Pressure transducer based on the phase characteristics of GMI effect for measuring the arterial pulse wave

L S Benavides¹, E Costa da Silva¹ and E Costa Monteiro²
¹Department of Electrical Engineering, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil
²Postgraduate Programme in Metrology, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil
E-mail: beth@puc-rio.br

Abstract. This paper presents a new technique for the measurement of arterial pulse waves, based on the development of a high-sensitivity pressure transducer. While previous investigations employed sensors based on the behavior of the magnitude of the impedance of Giant Magnetoimpedance (GMI) ribbon-shaped samples, this work highlights the importance of using the phase impedance characteristics of the GMI effect in order to increase the sensitivity. The new transduction system of pressure into voltage, for biomedical applications, is described, and the results of the pulse wave measurements from the carotid and radial arteries are presented.

1. Introduction

Transducers are devices capable of converting energy from one form to another. They provide an output quantity having a specified relation to the input quantity that affects their sensitive elements, the sensors [1]. Pressure transducers transform mechanical pressure into an electrical signal and can be used for control and monitoring in various application sectors; they can be classified according to their used transduction technique: Piezoresistive, piezoelectric, resonant, and optical [2]. Recent investigations, however, show that pressure transducer using magnetic sensors based on the giant Magnetoimpedance (GMI) present high-sensitivity [3-5].

The GMI effect is a large change in the impedance (magnitude and phase) of a ferromagnetic conductor subject to an external magnetic field when is excited by an alternating electric current. This effect is a result of the skin depth dependency with the magnetic permeability, which varies not only with the external magnetic field that is applied to the sample, but also with the amplitude of the current that passes through it [6]. GMI sensors present characteristics that are relevant for healthcare applications, including a low cost for scale production, high-sensitivity, operation at ambient temperature, portability and a wide range of operating frequencies [7].

In recent studies, some magnetic field transducers designed for measurement of the arterial pulse wave have been performed using the impedance magnitude characteristics of GMI sensors by employing a configuration which includes an incompressible chamber for mechanical transduction [3]. Further researches, however, indicated that phase-based GMI transducers are much more sensitive than the usual magnitude-based GMI transducers, increasing the sensitivity in at least 100 times [4]. Preliminary studies using this magnetic sensor based upon the impedance phase characteristics and magnetic markers [8], without a mechanical structure, revealed the promising potential of using the...
impedance phase characteristics of these sensors for pressure transduction with the high-sensitivity required for biomedical applications.

The most important characteristics that should be evaluated in the physical examination of the arterial pulse are frequency, rhythm, and amplitude; however, the recording of the arterial pulse wave, obtained with a measuring instrument allows the evaluation of relevant additional parameters for diagnostic purposes, such as the pulse wave contour. The physiological measurement of pulse wave velocity and the analysis of pulse waveform allow the assessment of the arterial wall properties, a relevant signal reflecting the arterial stiffness and the status of cardiovascular system [9]. The shape of the pressure pulse contour changes as it propagates from central to peripheral arteries of the cardiovascular system, presenting typical characteristics when measured at several locations throughout the body.

This work aims at developing a new pressure transducer based on the reading of the phase characteristics of GMI sensor elements, incorporating an incompressible chamber for mechanical amplification, intended to the non-invasive assessment of arterial pulse waveform and pulse wave velocity through the arterial vessels.

The new diagnostic instrumentation proposed here seeks to meet the essential aspects to be considered in metrology applied to the health sector, such as innocuity, non-invasiveness, accuracy, precision, low operation and production cost [7].

2. Materials and Methods
The sensitivity of the GMI sensor element used in the pressure transducer may be affected by parameters such as amplitude, frequency and DC level of the excitation current, composition and dimensions (length, width, thickness) of the GMI sample, the biasing magnetic field, among others [6]. Aiming at analysing the variations of the magnitude and phase of the impedance as a function of an applied external magnetic field, measurements for characterization were carried out in Co\textsubscript{70}Fe\textsubscript{5}Si\textsubscript{15}B\textsubscript{10} ribbon-shaped alloys with an average thickness of 60 μm, length of 2.5 cm and an average width of 1.5 mm. Previous investigations have examined the effect of the frequency and DC level of the excitation current on the sensitivity of the ribbons [4]. Such studies lead to the conclusion that the ribbons with characteristics similar to the sample used in this work, presented a maximum sensitivity for DC currents around 80 mA, superposed on a sinusoidal component with 15 mA of amplitude and 100 kHz of frequency. Thus, the GMI sample was excited with these parameters. The results of this characterization are presented and analysed in [5].

The idealized prototype of the transduction system of pressure into voltage, presented in Figure 1, contains an intermediate module based on a GMI magnetometer. A mechanical structure is responsible for converting pressure into magnetic field, and an electronic circuit is responsible for converting the magnetic field into a voltage output.

![Figure 1. Schematic description of the developed pressure transducer.](image-url)
The prototype structure includes an incompressible chamber for mechanical transduction. The pressure variation applied on a semi-rigid membrane is transmitted by the incompressible chamber and generates a displacement of the elastic membrane. This displacement moves the magnetic field source, a permanent magnet, in relation to a magnetic GMI sensor located on the base of the structure, causing a variation of the resulting magnetic field on the magnetic sensor. Following the signal processing chain, it is assumed that the field variation implies the change of the impedance phase of the sensor element, which is subsequently converted into voltage, by means of the electronic transducer circuit.

The determination of the sensitivity of the developed transducer was performed by applying different pressures on the transducer membrane. Thus, standard masses, ranging from 1 g to 100 g, were placed on the transducer membrane with an area of $0.71 \times 10^{-3}$ m$^2$.

3. Results
The high sensitivity of the developed transducer (0.26 mV/kPa) enabled its use in the non-invasive measuring of arterial pulse waves. Experimental measurements were performed by placing the transducer's semi-rigid membrane in direct contact with the volunteer's skin, in two regions of the body suitable for measurement of the pulse waves. The assessment of the carotid artery was achieved by positioning the device on either side of the front of the neck, just below the angle of the lower mandible; the measurement of radial artery pulse wave, in turn, was accomplished at a location of the wrist joint where this blood vessel crosses closer to the surface.

Fourier transforms of the carotid and radial pulse wave signals acquired directly from the output of the electronic circuit, in the time interval of 12 s, indicated no relevant spectral components at frequencies above 10 Hz for the physiological signal generated by the pulse wave. In order to reduce the influence of spurious spectral elements from various sources of noise/interference, the signals acquired directly from the output of the transduction circuit were post-processed by a digital filtering routine implemented in Matlab, based on a 6th order low-pass Butterworth filter, with 10 Hz cutoff frequency.

Figure 2 shows the pulse wave signals obtained after the digital filtering process. The signal quality improvement allows clear visualization of the morphological details of both the carotid (Figure 2a) and radial (Figure 2b) pulse wave contours.

![Figure 2. Pulse waveform signals measured with the developed GMI pressure transducer and post-processed by digital filtering, obtained from the carotid and radial arteries, respectively in (a) and (b).]
The morphology of the pulse waves measured using the developed GMI pressure transducer is evidenced (Figure 2), being possible to clearly identify the characteristic aspects of the signal associated with its measurement position in the arterial tree: the percussion wave, dicrotic notch and dicrotic peak for the carotid artery; and both the main and predicrotic peaks along with its dicrotic notch for the signal obtained from radial artery. These features are of great value for the diagnostic of cardiovascular diseases as well as for the monitoring of the effectiveness of therapeutic conduct.

4. Conclusions
In this work, a new measurement technique for arterial pulse wave recording is presented. The technique employs a high-sensitivity pressure transducer based upon the reading of the phase characteristics of GMI sensor element embedded in the prototype structure, which includes an incompressible chamber. The experimental results of the waveform records of the carotid and radial superficial arteries confirmed the possibility of a proper assessment of the characteristic details of the pressure wave's morphology using the developed system. The possibility of non-invasive measurements of the arterial pulse wave by means of the low-cost and high-sensitivity device proposed can contribute towards the efficiency in clinical diagnosis, adequate monitoring of treatments and prevention of cardiac disorders.

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