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A novel magnetic plethysmograph for non-invasive evaluation of arterial compliance

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Abstract— **Noninvasive evaluation of arterial compliance by measurement of Pulse Wave Velocity (PWV) has proven utility in cardiovascular screening. We present the design of a novel Magnetic PlethysmoGraph (MPG) for non-invasive estimation of PWV. The system uses a Giant Magneto Resistance (GMR) sensor to detect the fluctuations caused by blood flow in an ambient magnetic field encompassing the blood vessel. The design of an Electro Magnet (EM) based MPG transducer is presented. The ability of the proposed transducer to detect the blood pulse waveform is verified by in-vivo tests and an occlusion test. The design is further validated by demonstrating in-vivo measurements of carotid to radial artery PWV. The design of a dual element transducer for evaluation of local PWV is also presented. The proposed dual element plethysmograph is capable of measuring PWV over sections of the arterial tree as small as 15 mm.**

Keywords— **GMR sensor, blood pulse wave velocity**

I. INTRODUCTION

The Pulse Wave Velocity (PWV) is a clinically accepted measure of regional arterial stiffness whose utility in cardiovascular screening is well established [1]. Evaluation of PWV requires the measurement of two distinct blood pulse waveforms at two points on the arterial tree. The PWV between the two sites is then evaluated based on the distance D between the sites and the time difference, ΔT between the two measured waveforms as in (1).

$$\mathrm{PWV} = D / \Delta T \qquad (1)$$

The detection of the two waveforms, required for formal evaluation of PWV, could be performed using optical methods [2], pressure transducers [3] or even by advanced non-invasive imaging modalities such as ultrasound and MRI [4],[5]. We had previously demonstrated the utility of a Giant Magneto Resistance (GMR) sensor used along with a permanent magnet (PM) to detect the blood pulse [6]. Here, we present the design of an electromagnet (EM) based magnetic plethysmograph (MPG) for non-invasive detection of arterial blood flow. The capability of the proposed design to detect the blood flow waveform is illustrated by in-vivo tests and further verified by an occlusion test. An enhanced design of the single element MPG is used to measure the carotid to radial artery PWV. The design of a novel dual element transducer for measuring local PWV is also discussed.

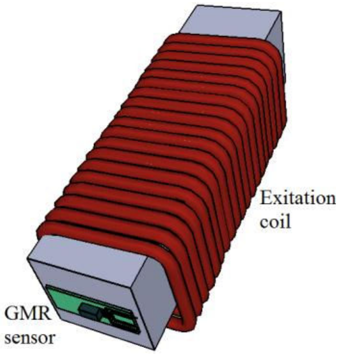

Figure 1. Design of an electromagnet based single element MPG transducer.

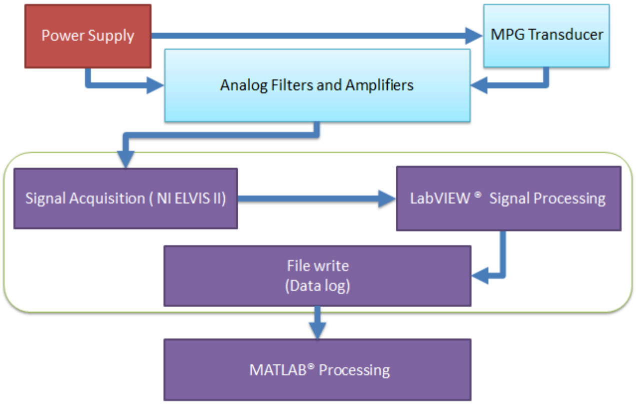

Figure 2. System architecture of the MPG

II. SINGLE ELEMENT MPG TRANSDUCER

A. Design

The design of a single element transducer MPG is shown in Fig. 1. A magnetic core of length 3.3cm was used in this design. The transducer uses a cylindrical coil with 600 turns to create an ambient field which encompasses the artery being measured. The field is also adjusted to bias the GMR field sensor (AAH002-02, NVE Corporation) in its linear region of operation [7]. The field sensor responds to the fluctuations created by the flow of the blood, in the ambient field created by the EM. The overall system architecture of the MPG is shown in Fig. 2. The system is implemented using the NI-ELVIS-II® hardware platform utilizing LabVIEW® software (National Instruments).

The EM coil is excited with a dc supply voltage. The coil excitation voltage is selected such that field sensor is biased in its linear region of operation while also ensuring that the magnetic field links with the blood vessel underneath the

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skin below the sensor. The system architecture programmatically ensures this trade-off, preventing the coil excitation from neither being too low or too high. The field sensor output is then filtered, amplified and captured at the rate of 4 kS s^{-1} with a resolution of 16 bits per sample. All the necessary filtering & amplification is done with a dedicated analog circuitry and further processed in LabVIEW®. Typical signal outputs from the radial and carotid artery are shown in Fig. 3 and Fig. 4 respectively.

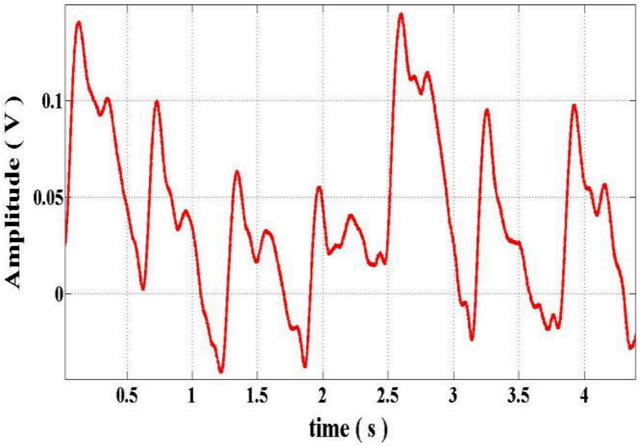


Figure 3. Magnetic plethysmogram obtained from the radial artery

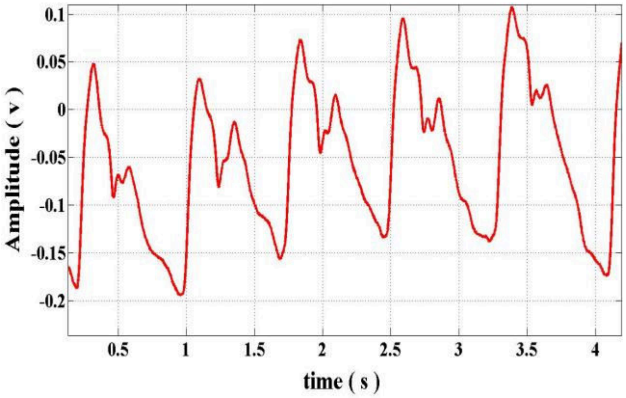


Figure 4. Magnetic plethysmogram obtained from the carotid artery

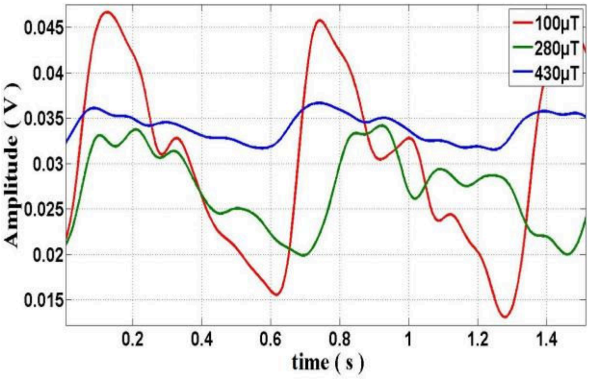


Figure 5. Influence on bias field on the shape and amplitude of the MPG signal

B. *In-vivo tests: Comparison with PM based transducer*

An electro magnet (EM) based MPG has more flexibility than a permanent magnet (PM) based design. The EM based design presented here provides the designer with a better control over the field strength and thus in turn provides a smarter way to fix the bias field for the sensor. In a PM based design, the relative geometry of the system has a huge impact on the output quality. The use of an EM field source, relaxes the constraint over source-sensor relative geometry, which helps in designing a more compact system. The influence of the variation of the bias field on the shape of the detected signal is illustrated in Fig. 5. It can be observed that over the linear range of operation (less than 300µT), the output shape remains more or less similar. This is an advantage over the PM design, where the shape of the output showed significant variations with different bias field [6].The signal amplitude drops once the magnetic bias field intensity is outside the linear range.

C. *Occlusion Test*

The clinical significance of the waveform detected by the MPG transducer has already been studied to illustrate that the detected signal is strongly related to the volumetric changes of the arterial blood in the vicinity of the sensor [6], [8]. To functionally verify that the EM based MPG transducer indeed detects the blood flow pulse, an occlusion test was performed. The single element MPG transducer was positioned over the radial artery to detect a stable pulse waveform. Then the blood flow was occluded using an inflatable cuff over the brachial artery. The results of the experiment are shown in Fig. 6. It can be seen that as the cuff pressure exceeds the systolic pressure, the artery is occluded and thus the MPG pulse vanishes. As the cuff pressure is released to a value less than the diastolic pressure, the blood flow gets re-established, which confirms the reappearance of the of a stable MPG waveform. This occlusion test illustrates that the MPG indeed detects the blood volume pulse.

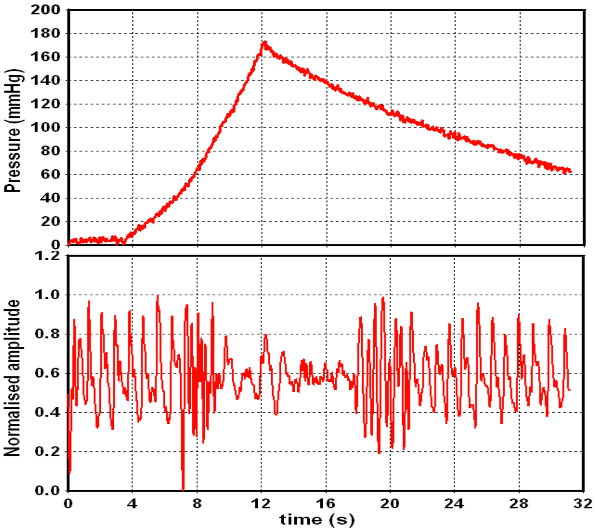


Figure 6. Occlusion test shows the MPG signal vanishing as the cuff pressure exceeds the systolic pressure.

D. Evaluation of arterial compliance using a pair of MPG transducers

A pair of single element MPG transducers was used to measure the carotid to radial PWV. One transducer was placed over the carotid artery, while the other was placed over the radial artery (The radial artery was chosen as preferred location rather than the femoral artery as the experiments were conducted in a laboratory facility and not in a clinical setting). The two MPG signals which were acquired simultaneously are shown in Fig. 7. It can be seen from Fig. 7 that the radial MPG lags behind the carotid MPG waveform. A semi-automated algorithm was used to identify the valleys of the waveforms and estimate the delay between the waveforms. The valleys detected in each of the two waveforms are also shown in Fig 7. The distance between the two sensors measured over the body surface was taken as the path length. Now, carotid to radial PWV was calculated using (1). The results of the radial to carotid PWV measurement performed on a few volunteers is summarized in Table I. The variation of the carotid to radial PWV over multiple cardiac cycles (for subject A) is illustrated in Fig. 8. It can be seen that the measured value of the PWV is consistent over multiple heart beats. The measured value of PWV was 11.7 ms^{-1} ± 0.9 ms^{-1} (mean ± standard deviation) which is within the expected range [10]. The precision of the measurement, estimated as the ratio of the standard deviation to the mean value of PWV, calculated over multiple cardiac cycles was found to be 8 %, which is acceptable for the estimation of arterial stiffness using PWV [11].

TABLE I. PULSE WAVE VELOCITY OF VOLUNTEERS

Volunteer	Age	Average of Pulse Wave Velocity ($ms^{-1)}$)
Subject A	22	11.7
Subject B	22	11.2
Subject C	23	11.7

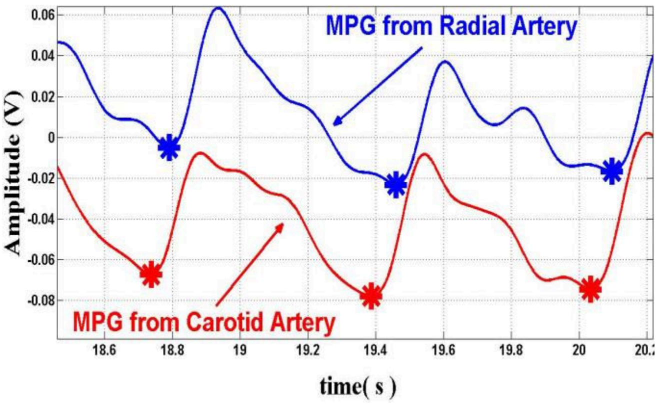


Figure 7. The MPG signals measured simulatneously from the carotid and radial arteries plotted for three beat cycles. The asterisk points indicate valleys that were used for the calculation of PWV in these cycles.

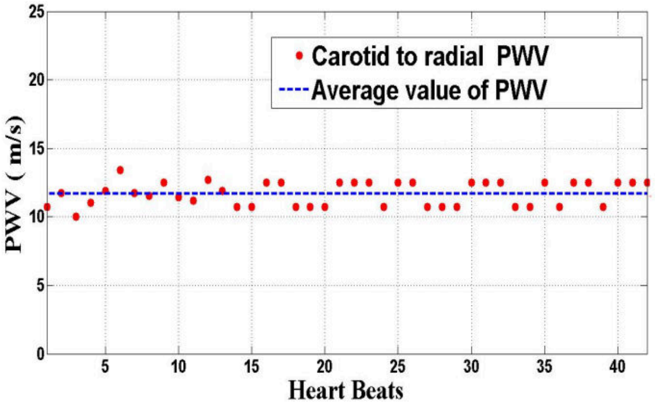


Figure 8. Beat to beat variation of carotid to radial PWV of subject A.

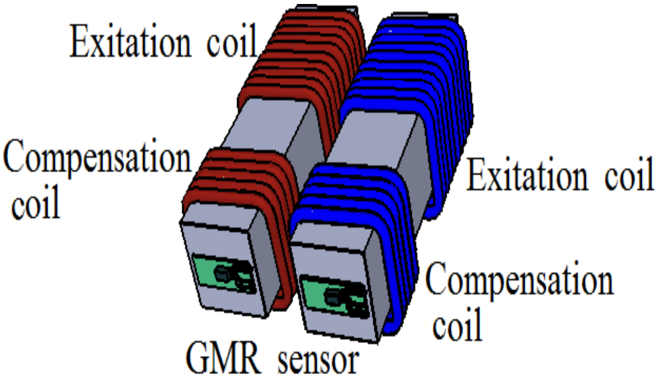
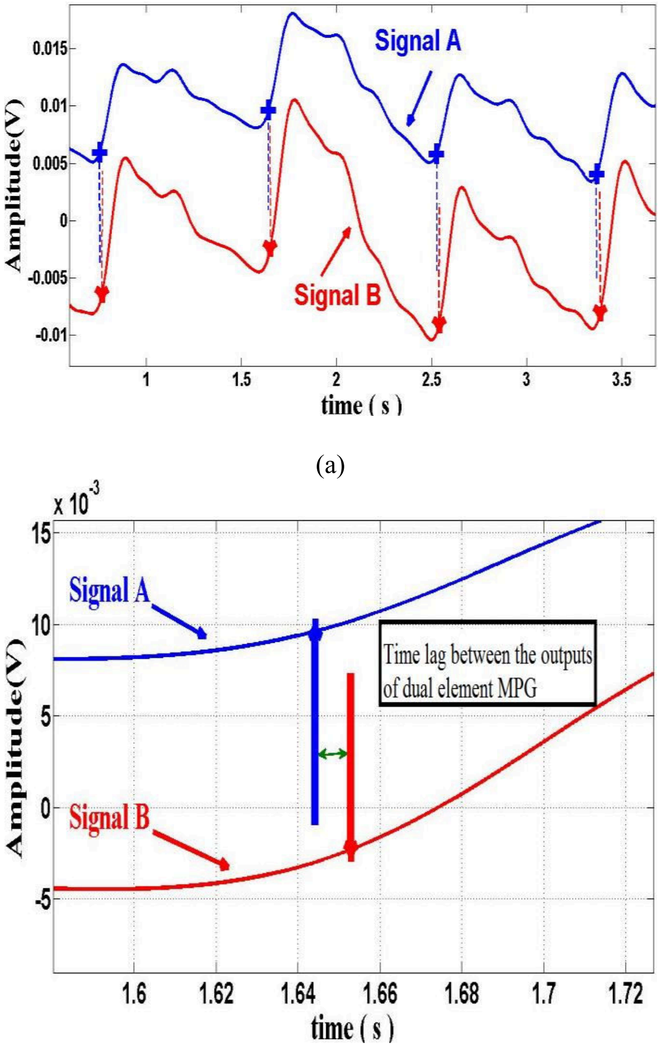


Figure 9. Design of a dual element MPG transducer

III. DUAL ELEMENT MPG TRANSDUCER

A. Design

The design of a dual element MPG transducer is illustrated in Fig. 9. The two field sensing elements are placed 15 mm apart and are provided with individual electromagnets (EM). Each EM has a main coil as well as a compensation coil. The main coil helps to generate enough flux lines to link to the artery underneath the skin. The compensation coil, wound on the same core, and positioned closer to the field sensor adjusts the field near the sensor to bring the sensor into its linear region of operation. The polarity of the compensation coil is reverse that of the exitation coil. The use of two coils in the electromagnet allows the generation of a field strong enough to link with the artery embedded beneath the skin while providing fine control over the field near the sensor to facilitate easy magnetic biasing. The compensation coil thus helps to programmatically nullify the external fields and relaxes the trade-off explained in Section II A. The number of turns in the compensation coil is 1/5th of that in the main excitation coil. The compensation and main coils can be independently excited. The number of turns in the main and the compensation coil for each sensor was kept identical to ensure uniformity in the behavior of the EM fields. The outputs from the sensors were processed independently, as performed in case of a single element MPG transducer.



(a)

(b)

Figure 10. The MPG waveforms measured at the carotid artery using the dual element transducer. The locations of the valleys in each cardiac cycle are indicated with a marker in (a). Magnified view of the waveform is shown in (b).

B. In- vivo test: Measurement of local PWV

The dual element MPG sensor was placed over the carotid artery of a subject. The MPG signals detected at the carotid artery are illustrated in Fig. 10 (a). The valleys of the waveforms were detected and are also shown in Fig. 10 (a). Signal B lags behind signal A. It's clearly illustrated in Fig 10 (b). It can be seen that the dual element MPG can detect two distinct blood volume signals at two points separated by 15 mm on the arterial tree. The measured value of the local PWV was 4.3 ms^{-1} which falls within the range of the reported values [9]. The EM based dual element MPG transducer is able to detect two distinct signals with a measurable time delay between them, and thus can be used for measuring local PWV. However, improvement in the overall design is required to enable the use of such a transducer in a clinical setting.

IV. CONCLUSION

The design of a novel, electromagnet based magnetic plethysmograph was presented. The ability of the proposed transducer to detect the arterial blood flow pulse was experimentally verified using in-vivo measurements and an occlusion test. The electromagnet based MPG offers better flexibility in design than a permanent magnet based transducer, while giving similar performance. A pair of electromagnet based MPG transducers was used to measure the carotid to radial PWV. The system could measure the carotid to radial PWV with a precision around 10 % during multiple in-vivo measurements, which is acceptable for evaluation of arterial compliance using pulse wave velocity. The utility of a novel dual element MPG transducer in detecting local PWV was also demonstrated by in-vivo trials.

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