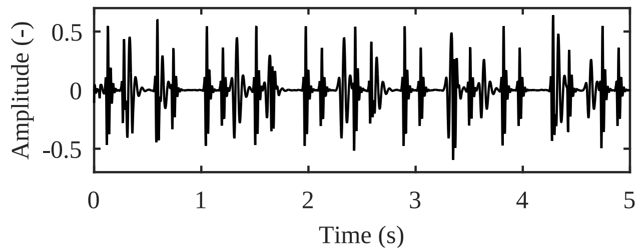

Fig. 8: Output of the adaptive NLMS system.

nent has been significantly reduced. This figure clearly shows that the elimination of the maternal component is not ideal; nevertheless, this component is reduced well under the level of fPCG signals. Using the filtered signal, we can use conventional techniques [35], [36] and [37] to determine the fHR information from the fPCG signals.

Table 1 summarizes our experimental results. The performance of our adaptive system using the NLMS Algorithm was evaluated by finding the differences between input (SNR_{in}) and output (SNR_{out}) values as well as the objective measure known as the Percentage Root-mean-square Difference (PRD) [38].

Tab. 1: Statistical results of the tested NLMS Algorithm.

$\mathbf{SNR_{in}}$ (dB)	$\mathbf{SNR_{out}}$ (dB)	PRD (%)
−7	0.98	14.61
−6	1.12	13.14
−5	1.33	10.74
−4	1.43	9.98
−3	1.48	9.35
−2	1.57	7.9
−1	1.65	6.74
0	1.71	5.69
1	1.70	5.74

The SNR_{in} value can be calculated by using the following Eq. (4):

$$SNR_{in} = 10\log\left(\frac{\sum_{n=1}^{N-1}\left[sig_{usef}(n)\right]^2}{\sum_{n=1}^{N-1}\left[sig_{noise}(n) - sig_{usef}(n)\right]^2}\right), \quad (4)$$

where $sig_{usef}(n)$ is a desired signal (modelled reference course of S_T) and $sig_{noise}(n)$ is a noise signal (mPCG is measured up in the abdominal part - S_A).

The SNR_{OUT} value can be calculated by using the following equation Eq. (5):

$$SNR_{out} = 10\log\left(\frac{\sum_{n=1}^{N-1}\left[sig_{des}(n)\right]^2}{\sum_{n=1}^{N-1}\left[sig_{pre}(n) - sig_{usef}(n)\right]^2}\right), \quad (5)$$

where $sig_{pre}(n)$ represents a predicted (estimated) signal, or more precisely, the output from the proposed NLMS adaptive system and $sig_{des}(n)$ represents the desired signal.

$$PRD\,(\%) = \left(\frac{\sum_{n=1}^{N}\left[sig_{usef}(n) - sig_{pre}(n)\right]^2}{\sum_{n=1}^{N} sig_{usef}(n)}\right)\cdot 100. \quad (6)$$

One way to quantify the difference between the reference and the output signal: $sig_{pre}(n)$ is by using the PRD as given by equation Eq. (6) below:

4. Conclusion

In this article we focused on the validation of our novel patent-pending interferometric PPG-based sensor and its associated adaptive filtering system using the NLMS Algorithm for effective processing of aPCG signals to extract fPCG signals and fHR information. In the evaluations of the signal filtering quality of our system, we used objective parameters such as SNR and PRD.

The main reason why we chose the fiber-optic technology to develop our system was that it enables fHR monitoring without exposing the fetus to any radiation (in contrast to the ultrasound-based CTG method). Our innovative system offers a number of advantages including applicability to continuous long-term fHR monitoring without exposing the fetus to any radiation as well as compatibility with Magnetic Resonance Imaging (MRI) environments. The long-term monitoring capacity of our system is highly desirable, especially in those cases when the pregnant woman faces a dangerous situation (such as after an accident), and it becomes absolutely necessary to perform a time consuming MRI examination to ensure that the unborn fetus is intact and safe. The other specific advantage of our technology is that it can be used in water deliveries.

In our future research, we intend to use data from clinical practice to investigate a variety of challenging research topics such as the influence of sensor placement, fetal position and gestational age on aPCG signal filtering, fPCG signal extraction, and fHR monitoring.

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References

[1] MARTINEK, R., J. NEDOMA, M. FAJKUS, R. KAHANKOVA, J. KONECNY, P. JANKU, S. KEPAK, P. BILIK and H. NAZERAN. A Phonocardiographic-Based Fiber-Optic Sensor and Adaptive Filtering System for Noninvasive Continuous Fetal Heart Rate Monitoring. *Sensors*. 2017, vol. 17, iss. 4, pp. 1–26. ISSN 1424-8220. DOI: 10.3390/s17040890.

[2] MARTINEK, R., R. KAHANKOVA, H. NAZERAN, J. KONECNY, J. JEZEWSKI, P. JANKU, P. BILIK, J. ZIDEK, J. NEDOMA and M. FAJKUS. Non-Invasive Fetal Monitoring: A Maternal Surface ECG Electrode Placement-Based Novel Approach for Optimization of Adaptive Filter Control Parameters Using the LMS and RLS Algorithms. *Sensors*. 2017, vol. 17, iss. 5, pp. 1–31. ISSN 1424-8220. DOI: 10.3390/s17051154.

[3] RORIZ, P., L. CARVALHO, O. FRAZAO, J. L. SANTOS and J. A. SIMOES. From conventional sensors to fibre optic sensors for strain and force measurements in biomechanics applications: A review. *Journal of Biomechanics*. 2014. vol. 47, iss. 6, pp. 1251–1261. ISSN 0021-9290. DOI: 10.1016/j.jbiomech.2014.01.054.

[4] DZIUDA, L. Fiber-optic sensors for monitoring patient physiological parameters: a review of applicable technics and relevance to use during MRI procedures. *Journal of Biomedical Optics*. 2015, vol. 20, iss. 1, pp. 1–23. ISSN 1560-2281. DOI: 10.1117/1.JBO.20.1.010901.

[5] CHETHANA, K., A. S. GURU PRASAD, S. N. OMKAR and S. ASOKAN. Fiber bragg grating sensor based device for simultaneous measurement of respiratory and cardiac activities. *Journal of Biophotonics*. 2016, vol. 10, iss. 2, pp. 278–285. ISSN 1864-063X. DOI: 10.1002/jbio.201500268.

[6] DZIUDA, L., M. KREJ and F. W. SKIBNIEWSKI. Fiber bragg grating strain sensor incorporated to monitor patient vital signs during MRI. *IEEE Sensors Journal*. 2013, vol. 13, iss. 12. pp. 4986–4991. ISSN 1530-437X. DOI: 10.1109/JSEN.2013.2279160.

[7] DZIUDA, L., F. W. SKIBNIEWSKI, M. KREJ and J. LEWANDOWSKI. Monitoring respiration and cardiac activity using fiber Bragg grating-based sensor. *IEEE Transactions on Biomedical Engineering*. 2012, vol. 59, iss. 7, pp. 1934–1942. ISSN 0018-9294. DOI: 10.1109/TBME.2012.2194145.

[8] FAJKUS, M., J. NEDOMA, R. MARTINEK, V. VASINEK, H. NAZERAN and P. SISKA. A Non-invasive Multichannel Hybrid Fiber-optic Sensor System for Vital Sign Monitoring. *Sensors*. 2017, vol. 17, iss. 1, pp. 1–17. ISSN 1424-8220. DOI: 10.3390/s17010111.

[9] NEDOMA, J., M. FAJKUS, P. SISKA, R. MARTINEK and V. VASINEK. Non-invasive fiber optical probe encapsulated into polydimethylsiloxane for measuring respiratory and heart rate of the human body. *Advances in Electrical and Electronic Engineering*. 2017, vol. 15, no. 1, pp. 93–100. ISSN 1336-1376. DOI: 10.15598/aeee.v15i1.1923.

[10] FAJKUS, M., J. NEDOMA, P. SISKA and V. VASINEK. FBG sensor of breathing encapsulated into polydimethylsiloxane. In: *Proceedings of SPIE: Optical Materials and Biomaterials in Security and Defence Systems Technology XIII*. Edinburg: SPIE, 2016, pp. 1–6. ISBN 0277-786X. DOI: 10.1117/12.2241663.

[11] FAJKUS, M., J. NEDOMA, S. KEPAK, L. RAPANT, R. MARTINEK, L. BEDNAREK, M. NOVAK and V. VASINEK. Mathematical model of optimized design of multi-point sensoric measurement with Bragg gratings using wavelength divison multiplex. In: *Optical Modelling and Design IV*. Brussels: Proceedings of SPIE, 2016, pp. 1–7. ISBN 978-1-5106-0134-5. DOI: 10.1117/12.2239551.

[12] TAN, B. H. and M. MOGHAVVEMI. Real time analysis of fetal phonocardiography. In: *IEEE Region 10 Annual International Conference*. Kuala Lumpur: IEEE, 2000, pp. 135–140. ISBN 0-7803-6355-8. DOI: 10.1109/TENCON.2000.888405.

[13] MOGHAVVEMI, M., B. H. TAN and S. Y. TAN. A non-invasive PC-based measurement of fetal phonocardiography. *Sensors and Actuators A: Physical.* 2003, vol. 107, iss. 1, pp. 96–103. ISSN 0924-4247. DOI: 10.1016/S0924-4247(03)00254-1.

[14] VARADY, P., L. WILDT, Z. BENYO and A. HEIN. An advanced method in fetal phonocardiography. *Computer Methods and programs in Biomedicine.* 2003, vol. 71, iss. 3, pp. 283–296. ISSN 0169-2607. DOI: 10.1016/S0169-2607(02)00111-6.

[15] LOPEZ-HIGUERA, J. M. *Handbook of optical fibre sensing technology.* 1st ed. New York: Wiley, 2002. ISBN 978-0-471-82053-6.

[16] GOODWIN, E. P. and J. C. WYANT. *Field guide to interferometric optical testing.* 1st ed. Bellingham: SPIE, 2006. ISBN 978-0819465108.

[17] DEVANE, D., J. G. LALOR, S. DALY, W. MCGUIRE, A. CUTHBERT and V. SMITH. Cardiotocography versus intermittent auscultation of fetal heart on admission to labour ward for assessment of fetal wellbeing. *Cochrane Database of Systematic Reviews.* 2017, vol. 2017, iss. 1, pp. 1–46. ISSN 1469-493X. DOI: 10.1002/14651858.CD005122.pub5.

[18] GRIVELL, R. M., Z. ALFIREVIC, G. M. GYTE and D. DEVANE. Antenatal cardiotocography for fetal assessment. *The Cochrane database of systematic reviews.* 2015, vol. 123, iss. 4, pp. 1–30. ISSN 1469-493X.

[19] KENNEDY, E. *Observations on Obstetric Auscultation: With an Analysis of the Evidences of Pregnancy, and an Inquiry Into the Proofs of the Life and Death of the Fetus in Utero (Classic Reprint).* 2nd ed. New York: Forgotten Books, 2015. ISBN 978-1332272440.

[20] AYRES-DE-CAMPOS, D., C. Y. SPONG and E. CHANDRAHARAN. FIGO consensus guidelines on intrapartum fetal monitoring: Cardiotocography. *International Journal of Gynecology & Obstetrics.* 2016, vol. 133, iss. 1, pp. 13–24. ISSN 0020-7292. DOI: 10.1016/j.ijgo.2016.02.005.

[21] NEDOMA, J., M. FAJKUS, L. BEDNAREK, J. FRNDA, J. ZAVADIL and V. VASINEK. Encapsulation of FBG sensor into the PDMS and its effect on spectral and temperature characteristics. *Advances in Electrical and Electronic Engineering.* 2016, vol. 14, no. 4, pp. 460–466. ISSN 1336-1376. DOI: 10.15598/aeee.v14i4.1786.

[22] NEDOMA, J., M. FAJKUS and V. VASINEK. Influence of PDMS encapsulation on the sensitivity and frequency range of fiber-optic interferometer. In: *Proceedings of SPIE: Optical Materials and Biomaterials in Security and Defence Systems Technology XIII.* Edinburg: SPIE, 2016, pp. 1–7. ISBN 978-1-5106-0392-9. DOI: 10.1117/12.2243170.

[23] FENDINGER, N. J. *Polydimethylsiloxane (PDMS): Environmental Fate and Effects.* 1st ed. Weinheim: Wiley-VCH Verlag GmbH, 2005. ISBN 978-94-009-1507-7.

[24] TODD, M. D., M. SEAVER and F. BUCHOLTZ. Improved, operationally-passive interferometric demodulation method using 3×3 coupler. *Electronics Letters.* 2002, vol. 38, iss. 15, pp. 784–786. ISSN 0013-5194. DOI: 10.1049/el:20020569.

[25] HAYKIN, S. S. *Adaptive filter theory.* 5th ed. New Jersey: Pearson Education, 2008. ISBN 978-0132671453.

[26] VASEGHI, S. V. and V. SAEED. *Advanced signal processing and digital noise reduction.* 1st ed. Berlin: Springer-Verlag, 2013. ISBN 978-3-322-92773-6.

[27] UNCINI, A. *Fundamentals of adaptive signal processing.* Cham: Springer International Publishing, 2015. ISBN 978-3-319-02807-1.

[28] FARHANG-BOROUJENY, B. *Adaptive Filters: Theory and Applications.* 2nd ed. Chichester: John Wiley & Sons, 2013. ISBN 978-1-119-97954-8.

[29] ZAZULA, D., D. DONLAGIC and S. SPRAGER. Application of Fibre-Optic Interferometry to Detection of Human Vital Sign. *Journal of the Laser and Health Academy.* 2012, vol. 2012, no. 1, pp. 27–32. ISSN 1855-9921. DOI: 10.13140/2.1.2033.4726.

[30] BRANDSTETTER, P. and L. KLEIN. Second Order Low-Pass and High-Pass Filter Designs using Method of Synthetic Immittance Elements. *Advances in Electrical and Electronic Engineering.* 2013, vol. 11, no. 1, pp. 16–21. ISSN 1336-1376. DOI: 10.15598/aeee.v11i1.800.

[31] ZHANG, D. Wavelet Approach for ECG Baseline Wander Correction and Noise Reduction. In: *IEEE Engineering in Medicine and Biology 27th Annual Conference.* Shanghai: IEEE, 2005, pp. 1212–1215. ISBN 0-7803-8741-4. DOI: 10.1109/IEMBS.2005.1616642.

[32] ALMASI, A., M. B. SHAMSOLLAHI and L. SEDHADJI. Bayesian denoising framework of phonocardiogram based on a new

dynamical model. *IRBM*. 2013, vol. 34, iss. 3, pp. 214–225. ISBN 978-1-4244-4121-1. DOI: 10.1016/j.irbm.2013.01.017.

[33] ALMASI, A., M. B. SHAMSOLLAHI and L. SEDHADJI. A dynamical model for generating synthetic Phonocardiogram signals. In: *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*. Boston: IEEE, 2011, pp. 5686–5689. ISBN 978-1-4244-4121-1. DOI: 10.1109/IEMBS.2011.6091376.

[34] MARTINEK, R., A. SINCL, J. VANUS, M. KELNAR, P. BILIK, Z. MACHACEK and J. ZIDEK. Modelling of fetal hypoxic conditions based on virtual instrumentation. *Advances in Intelligent Systems and Computing*. Paris: Springer, 2016, pp. 249–259. ISBN 978-3-319-29504-6. DOI: 10.1007/978-3-319-29504-6_25.

[35] MARTINEK, R., M. KELNAR, P. KOUDELKA, J. VANUS, P. BIKIK, P. JANKU, H. NAZERAN and J. ZIDEK. A novel LabVIEW-based multi-channel non-invasive abdominal maternal-fetal electrocardiogram signal generator. *Physiological Measurement*. 2016, vol. 37, iss. 2, pp. 238–256. ISSN 0967-3334. DOI: 10.1088/0967-3334/37/2/238.

[36] TANG, H., T. LI, T. QIU and Y. PARK. Fetal Heart Rate Monitoring from Phonocardiograph Signal Using Repetition Frequency of Heart Sounds. *Journal of Electrical and Computer Engineering*. 2016, vol. 2016, no. 2404267, pp. 1–6. ISSN 2090-0147. DOI: 10.1155/2016/2404267.

[37] CHETLUR ADITHYA, P., R. SANKAR, W. A. MORENO and S. HART. Trends in fetal monitoring through phonocardiography: Challenges and future directions. *Biomedical Signal Processing and Control*. 2017, vol. 33, iss. 1, pp. 289–305. ISSN 1746-8094. DOI: 10.1016/j.bspc.2016.11.007.

[38] BLANCO-VELASCO, M., F. ROLDAN, J. GODINO, J. BLANCO, C. ARMIENS and F. LOPEZ-FERRERAS. On the use of PRD and CR parameters for ECG compression. *Medical Engineering and Physics*. 2005, vol. 27, iss. 9, pp. 798–802. ISSN 1350-4533. DOI: 10.1016/j.medengphy.2005.02.007.

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