Doctoral School on Engineering Sciences
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Extended summary

Respiration activity monitoring by use of electromagnetic waves

Curriculum: Electromagnetism and Bioengineering

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Abstract. Non-contact measurement of respiration activity, using Doppler or ultra wideband (UWB) radar techniques, is getting an important task in different medical services, in emergency rubble rescue radars, in active aging, ambient assisted living, in newborn monitoring and many other applications. Several tests were performed in order to demonstrate the feasibility of the proposed electromagnetic measurement method. It is based on the measurement of the phase variation of the total reflection coefficient signal S_{11}, using a vector network analyzer connected to a double ridge horn antenna aiming to the subject under observation. A laser Doppler vibrometry (LDV) is used as a reference measuring system. An electromagnetic model is developed in order to analyze the scattering problem, using appropriate analytical and numerical techniques. The numerical simulation activities are based on the use of CST Microwave Studio software, working in both frequency and time domain, and therefore suitable on evaluating the performance of the electromagnetic model. It allows fixing the electromagnetic characteristics in terms of permittivity, conductivity and magnetic permeability. The proposed model has been validated by comparing its results with the experimental measurements. The evaluation of the admittance matrix, specific for the considered human thorax model, permits a parametrical analyze, varying the antenna half power beamwidth and the position of the target in respect with the antenna maximal gain direction. This feature will be important for the design stage of the electromagnetic system.

Keywords. Admittance matrix, electromagnetic UWB radar, human thorax model, laser Doppler vibrometry, respiration activity.

1 Problem statement and objectives

Clinical practice often requires the continuous monitoring of some important physiological parameters of the patient vital signs. Among vital signs, the monitoring of respiration activity is particularly important in evaluating pathologies on the respiration activity and in preventing diseases such as the sudden infant death syndrome (SIDS) and the obstructive sleep apnea (OSA). The use of contact devices can be quite cumbersome, interfering with the usual patients actions and behavior. By using the electromagnetic radiation in the microwave region, it is potentially possible to monitor the cardio respiratory activity in a non-invasive way [1], mainly based on Doppler [2,3] or UWB [4,5] techniques. In most of the applications requiring cardio respiratory monitoring, the subject can be sitting, standing or lying in front of the antenna maximal gain direction. Different measurements, by changing the distance and the position of the subject, were performed. They are particularly important for the definition of the parameters for the design stage of the system. For this purpose an accurate electromagnetic model is necessary to describe the interaction of the electromagnetic waves with the human body. Accurate numerical techniques, such as the finite difference time domain (FDTD) or the method of moments (MoM), require high computational time, and are not suitable for a parametrical study of the electromagnetic scattering problem. A very simple one dimensional electromagnetic model has been proposed in [1] where the human thorax is described as a stratified medium [6]. Since a real antenna with a certain radiation pattern doesn't have infinite directivity, signals are reflected and captured from different parts of the body. When signals on different paths with different intensity and residual phases are received they are simply summed together by the receiving antenna, either cancelling out or enhancing the desired signal components. Therefore, a ray tracing model was developed in [7] to compensate for the shortage of the single beam model. A ray tracing based simulation model is more appropriate for high operating frequencies, as in [8], where a Ka-band Doppler radar was studied, and it doesn't take into account the electromagnetic interaction between the different parts of the human body.

2 Research planning and activities

2.1 Laboratory measurements of vital signs on healthy subjects

The measurement method used for the detection of the respiratory activity is schematically reported in (Fig. 1). A vector network analyzer HP-8753D is used to generate the output signal at 6GHz feeding the antenna with 1mW of input power. A broadband, double ridge, horn antenna (DRH) has been used to transmit and receive the electromagnetic waves. The antenna, which is well matched on the frequency range from 700MHz to18GHz, exhibits a mean half power beam width of about 30° in the horizontal H-plane and 48° in the vertical E-plane.

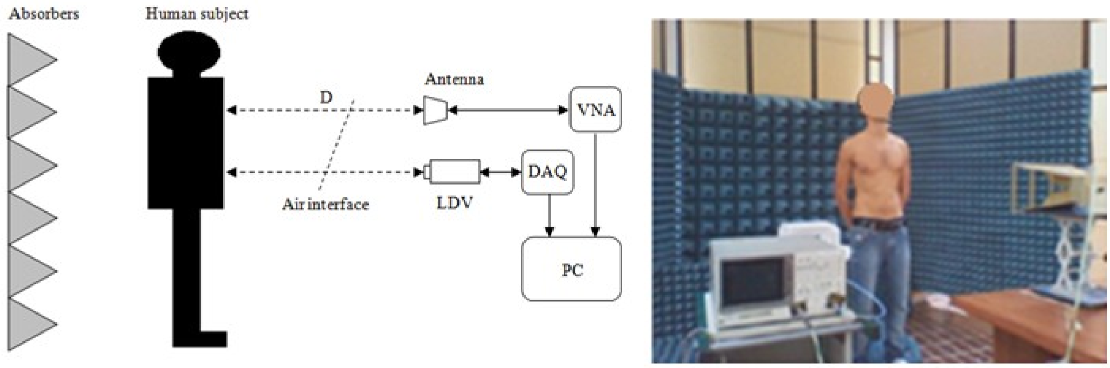

Figure 1. Scheme of the experimental setup of the electromagnetic system.

In order to have higher sensitivity the VNA measures the phase of the total reflection coefficient S_{11}, which gets modulated by the subject thorax displacement due to respiration activity. The subject thorax displacement has been simultaneously measured with a LDV. A possible limit of the LDV measuring system is the need to have a direct optical access to the skin of the subject. On the other hand using the electromagnetic system is possible to measure through clothes or tissues without significant signal disturbances. Different healthy subjects were asked to breath normally or to stay in apnea for a few seconds in order to monitor the heartbeat activity. The external cardiac region of the human thorax vibrates with 0.2mm to 0.5mm [9] in amplitude due to cardio activity and with a mean displacement 0.4cm to 1.2cm [10] due to respiration activity, as the respiration can be thoracic or abdominal depending on the position of the subject and on his physical conditions. Such properties of the cardio respiratory activity can be analyzed by an electromagnetic model, giving us the possibility to model the respiration act and to optimize the system parameters, in order to have a better signal to noise ratio (SNR) of the considered signal. Third harmonic respiration frequency problem has also been encountered, hiding the main heartbeat frequency. Measurements up to 2.5m has been held for the monitoring of the respiration activity. The chosen system's parameters allow to measure the heartbeat frequency at distances up to 50 cm. An appropriate design of the antenna would further improve the SNR and the vital detection range.

2.2 Electromagnetic model description

A hybrid model using analytical and numerical techniques is proposed, in order to analyze the interaction between the electromagnetic waves and the target. Rectangular metallic panel and dielectric geometries has been used to model the human thorax. The study of such simplified structure is necessary for the choice of numerical techniques that can be adopted for solving the electromagnetic problem, in terms of accuracy and computational efficiency and permits to analytically analyze the problem. This issue will be accomplished by experimental verification, using a measurement setup similar to the one shown in Figure 1, where the subject was replaced by the target chosen to model the human thorax. In order to avoid the null points problem, the target position has been slightly changed around the considered distance. The null points distance varies from 2.5cm at 3GHz to 3.75cm at 2GHz. Furthermore, the study of the electromagnetic problem was simplified by subdividing it in more elementary problems:

- Transmission and propagation of the electromagnetic energy. It will be analyzed by an analytical approach, modeling the transmitting antenna with an equivalent aperture.
- Interaction of the incident electromagnetic energy with the considered human thorax model. The coupling coefficient will be evaluated by appropriate numerical simulations and the induced current will be evaluated analytically.
- Reception of the scattered electromagnetic energy. The total reflection coefficient will be evaluated, taking into account the analytic effective length of the considered aperture.

Relating to the first problem, near field to far field transformation algorithms already exist in the literature and can be used for this purpose. The plane wave spectrum technique of the near field approximation requires a high number of plane waves in order to converge, consequently a high computational time. The far field properties of the radiated field from the used antenna was approximated to the far field properties of a rectangular aperture over a ground plane. The dimensions of the aperture were chosen so that it can have the same gain as the measured gain of the laboratory DRH antenna. The measured gain of the antenna at 1m of distance for the considered frequencies of 2GHz and 3GHz is respectively 8.6dBi and 8.9dBi and doesn't assume significant changes over the considered range.

The interaction of the incident field with the human thorax model was taken into account by evaluating the admittance matrix Y, which is specific for the considered geometry and operating frequency. Having the incident electric field E_q and the admittance matrix coupling coefficients Y_{pq}, the induced density current J_p can be evaluated for each sub-surface as:

$$\begin{cases} J_1 = Y_{11}E_1 + \ldots + Y_{1q}E_q + \ldots + Y_{1P}E_P \\ J_p = Y_{p1}E_1 + \ldots + Y_{pq}E_q + \ldots + Y_{pP}E_P \\ J_P = Y_{P1}E_1 + \ldots + Y_{Pq}E_q + \ldots + Y_{PP}E_P \end{cases} \tag{1}$$

where p, $q = 1 \div P$ and P is the number of the considered sub-surfaces. By using the radiation properties of a pencil beam antenna, analytically imported on the CST project, it was possible to illuminate only one of the sub-surfaces of the target, and to evaluate the coupling coefficient in (Eq. 1). The sea water, having a conductibility of 3.1 S/m and a relative permeability of 74 at a frequency of 2GHz, was used to test the human thorax model, having a penetration depth less than 1.5cm at the operating frequency.

The approach in (Eq. 1) reduces the scattering problem to the evaluation of the radiation far field properties of an elementary rectangular sub-surface, having a constant current density distribution as shown in (Fig. 2).

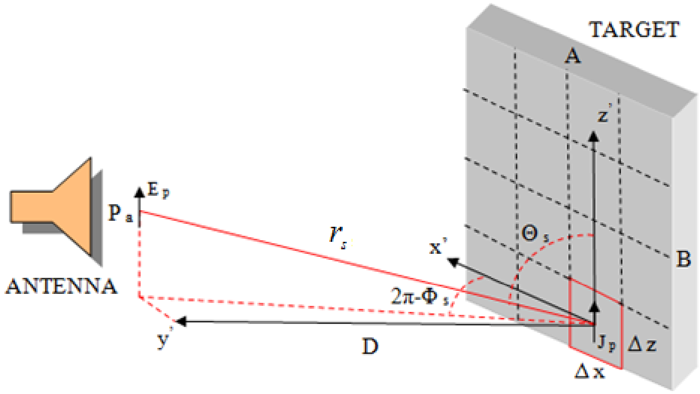

Figure 2. Scattered electric field by the *p*-th sub-surface.

The scattered electric field could be approximated as the sum of each elementary surface back radiation contribution, as the coupling coefficients are known. That gives a phase and magnitude variations of the total reflection coefficient S_{11}:

$$S_{11} = \Gamma_a + \frac{(1-\Gamma_a)}{E_0}\sqrt{\frac{\eta(1-|\Gamma_{ant}|^2)}{2Z_0 ab}}\sum_{p=1}^{P}\vec{E}_p(r_s,\theta_s,\phi_s)\cdot\vec{l}_{e,p}(\theta_s,\phi_s) \quad (2)$$

where Γ_a is the reflection coefficient of the antenna, Z_0 is the characteristic impedance of the connection cable, E_0 is the maximal electric field over the aperture plane, a and b are the equivalent aperture dimensions, E_p is the main component of the scattered electric field from the p-th subsurface and $l_{e,p}$ is the respective main component of the effective length vector of the antenna. It can be observed from (Eq. 2) that a reduction of the static component, due to the antenna reflection coefficient or to the static clutter, would increase the phase variations of S_{11}.

3 Analysis and discussion of main results

3.1 Measurement results of the respiration frequency

The mean respiratory frequency for each test has been calculated for both systems from the power spectrum of the measured signals. A db8 wavelet filter, of the fifth level for the VNA signal and of the tenth level for the LDV signal, was applied in order to reject the disturbances caused by motion artifacts, high frequency noise and heartbeats, on both measured signals in (Fig. 3a, d). The LDV velocity signal was integrated in order to obtain the surface displacement time history as in (Fig. 3e). A Fast Fourier Transform (FFT) was used to obtain the normalized power spectrum of the signals in order to evaluate and compare the main respiration frequency measured by considered systems.

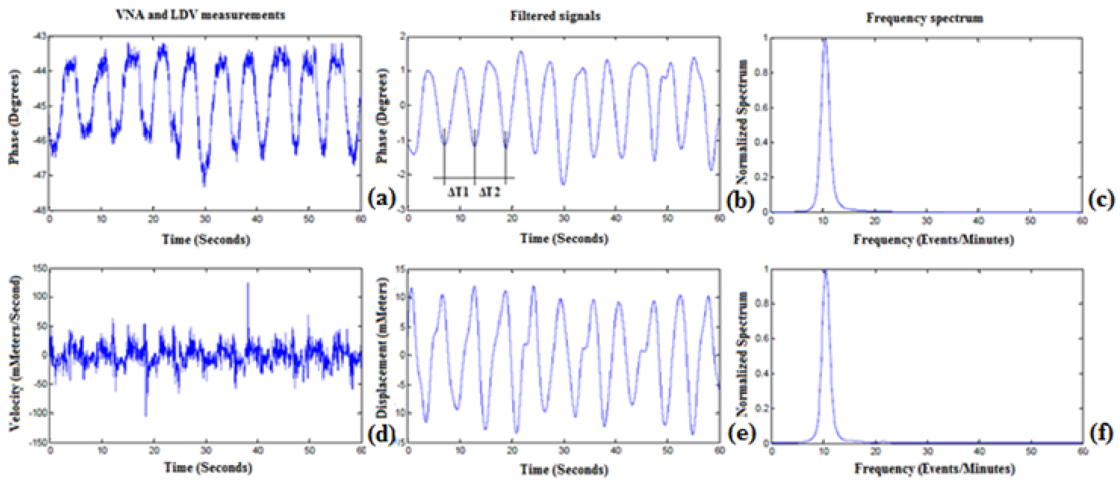

Figure 3. LDV and electromagnetic system measurement signals for a subject sitting at 150cm in front of the antenna. The original signal of the VNA (a) and LDV (d), the filtered signals (b) and (e) and the respective power spectrum (c) and (f) are shown.

Three tests, each of 60 s of duration, for different distances and positions, sitting, standing or lying in front of the antenna, were considered in order to study the electromagnetic system's response. In (Fig. 4), the scatter plot of the mean respiration frequencies measured by the LDV and the proposed electromagnetic system, together with the fitting line of the mean square is reported. In this case, the correlation coefficient calculated between the two systems is 0.97.

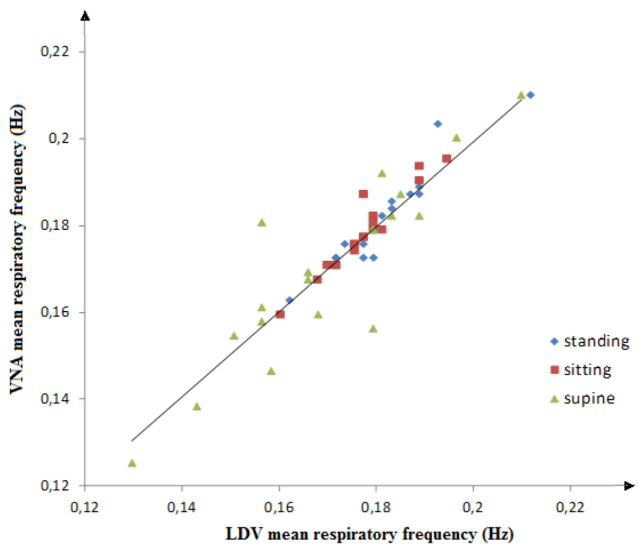

Figure 4. Scatter plot of mean respiration frequencies. LDV and proposed electromagnetic method results for the subject being standing, sitting and in supine position.

3.2 Electromagnetic model results

In order to validate the proposed model different scenarios were considered. Measurements of the total reflection coefficient at 2GHz and 3GHz were held in the considered distance range from 50cm to 2.5m. An example of the output model and experimental measurements results is shown in (Fig. 5). A metallic panel of 40cm x 40cm was placed at 2m of distance from the antenna, operating at 3GHz.

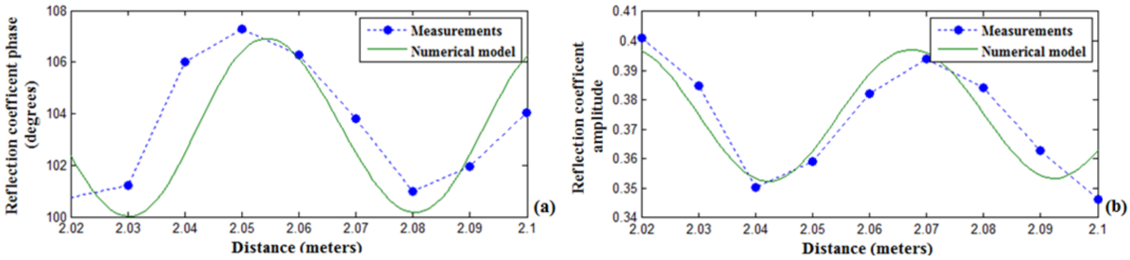

Figure 5. Example of model output results. Phase (a) and amplitude (b) of the total reflection coefficient S11 as defined in (Eq. 2).

The model validation is performed by comparing the phase variations of the total reflection coefficient, as shown in (Fig. 5a). The phase variations due to 1cm of displacement, over an optimal measurement point, for the metallic panel rotated to 10°, at the operating frequency of 2GHz, are reported in (Fig. 6).

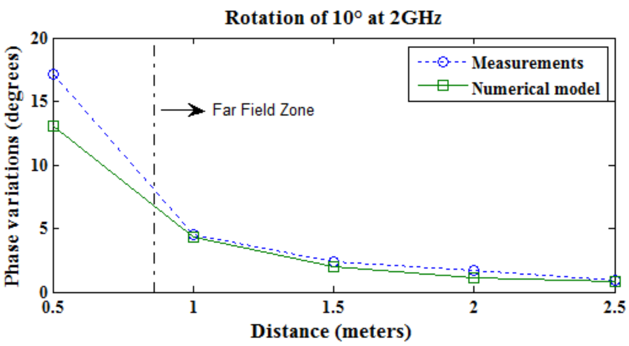

Figure 6. Model and measurement results for 1cm of displacement in the considered range.

Using the same admittance matrix, the model results seem to converge to the measurement results. So it can be used for all the considered electromagnetic scenarios without the need of recalculating it, and consequently reducing the computational time. A good convergence of the results for the dielectric case was also achieved, assuming a static error which doesn't extend a few degrees in the far field zone.

3.3 Parametrical analysis

The proper choice of the antenna radiation pattern and measurement distance is critical for precision measurements in most of the microwave displacement sensing systems. In this aspect the numerical model can be very useful, by analyzing the effect of illumination for different positions of the target, considering small horizontal displacement or rotation around the initial position, as shown in (Fig. 7).

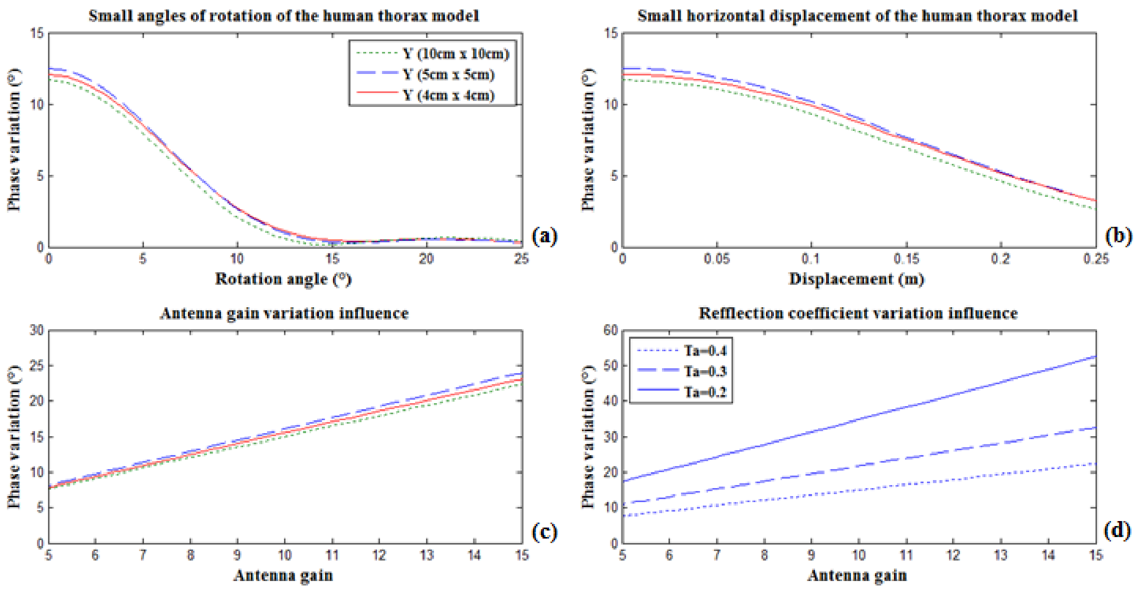

Figure 7. Maximal phase variations due to rotation (a) and horizontal displacement of the target, and due to antenna gain (c) and reflection coefficient (d) variations.

A high directive antenna increases the phase variations as the detected signal contains only the information from the illuminated part of the human body, usually the cardiac region of the human thorax. It would also increase the ratio of first heartbeat harmonic power to third respiration harmonic power. On the other hand it can limit the mobility of the monitored subject. By using well adaptive antennas, the contribution in (Eq. 2) of the reflection coefficient Γ_a decreases, increasing the phase variations of the S_{11} coefficient. It can be further noticed the convergence of the results while changing the dimensions of the rectangular sub-surface for the admittance matrix evaluation. The chosen dimensions for the rectangular sub-surface mainly depends on the operating frequency, on the cardio respiratory activity modeling and on the computational time.

4 Conclusions

A noncontact approach to measure the respiration activity on human subjects has been described, using an electromagnetic sensing system. The method is based on the measurement of the phase variations of the reflection coefficient S_{11} caused by the displacement of healthy subject's thorax due to respiration. A good correlation coefficient of 0.97, with the LDV reference system, was reported for the measured mean respiration frequencies.

Furthermore, the comparison between the experimental and numerical data confirm the validity of the proposed electromagnetic model, for the considered metallic and dielectric geometries. It takes into account the coupling coefficients between the different parts of the human thorax model and there is no need to revaluate the admittance matrix, making the used algorithm more efficient, instead of using high computational time accurate numeric techniques like FDTD or MoM. The model allows a parametrical analysis of the electromagnetic system taking into account changes in the distance between the antenna and the scattering object, in the position of the scattering object and in the antenna gain and reflection coefficient. Moreover, the proposed technique allows to model the cardio respiratory activity.

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