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Original Research Article

A new approach to ballistocardiographic measurements using fibre Bragg grating-based sensors

Łukasz Dziuda [*], Franciszek W. Skibniewski

Technical Department of Aeromedical Research and Flight Simulators, Military Institute of Aviation Medicine, Warsaw, Poland

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ABSTRACT

A method for acquiring a ballistocardiographic (BCG) signal from the feet of a standing person and the back of a sitting or lying patient is described. The measurements are carried out using in-house constructed fibre-optic sensors interrogated with a commercially available system. The sensor head consists of a fibre Bragg grating (FBG) attached to an elastic board that is placed between the monitored person's body and a soft surface, enabling the board to deform in an unobstructed way. The body's movements, including the BCG component, exert pressure on the board and make it deform along with the attached FBG. The changes to the Bragg wavelength are proportional to the body's movement and a BCG signal can be extracted from the obtained recording. The measuring capabilities of the sensors were evaluated by comparing the heart rate (obtained on the basis of the BCG signal) with the reference signal registered by an ECG recorder. An RMS value of the relative error is below 1.8% and statistical analyses show a satisfactory reconstruction of measurements. Tests carried out in the MRI environment proved the method to be immune to strong electromagnetic fields. The presence of the sensor in an MRI scanner does not affect the quality of imaging.

1. Introduction

Ballistocardiography (BCG) alongside some other methods belongs to mechanocardiographic (MCG) procedures for measuring low-frequency body vibrations caused by the heart [1]. Each cardiac cycle is a complex mechanical movement resulting from changes in the heart volume, its shape and its position inside the chest. Mechanical activity of the heart is visible on the outer surface of the chest in the form of mechanical vibrations. Mechanograms [2] can be recorded from various places in the body, as shown in Fig. 1.

Historically, BCG methods, among which direct and indirect measurements can be distinguished, appear first [3]. The first of these are carried out by applying the sensor directly into the easily accessible parts of the osseous system such as the head or knee [4]. Indirect measurements rely on recording movements of a specially designed bed with built-in sensors,

* *Corresponding author at*: Technical Department of Aeromedical Research and Flight Simulators, Military Institute of Aviation Medicine, ul. Zygmunta Krasińskiego 54/56, 01-755 Warszawa, Poland.
E-mail addresses: ldziuda@wiml.waw.pl (Ł. Dziuda), fskib@wiml.waw.pl (F.W. Skibniewski).

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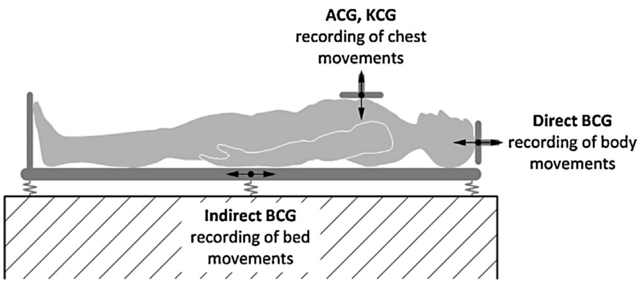

Fig. 1 – Locations of acquisition of mechanograms [1].

on which the monitored person lies. Later, the chest becomes the main location for MCG measurements, and apexcardiography (ACG), i.e., recording the heartbeat in the apex region, begins to play a significant role [5]. In this method, the reference point for the studied movement is the chest surface being away from the apex by a few centimetres, upon which the transducer housing can be fixed. This facilitates the measurement process, as it eliminates most of the artefacts caused by breathing and movement of the patient. Vibration measurements of the chest surface can be also realised in relation to an independent point, such as a stand placed beside the patient's bed. This method, known as kinetocardiography (KCG), enables the recording of the distribution of vibration across the chest [6]. Two methods exploring large veins and arteries during blood flow, i.e., sphygmography and phlebography, are also classified as MCG techniques [7].

In all of the methods mentioned above, the measurement concerns various parameters characterising the studied mechanical motion; hence, displacements, velocity and acceleration [5]. However, only the measurement of displacements allows for the direct interpretation of results; therefore, it was developed and used in clinical diagnosis for several decades. The clinical significance of MCG methods, intensively researched since the 40 s [2], noticeably decreased in the 80 s [8] after the introduction of new, more accurate techniques of testing heart mechanics, such as ultrasonography, computed tomography (CT) and magnetic resonance imaging (MRI). A major contribution to the abandonment of works on MCG was a large variety of signal shapes, depending critically on the method of recording. Different MCG morphologies impeded the comparison of results and were not conducive to the practical use of MCG at that time.

Currently, renewed interest is observed in the field of MCG, mainly BCG, due to the development of novel measurement techniques and data processing methods [8,9]. The latest literature describes a number of BCG devices including strain gauge bridge- [10], piezoelectric- [11], accelerometer- [12], load cell- [13], electromechanical film- (EMFi) [14], macrobending optical fibre- [15] and optical interferometer- [16] based sensors. It should be emphasised that most of the newly designed sensing solutions are intended for home monitoring rather than clinical use. This trend is associated with the rapid development of telemedicine systems [17], whose main task is monitoring vital parameters in patients during their normal life activities, and, if required, sending data to the medical personnel through the Internet or a GSM network [18]. Sensors can be embedded into beds, chairs, car seats, wheelchairs, toilet seats, bathtubs, bathroom scales, pillows, blankets or wearable textiles. Lying and sitting positions are ideal for monitoring basic vital signs such as heart activity. Despite the high vulnerability of BCG to any body movements, sections without motion artefacts can be extracted from long-term recording, enabling heart rate (HR) determination. An early detection of irregular heart rhythm or other abnormalities in the acquired BCG signal could lead to extensive medical examinations using advanced diagnostic tools.

The article presents the results of our consecutive works focused on a fibre Bragg grating (FBG)-based sensor for monitoring cardiac activity. In relation to the sensor presented earlier [19,20], two current versions are simplified; one of them is designed to be immune to the electromagnetic (EM) field, and is thus suitable for the MRI environment. Both sensors enable monitoring that does not require any special wearable textiles, and avoids the need to carry out processes for preparing the patient. The BCG signal measurement capability of the sensors was evaluated in standing and sitting positions under laboratory conditions, and in the supine position during an MRI examination.

2. Background

2.1. *Fibre Bragg gratings*

A Bragg grating inscribed throughout holographic or phase mask exposure techniques [21] into the core of a single-mode optical fibre is the key element of the sensor. FBGs were accommodated initially in telecom applications, and later began to be used as sensors for monitoring structural health [22], conditions in electrical plants [23], biomedical parameters [24] and many other factors [25,26]. They are very attractive and widely used in sensory applications, mainly due to their excellent multiplexing and self-referencing capabilities, allowing several sensors to be addressed with one optical fibre cable. Additionally, due to spectral encoding, they are immune to optical signal intensity modulation. At the same time they offer the standard benefits of fibre-optic technology, i.e., EM immunity, intrinsically safe modes of operation, chemically inert natures, small sizes, and light weights.

The FBG acts as a stop-band filter, except for the fact that part of the incident light, I_{in}, is not stopped but is reflected from periodically arranged layers formed by the refractive index modulation. The reflected beams from each of the layers destructively interfere with each other unless they are all in phase. This only occurs at one wavelength, which is known as the Bragg wavelength (or the central wavelength), λ_B, and can be written as:

$$\lambda_B = 2n_{eff}\Lambda, \quad (1)$$

where n_{eff} is the effective refractive index of the fibre core [27] and Λ is the period of the refractive index modulation (sometimes referred to as the grating pitch).

Sensor systems involving FBGs usually work by injecting light from a spectral broadband source into the fibre, with the result that the grating reflects a narrow spectral component