

Enhancing Cardiac Magnetomechanical Sensing via a Tunable Non-Linear Spring Transduction Layer

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Summary:

Conventional wearable cardiac monitoring predominantly uses optical or electrical modalities, which are highly susceptible to skin variability and motion-induced noise. Here, we introduce a magneto-mechanical sensing approach that captures cardiac signals through skin vibrations mechanically coupled into a magnetic spring transduction layer. This tunable, non-linear interface improves mechanical coupling and signal amplification, promising more robust and sensitive heartbeat detection

Keywords: Pulsatility, Magnetics, Magneto Mechanical Transduction, Wearables, Contactless Coupling

Introduction

Cardiovascular diseases remain the leading cause of mortality worldwide, driving demand for continuous, non-invasive wearable monitoring technologies capable of capturing early physiological changes [1]. Mechanical vibration-based modalities such as ballistocardiography and seismocardiography enable unobtrusive sensing of cardiogenic micro-motions within the low-frequency physiological band (~ 0.5 – 5 Hz), offering rich information on cardiac mechanical dynamics

while avoiding optical attenuation and electrical contact limitations [2]. However, these approaches suffer from low signal-to-noise ratio, motion artifacts, and strong dependence on sensor placement and mechanical coupling, which significantly degrade reliability in real-world use. Existing solutions largely rely on signal processing rather than improving the physical sensing interface [2]. Magneto-mechanical sensing (MMS) provides a low-power alternative by converting vibration-induced displacement into measurable magnetic field variations [3], yet it has been rarely implemented with current designs employing fixed mechanical structures that limit adaptability and sensitivity. Here, a magnetic spring-based architecture is introduced to enable impedance-matched coupling to the skin while passively amplifying signals through non-linear stiffness oscillatory dynamics. This tunable compliance enhances displacement-to-field conversion by increasing mechanical response without active power input. Magnetic springs offer non-linear, adjustable compliance without mechanical wear, improving robustness to placement variability and noise [4]. This approach establishes a framework for mechanically amplified, magnetic biosensing in wearable cardiovascular monitoring.

Methods

The sensor (Fig.1) comprises a tunnel magneto-resistive (TMR) element positioned parallel to a disk Neodymium permanent magnet (Total

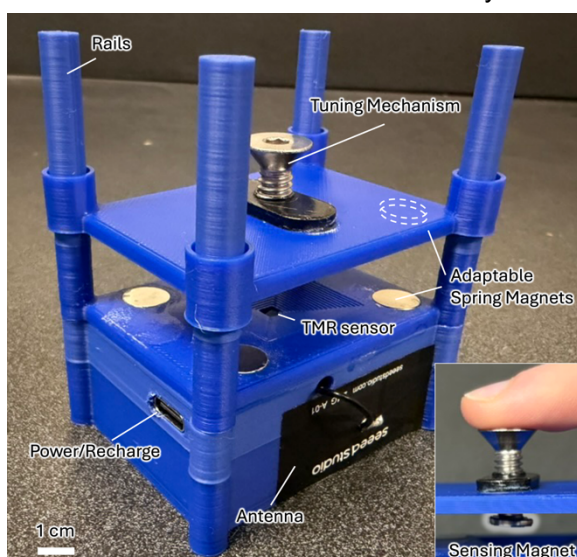


Fig. 1. Design of the tunable transduction mechanomagnetic Cardiac Sensor, showing the spring-mounted magnets and the tunable mechanism for precise transduction in the sensors' regime.

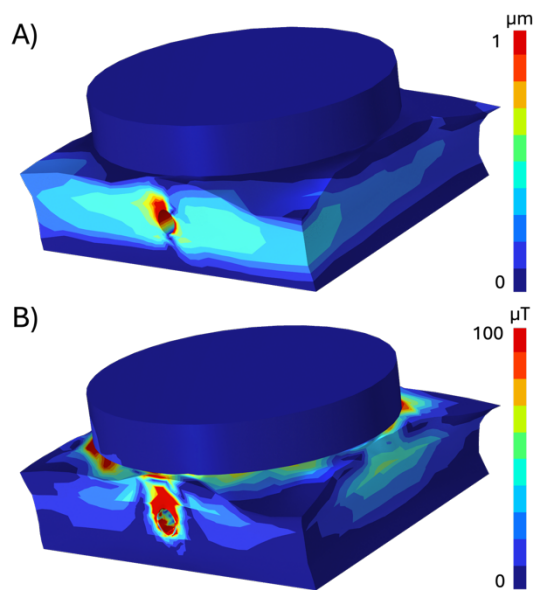


Fig. 2. COMSOL simulation of the expected displacement in rigid setup, when magnet is coupled to skin above a pulsing blood vessel. A) Change in Displacement B) Change in magnetic field

$$\mathbf{G} = \begin{pmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{pmatrix} \begin{matrix} \text{Displacement} \\ \\ \text{MagField} \end{matrix}$$

$$\mathbf{G}_{Sim} = \begin{pmatrix} 1376 & 51 & 614 \\ -265 & -10 & -118 \\ -199 & -7 & -89 \end{pmatrix}$$

Fig. 3. Tensor of Displacement/MagneticField relationship at the skin-magnet interface obtained from COMSOL simulation

Elements) which is mounted on a magnetically levitating platform held via rails. Cardiac-induced skin vibrations drive magnet displacement, modulating the local magnetic field and resistance of the TMR. COMSOL simulations were done to establish the transfer from the skin over a pulsing blood vessel and the sensing magnet upon contact (Fig. 2). Two models of the sensor were done: 1) using traditional fixed platform 2) using magnetic springs. Both devices' responses were characterized via palmar-recording and compared to ElectroCardioGram (ECG) obtained simultaneously through Apple Watch on the same arm (n=3). Signal to Noise Ratio (SNR) was evaluated via spectral analysis.

Results and Discussion

The simulations (Fig. 2-3) show a passive amplification of the mechanical displacement through the magnetic field of almost 3 orders of magnitude. Experimental results using both MMS recording systems show cardiac activity peaks matching Q peaks in ECG lead I (Fig. 4). Rigid transduction exhibits weak cardiac activity, yielding low-amplitude signals with correspondence

to ECG peaks (Fig. 4, top). The tunable magnetic spring markedly improves peak amplitude (~10x) and SNR of the system by about 11 dB while maintaining visible alignment with ECG (Fig. 4, bottom), indicating enhanced transfer of cardiac-induced skin vibrations no additional power cost. These results arise from nonlinear stiffness-mediated impedance matching, where distance-dependent restoring forces increase oscillatory amplitude and enhance displacement-to-field transduction. While promising, the approach remains limited to testing via mechanical pulsatility and further characterization is necessary, for validation of real-world robustness.

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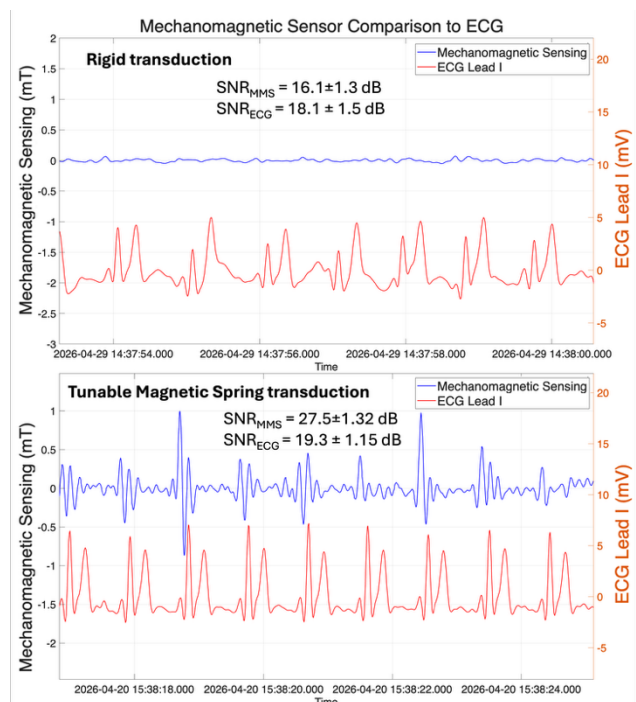


Fig. 4. Measured Comparison of rigid transduction to the tunable magnetic spring transduction. Peaks aligning with Lead I ECG are visible in both, but are more evident in the second by almost a factor of 10.