SENSITIVITY
NO

Carleton
UNIVERSITY

Canada's Capital University

OF A SINGLE COIL
N-CONTACT MONIT

Rosalyn Seeton
Department of Systems and
Carleton University,

ELECTROMAGNETIC
ORING OF BREATHI

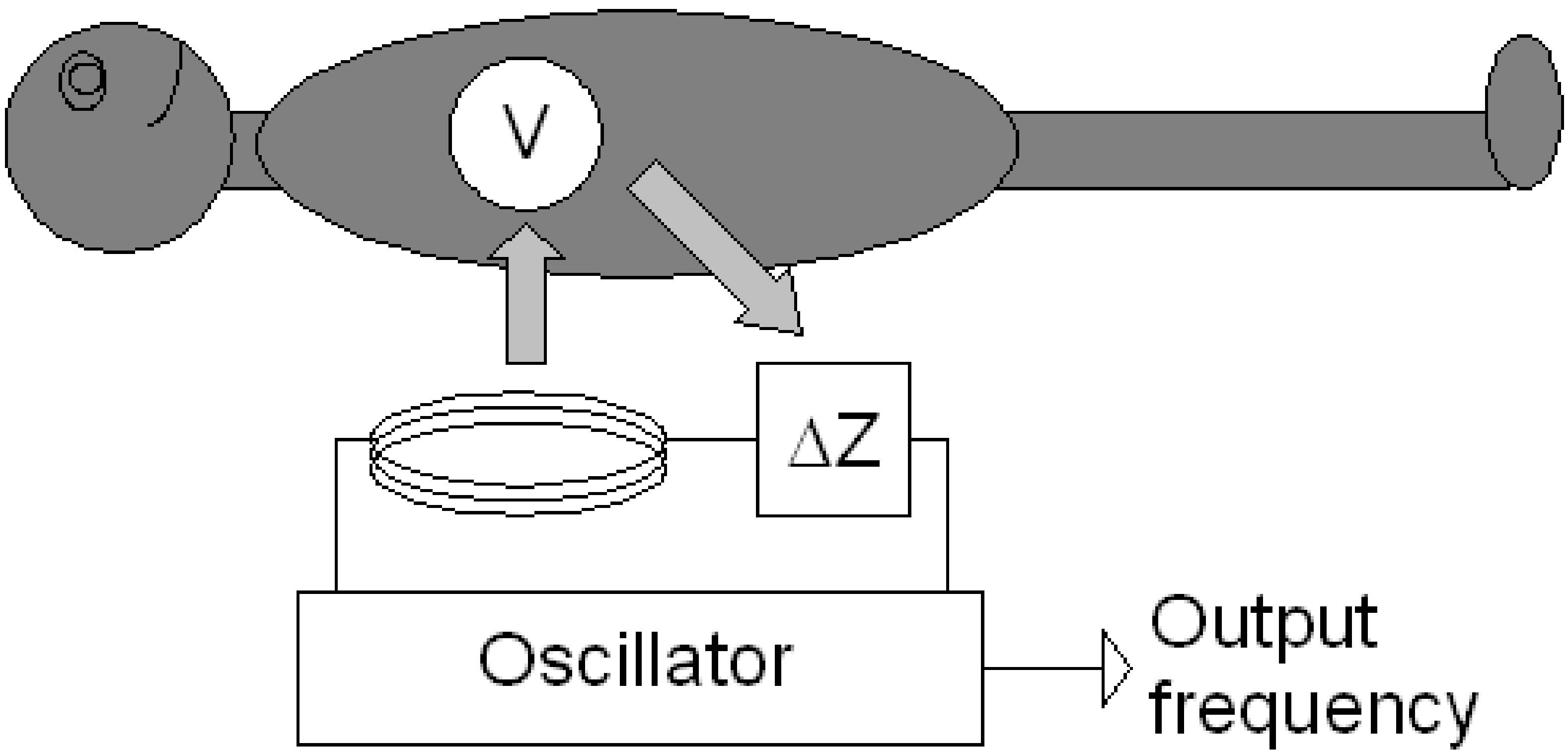
and Andy Adler
Computer Engineering
Ottawa, Canada

SENSOR FOR
NG

Abstract

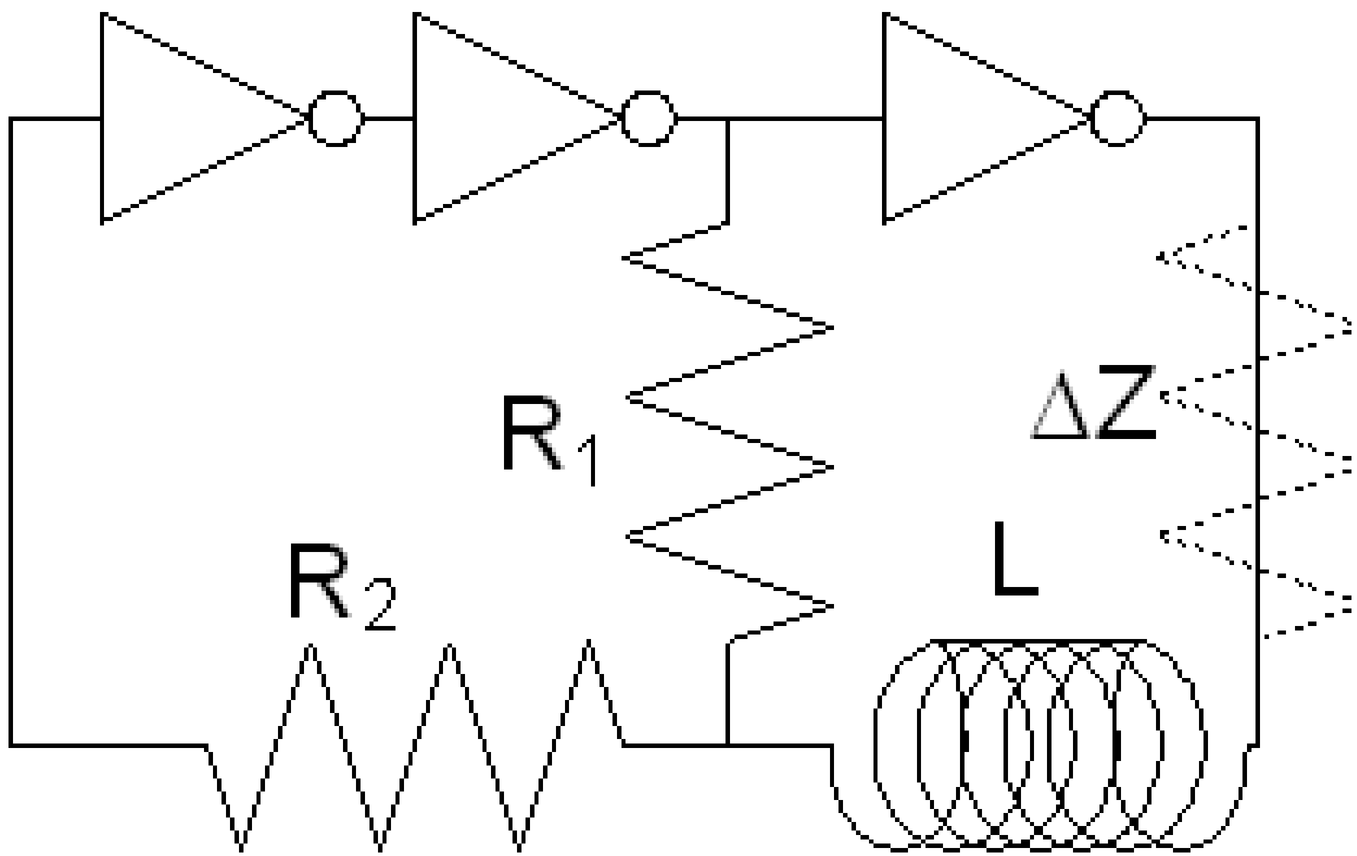
We design and analyse a flexible non-contact electromagnetic sensor for monitoring breathing. This paper presents the sensor design and the theoretical model for the expected sensitivity from which we optimize design components. The primary application of this device is in non-invasive sleep monitoring and it has

Experimental Setup

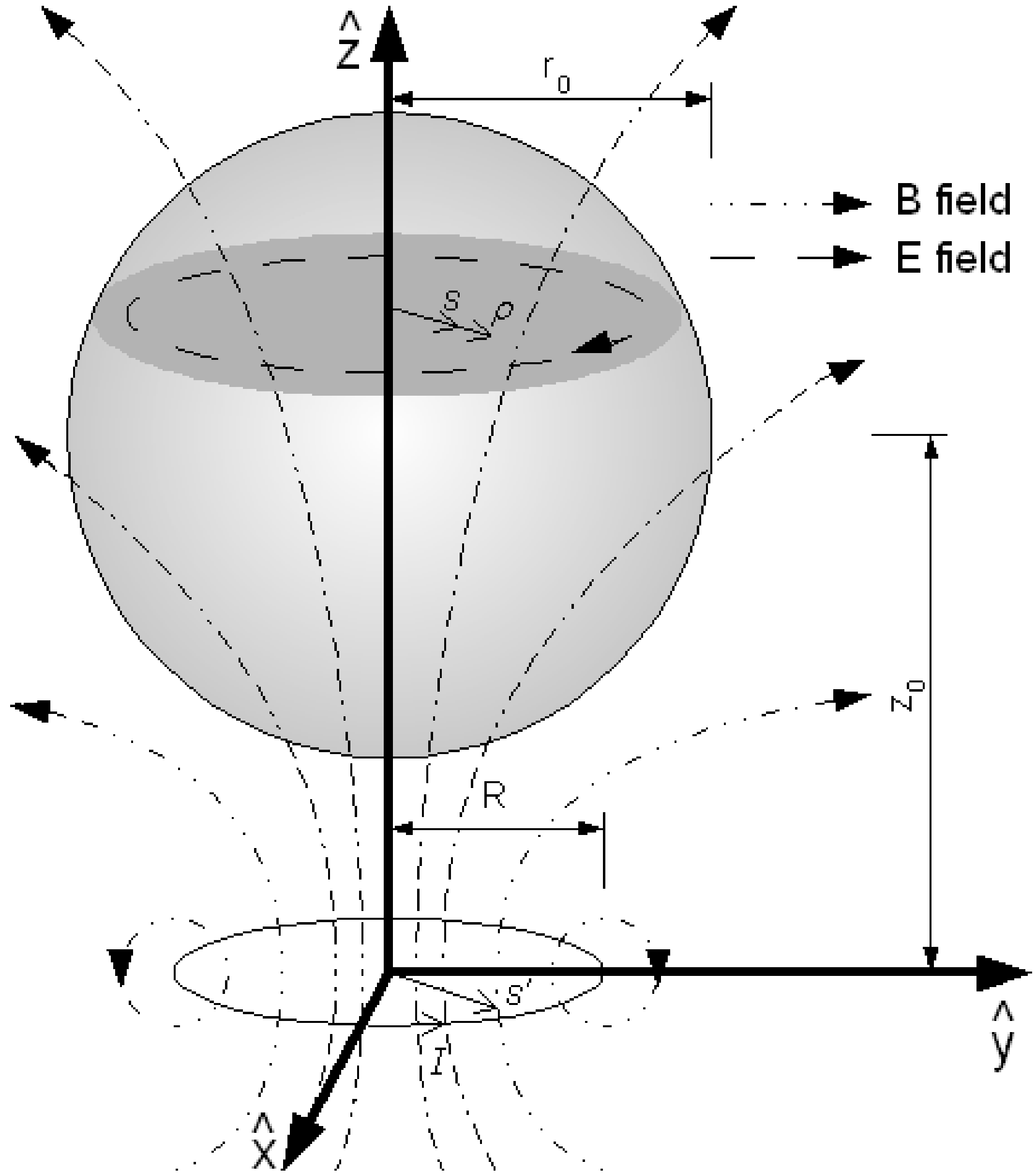


Electronic Design

LR Oscillator with $$f \approx \frac{R_1 + \Delta Z}{2L\ln 3}$$



Theoretical Model



the potential to be useful for detection of both adult and infant apnea. The conductivity changes of the lungs during breathing are monitored by inducing eddy currents within them. The sensor consists of a small coil that acts as both a transmitter and a receiver. The theoretical sensitivity of the sensor to breathing changes is calculated and corresponds within the assumptions of the model to the measured results.

Experimental Setup

- A single sensor is positioned in a mattress under the subject’s thorax such that the coil is flat with the axis pointing to the lung [Richer and Adler]
- The subject performs breathing manoeuvres and the conductivity in the thorax varies
- We model breathing as a change in conductivity over a spherical volume **V** representing the lung
- The physiological effects are seen by the sensor as a change in equivalent impedance of our coil and this alters the oscillation frequency

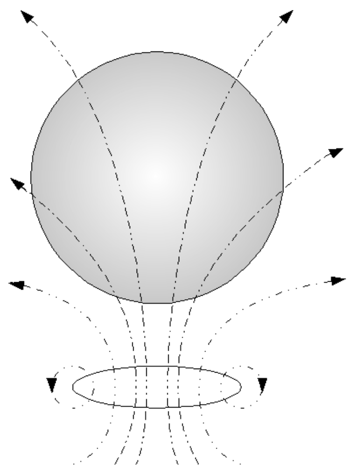
Electronic Design

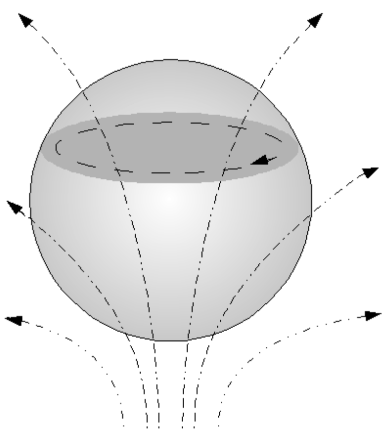
- Our sensor is constructed using a single coil within an LR circuit which oscillates due to an odd number of inverters
- Several LC oscillator circuits are also being investigated, particularly a Colpitts oscillator circuit using an Operational Amplifier
- Oscillations in the coil create eddy currents in conductive tissue which are seen by the circuit as a change in coil impedance from $j\omega L$ to $j\omega L + \Delta Z$ as represented by an additional dashed resistor

Theoretical Model

- To simplify our analysis we take the body to be a constant arbitrary shape, which we can therefore ignore, and we model the lung as a conductive sphere
- Our coil sensor is centred on the x-y axis below the sphere and carries an alternating current which creates electromagnetic fields as shown
- The theoretical model is derived from quasistatic electromagnetic theory and our analysis follows the same approach as Hart et al

Electromagnetic Analysis





- We use the Biot-Savart law to find the z component of the magnetic field within the sphere $B_z(s,z,t)=IB_z(s,z)$

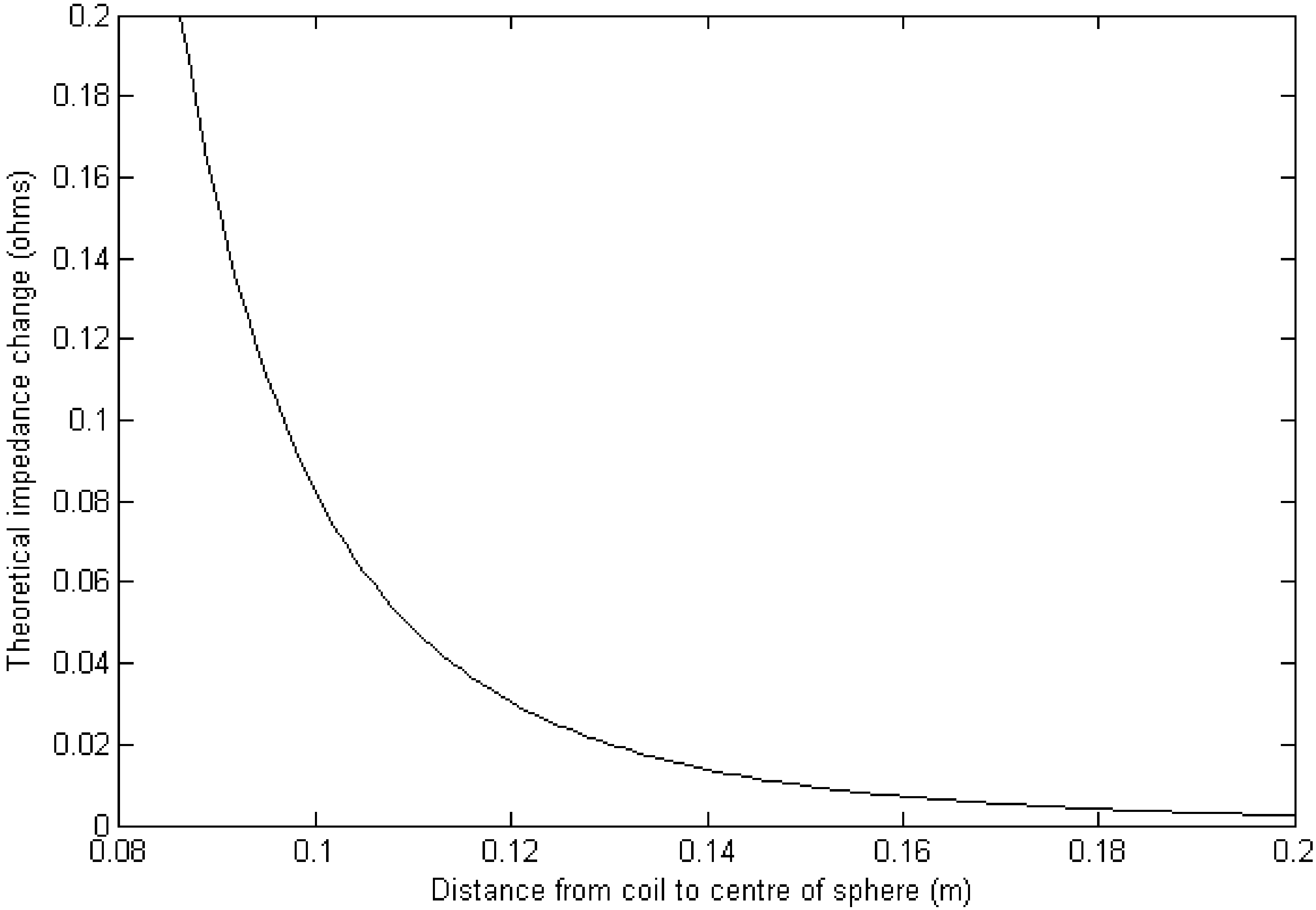
$$B_z(s,z) = \frac{\mu_0 NR}{4\pi}\int_0^{2\pi} \frac{(R - s\cos\phi)d\phi}{(s^2 + R^2 + z^2 - 2sR\cos\phi)^{3/2}}\hat{z}$$

- The electric field is found using Faraday's law

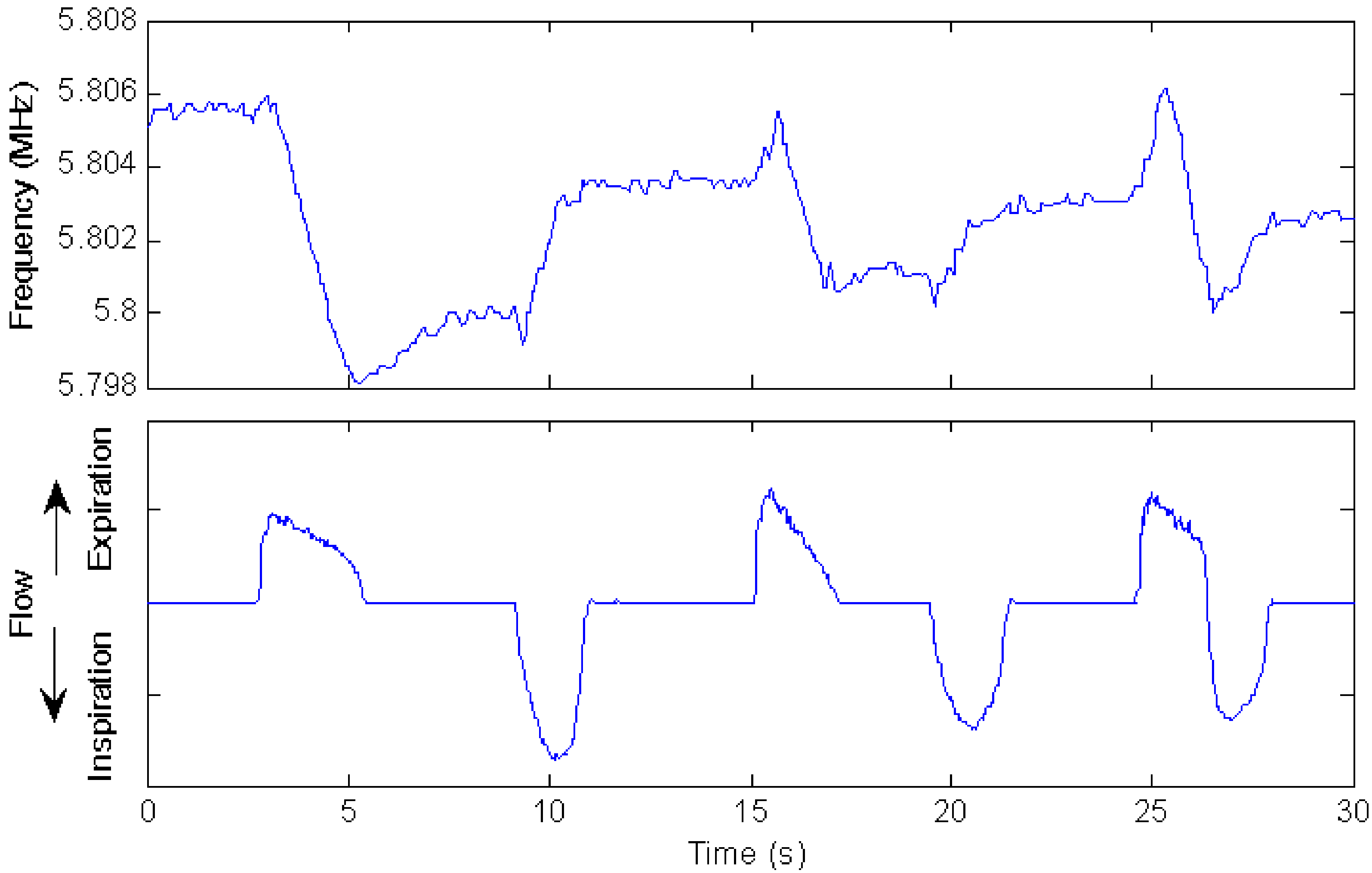
$$E(\rho,z,t) = \frac{-1}{\rho}\frac{dI}{dt}\int_0^{\rho} sB_z(s,z)ds\hat{\phi}$$

- The current density at each point is then given by Ohm's law

Theoretical Results



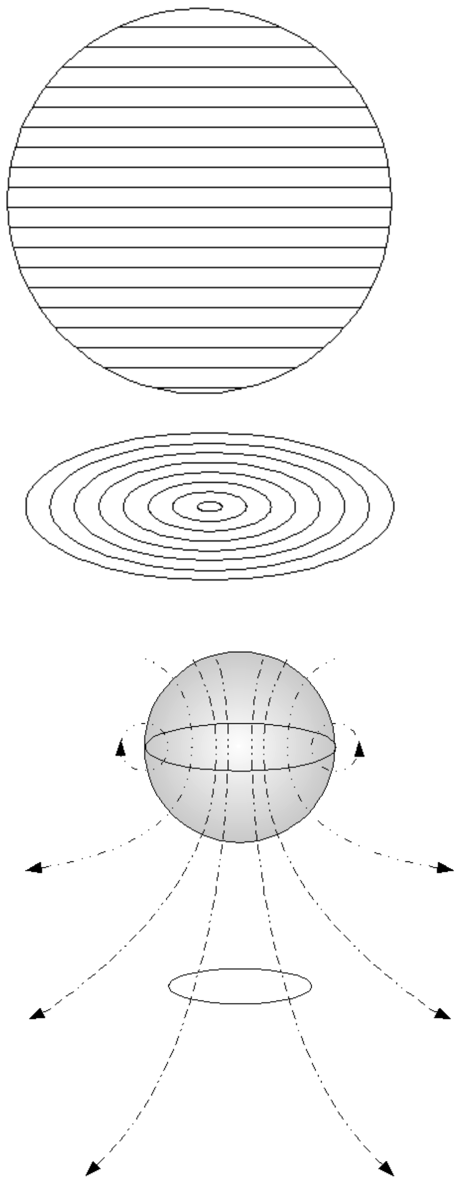
Experimental Results



Results

- A model of the sensitivity of a single coil electromagnetic sensors is derived
- The circuit components are optimized to maximize sensitivity
- Experimental results from measurements in healthy volunteers show plausible agreement with the theoretical predictions

Electromagnetic Analysis



- We break our conductive sphere into very thin disks and sum the current contributions from each
- Each disk is modeled as concentric eddy current carrying loops which we sum over the radius of the disk
- We project backwards and calculate the axial magnetic field induced at the plane of the coil by each element of eddy current

Theoretical Results

- The theoretical impedance change that the coil sensor will experience with our model is shown as a function of the distance from the coil to the centre of the conductive sphere
  - Coil radius R=0.035 m
  - Number of turns N=10
  - Frequency f=5.8 MHz
  - Sphere radius r=0.0842 m (one lung with 2.5 L volume change)
  - Sphere conductivity σ=0.18 S/m

Experimental Results

- The circuit oscillation frequency is shown for a subject during an episode of maximal lung manoeuvres (from Richer and Adler)
- Flow measurements, which are taken simultaneously with a pneumotach, are also shown
- Changes in sensor output correspond to inspiration and expiration manoeuvres as shown by the pneumotach output

References

1. A. Richer and A. Adler, ”Eddy Current Based Flexible Sensor for Contactless Measurement of Breathing”, in Instrumentation and Measurement Technology Conference, Ottawa, Canada, 2005, pp.257-260.

2. L. W. Hart, H. W. Ko, J. H. Meyer Jr., D. P. Vasholz and R. Joseph, A Noninvasive Electromagnetic Conductivity Sensor for Biomedical Applications, IEEE Transactions on Biomedical Engineering, vol. 35, no. 12, 1988, pp 1011-1022.

Electromagnetic Analysis

- The induced magnetic field causes a change in the magnetic flux inside a loop of the coil which manifests as an electromotive force (EMF) proportional to the number of loops in the coil
- The EMF can be seen by the coil as an effective series impedance ΔZ
- We have assumed that the permeability and the permittivity remain constant at their free space values and that the conductive sphere has isotropic and homogeneous conductivity and permittivity

Theoretical Results

- We want to maximize our relative change in frequency in order to optimize the sensitivity

$$\frac{\Delta f}{f} = \frac{\Delta Z}{R_1}$$

- The theoretical impedance change is a function of the coil radius and is proportional to the square of the frequency and number of turns

$$\Delta Z \propto f^2 N^2 F_R$$

- The frequency depends on the choice of resistor and the inductance of the coil

$$f \approx \frac{R_1}{2Lln3}$$

- Using Wheeler's formula for the inductance of an air core coil we find we need to choose the coil radius carefully, minimize the number of turns, and maximise the resistor value

Maximize $\frac{R_1}{N^2}\frac{F_R}{R^2}$

Experimental Results

- Note a frequency change of ~2 kHz from 18 to 23 seconds which corresponds to the subject inspiring to total lung capacity after residual volume
- Based on circuit values of $R_1=180\ \Omega$ and $L=14$ H, we calculate a change in impedance $\Delta Z \approx .062\ \Omega$
- According to our theoretical model, this would mean that the edge of the conductive sphere is at a distance of just over 2 cm from the sensor.
- The tissue thickness between skin and lung is approximately 5 cm, so this value is small, but in the right range, especially considering the number of assumptions in our theoretical model