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Inductive Feeding Tube Position Determination

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Abstract—A new, reliable and inherently safe nasogastric feeding tube position determination system has been developed. The system is particularly useful for preterm born infants. The system uses low-frequency transmit, reflection and receive coils. Transmit and receive coils are positioned in a handheld detection module in such a way that the mutual coupling is minimized, resulting in a good spatial resolution. The reflection coil is positioned at the distal end of the nasogastric feeding tube and uses a diode to double the frequency. The frequency doubling improves the detectability, making it possible to neglect reflected signals at the fundamental frequency. The design is based on analytical sub models and results in a detection accuracy of millimeters.

Index Terms—induction, mutual coupling, coupled coils, harmonic response, in body measurement.

I. INTRODUCTION

Tube feeding is practiced in medicine for patients that are unable to take oral feeding. Although usually considered an innocuous procedure, several studies have shown that blind placement of a nasogastric (NG) feeding tube can result in serious and even lethal complications due to misplacement [1, 2]. Current detection methods suffer from reliability problems [3] and those that are reliable may harm the safety of the patient. Examples of the latter are endoscopy and X-ray imaging. These methods are considered especially undesirable for preterm born babies.

New solutions are proposed using permanent magnets placed on the feeding tube [4], using electromagnetic field transmitters in the tube [5] and using electromagnetic resonators placed on or in the tube [6]. These systems are, in general, rather complex – e.g. using time gating [6] - to avoid interference from surrounding metal structures (bed).

Therefore, a new, reliable, easy-to-implement and harmless system for determining the feeding tube position has been developed. The system, especially aimed at preterm born infants, is based on inductive coupling, see Figure 1.

The Detection Module (DM) contains transmit and receive coils. The transmit coil transmits a localized low-frequency signal at a frequency f_0 that is picked up by a coil in the tip of the NG feeding tube. The frequency is doubled, using a non-linear device (diode), and a signal of frequency $2f_0$ is reflected and picked up by a receiver coil in the DM. This innovative frequency-doubling characteristic makes that interference from reflected f_0 signals is minimized. These reflections may originate from metal structures, like the bed frame, in the vicinity of the patient. Thus, a robust and reliable detection

system is created. Through scanning the body with the DM, the position of the NG feeding tube can be determined by finding the maximum received signal (at $2f_0$). Transmit and receive coils are realized as planar spiral coils and are positioned in a partly overlapping configuration to minimize the mutual coupling between the two [7]. In addition, this configuration results in high spatial selectivity for detecting the feeding tube. The ElectroMagnetic Reflector (EMR) is a small spiral coil, connected in series with a Schottky diode, that is wound around the tip of the NG feeding tube.

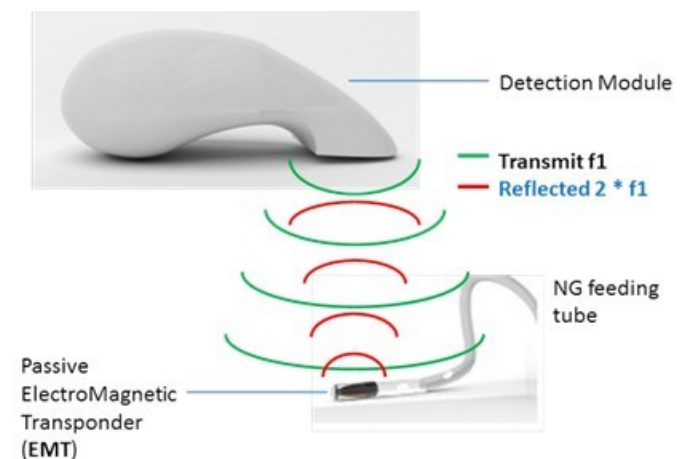


Fig. 1. Nasogastric (NG) feeding tube detection. Top: Schematic functioning of the system. Bottom: Using the realized detection system.

II. SYSTEM

The equivalent electric system of transmit, reflection and receive coils is shown in Figure 2.

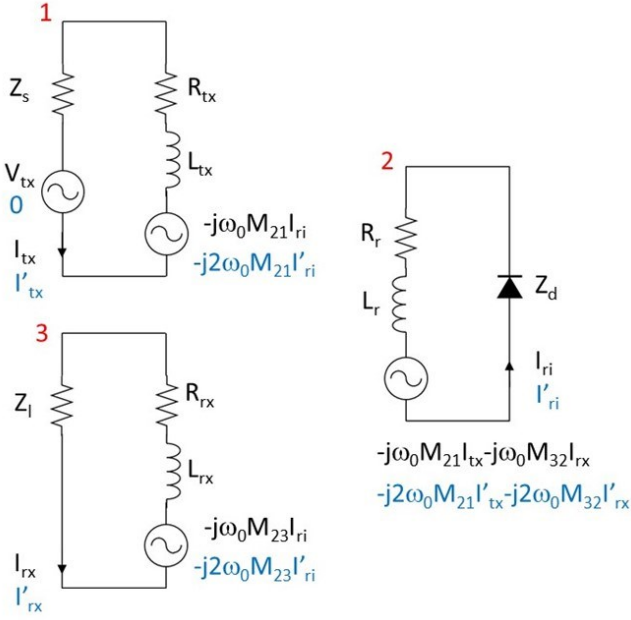


Fig. 2. Equivalent circuit model of the detection system. Black: at f_0 . Blue: at $2f_0$. 1 and 3 are the transmit and receive coils of the DM. 2 is the EMR.

In the Figure, two parameters sets are given: the black ones are for the system at a frequency f_0 (angular frequency ω_0) and the blue ones refer to a frequency $2f_0$ ($2\omega_0$).

Furthermore, V_{tx} is the source voltage. Z_s and Z_l are the source and detector internal impedances, respectively. R_{tx} , R_{rx} , R_r and L_{tx} , L_{rx} , L_r are the resistances and self-inductances of the transmit, receive and reflection coil, respectively. Z_d is the impedance of the diode. $M_{21}=M_{12}$ is the mutual inductance between transmit and reflection coil and $M_{23}=M_{32}$ is the mutual inductance between reflection and receive coil. The mutual inductance between transmit and receive coils is minimized by design, so $M_{13}=M_{31}=0$.

The system is described by

$$\begin{pmatrix} V_{tx} \\ 0 \\ 0 \end{pmatrix} = Z1 \begin{pmatrix} I_{tx} \\ I_{ri} \\ I_{rx} \end{pmatrix} \text{ for } \omega = \omega_0, \quad (1)$$

$$\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} = Z2 \begin{pmatrix} I'_{tx} \\ I'_{ri} \\ I'_{rx} \end{pmatrix} \text{ for } \omega = 2\omega_0,$$

where

$$Zi = \begin{pmatrix} (Z_s + R_{tx}) + j\omega_0 L_{tx} & -j\omega_0 M_{12} & 0 \\ -j\omega_0 M_{12} & (Z_d + R_r) + j\omega_0 L_{ri} & -j\omega_0 M_{23} \\ 0 & -j\omega_0 M_{23} & (Z_l + R_{rx}) + j\omega_0 L_{rx} \end{pmatrix},$$

$i = 1, 2.$

(2)

From equations (1) and (2), the current in the receive coil, I'_{rx} , can be calculated once all the impedances, resistances, self-inductances and mutual inductances are known.

III. ANALYSIS AND DESIGN

The self-inductance of a spiral coil is calculated using [8], that of a spring coil using [9]. The dc resistance is calculated using [10]. A low ac resistance is achieved by using Litz wire, designed using [11, 12]. The calculation of the mutual inductance between coils is based on the mutual inductance between two circular filaments, arbitrarily positioned in space [13]. The diode impedance is obtained using harmonic balance simulation.

First it was verified through calculation and measurement that the transmit and receive coils can be positioned such that the mutual coupling between the two reduces to practically zero ($M_{13}=M_{31}=0$), see Figure 3. This applies both to the fundamental frequency f_0 and twice that frequency $2f_0$ (for $f_0 < 5$ MHz).

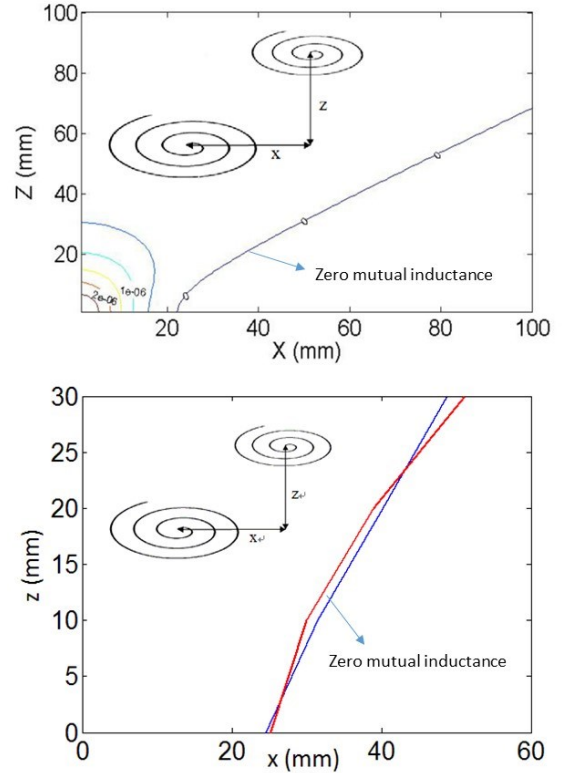


Fig. 3. Equi-mutual inductance contours. Top: calculation. Bottom: calculation and measurement. Spiral Tx and Rx coils. Diameter: 43.2mm, wire width: 1.1mm, 10 windings. Turn separation: 0.1mm. Tx coil: two layers, Rx coil: 1 layer. $f_0 = 100$ kHz.

The optimum operation frequency (f_0) is found from the relation between the received current at $2f_0$, the mutual inductances and the Schottky diode used. Analyzing I_{rx} vs. frequency for different choices of coil diameters and distances revealed that a maximum current is obtained for frequencies in the range of 100 kHz to 1 MHz.

Then, through optimizing various subsystems it was found, both theoretically and in practice that a feeding tube tip can be detected if the transmit and receive coils are within a distance of 5 cm from the feeding tube coil.

For the measurements, the transmit coil is connected to a signal generator, delivering a 5 V, 100 kHz sinusoidal signal. The receive coil is connected to a spectrum analyzer.

First, the relative positions of transmit and receive coil are determined such as to create a zero mutual inductance. In accordance with the results shown in Figure 3, this position is found for a horizontal (x) displacement of 25.2 mm and a vertical (z) displacement of zero. Transmit and receive coils are then fixed in this position. On top of this configuration a sheet of paper with a coordinate system is placed, see Figure 4. On top of that a foam support with a thickness (z) of 3mm is placed on which the feeding tube tip with EMR is placed, see also Figure 4.

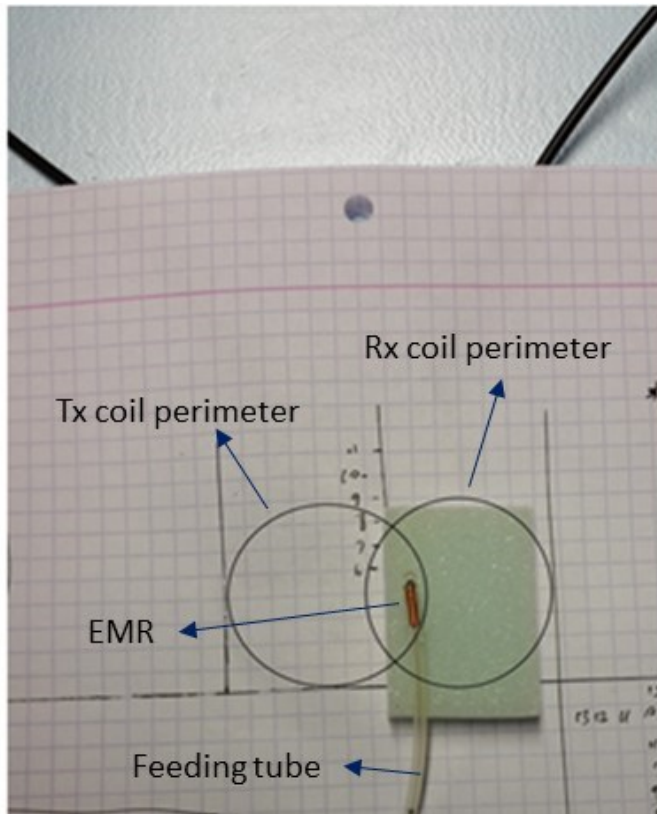


Fig. 4. Measurement setup. The Tx and Rx coil are fixed. On top, at a fixed distance $z = 3$ mm, the EMR can be moved in the plane parallel to the Tx and Rx coils.

Then, for different EMR positions in the plane $z = 3$ mm, the current amplitude at $2f_0$ is recorded. Figure 5 shows the

results as calculated (top) and as measured (bottom) in a 3D fashion.

The EMR is a spring coil with 110 windings in two layers. The diameter of the coil is 1.85 mm, the coil length is 8 mm and the wire diameter is 0.08mm.

The results show a fair agreement, both in shape and amplitude. The peaks are found at the intersections of transmit and receive coil, where the coupling, through the EMR and at $2f_0$, is strongest.

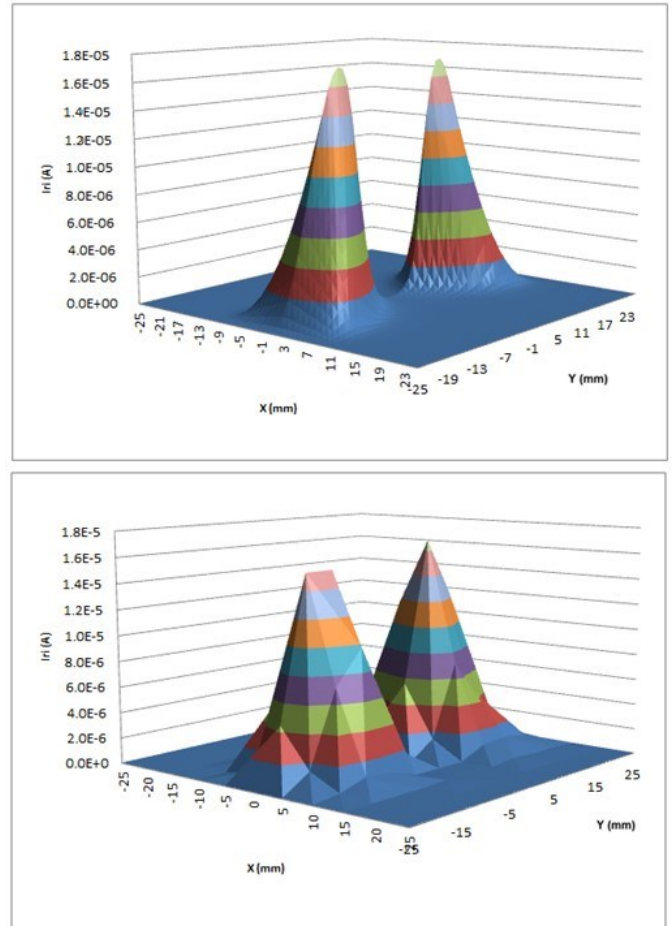


Fig. 5. Calculated (top) and measured receive current at $2f_0$ for the measurement setup shown in Figure 4. Tx and Rx coil dimensions as stated in the caption of Figure 3. $f_0 = 100$ kHz. The current is shown along the vertical (z) axis. The EMR is scanned in the x,y -plane.

The slightly lower peak current amplitude in the measurement results with respect to the calculated values is believed to be due to losses not accounted for in the calculations. One such a loss mechanism is the direct coupling between transmit and receive coil. In the calculations this coupling is assumed to be zero. In the setup, a small amount of power is still transferred directly from transmit to the receive coil.

Figure 6 shows the results in a top view with, superimposed on the current amplitude, the contours of transmit and receive coil. This Figure clearly shows the maximum current amplitude

for the EMR positioned at the intersections of transmit and receive coil. This high spatial resolution is an added advantage of the transmit and receive coil being positioned at their minimum for mutual inductance.

transmit-receive coil pair is rotated. Thus the maximum current detected corresponds to the EMR position.

IV. CONCLUSIONS

A new, reliable and inherently safe nasogastric feeding tube position determination system - particularly useful for preterm born infants - has been developed. It uses low-frequency transmit, reflection and receive coils. The reflection coil is positioned at the distal end of the nasogastric feeding tube and uses a diode to double the frequency. The frequency doubling improves the detectability, making it possible to neglect reflected signals at the fundamental frequency. The system can be designed using an equivalent electric circuit and analytic equations for self- and mutual inductances and resistances. First measurement results show the feasibility of the new detection method.

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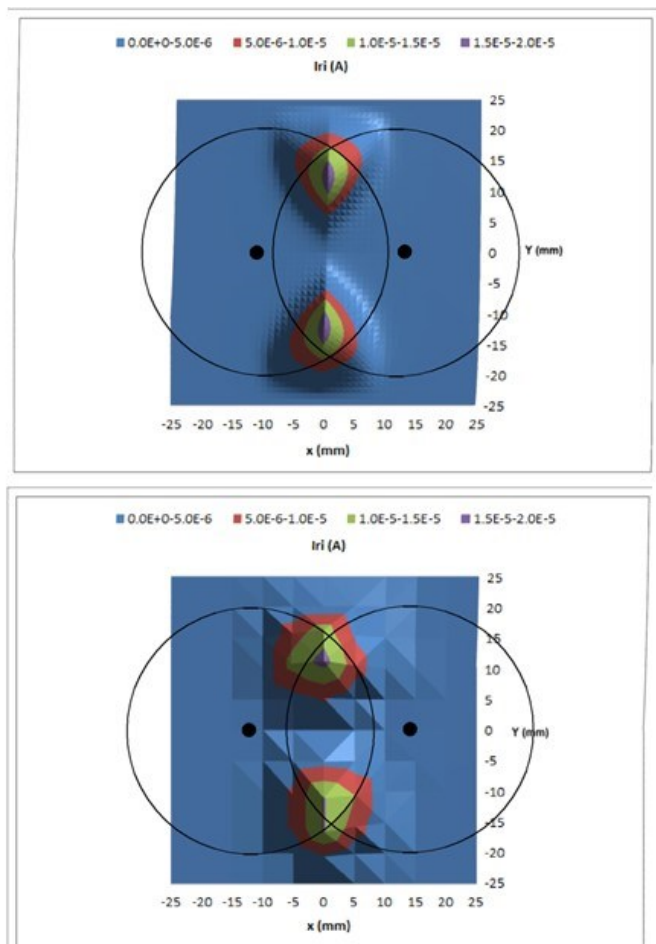


Fig. 6. Calculated (top) and measured receive current at $2f_0$ for the measurement setup shown in Figure 4. Tx and Rx coil dimensions as stated in the caption of Figure 3. $f_0 = 100$ kHz. The EMR is scanned in the x,y -plane. Top view of the graphs shown in Figure 5. The black circles indicate the contours of the transmit and receive coils.

In practice, while scanning the transmit and receive coils pair over the patient's torso, the position of the tip of the feeding tube can be accurately determined by searching for one of the current maxima shown in Figures 5 and 6. To avoid that the other maxima is mistakenly detected the coils are placed in the Detection Module, see Figure 1, such that the transmit coil is further away from the torso than the receive coil, i.e. the