Respiratory Dynamics of Thoracic and Abdominal Motion in Doppler Radar Measurements

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***Abstract*—A Doppler radar measurement of respiration is a well-known technique for assessment of respiratory rates and patterns. Torso respiratory motion is a result of thoracic and abdominal motion during normal breathing. These two contributions produce breathing patterns that are important to understand for assessing respiratory health and sleep disorders. Doppler radar systems often use an antenna beam that illuminates the whole torso, effectively combining the contributions from the two regions. This paper presents theory, simulation, and measurement results that analyze and validate thorax and abdomen motion contributions in Doppler radar respiratory measurement.**

***Index Terms*—Respiratory motion, IR camera markers, respiration dynamics, abdominal contribution, thoracic contribution, torso mapping**

I. Introduction

Respiration measurements can provide valuable insight into overall health, yet are commonly unused in clinical care due to a lack of unobtrusive and accurate measurement methods [1]. Respiratory parameters of interest include not only respiratory rate but also respiratory patterns and depth of respiration. Doppler radar measurement of respiratory torso displacement is a well-known technique that has been used to assess respiration rate, depth, and motion patterns, and it has the potential to make an impact in clinical practice [2], [3]. While Doppler radar measurements of respiration rate and patterns have been demonstrated with high accuracy [4], [5], respiration depth measurements are more challenging to validate experimentally.

Respiratory effort is produced by the contraction and relaxation of muscles of respiration, intercostal muscles, and the diaphragm, resulting in the thoracic and abdominal displacement [6]. These two contributions produce breathing patterns that are important to understand for assessing respiratory health and sleep disorders. Doppler radar measurements often use an antenna beam that illuminates the whole torso area, thus effectively measuring an average displacement in the direction of the antenna. Respiratory displacement measured using Doppler radar and infrared cameras with a marker placed on the thorax was previously compared during normal and deep breathing [7]. The difference between radar and infrared camera measured displacement ranged from about 10% to about 90%, indicating that the contribution of thorax breathing varied between subjects, and also changed for each subject between normal and deep breathing.

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Dynamics of thorax and abdomen respiratory motion were previously studied using two respiration belts [8], and using infrared cameras with an array of markers attached to the skin [9]. This paper presents an analysis of thorax and abdomen displacement in Doppler radar respiratory measurements. A theoretical model is proposed to account for the contributions of the thorax and abdomen in terms of their individual effective radar cross-section (ERCS) and displacement. Experimental results including Doppler radar data taken simultaneously with infrared cameras tracking 13 markers attached to the skin confirm the validity of this model. This is the first reported verification of Doppler radar-measured respiratory displacement using a comprehensively recorded reference signal displacement.

II. Theory

The chest motion during respiration having an amplitude of X and frequency of f_R can be represented by a sinusoidal half cycle with a rounded cusp given by p [10].

$$x_R(t) = X sin^p \pi f_R(t) \quad (1)$$

The abdomen and thorax contributions can be modeled as two surfaces with effective radar cross sections resulting in baseband signal amplitudes of A_1 and A_2 and moving with different displacement $x_1(t)$ and $x_2(t)$. Based on previously studied dynamics of breathing [8-9], it is assumed that there will be some phase delay between the two components. If a

CW quadrature radar is used, the received baseband I and Q outputs can be written as -

$$\begin{aligned} B_I(t) =& A_2 cos[\frac{4\pi}{\lambda} x_2(t)] \\ &+ A_1 cos[\frac{4\pi}{\lambda} x_1(t) + (\frac{\pi}{n}) + (\frac{\pi}{k})] \\ =& A_R cos \frac{4\pi x_R(t)}{\lambda} \end{aligned} \quad (2)$$

$$\begin{aligned} B_Q(t) =& A_2 sin[\frac{4\pi}{\lambda} x_2(t)] \\ &+ A_1 sin[\frac{4\pi}{\lambda} x_1(t) + (\frac{\pi}{n}) + (\frac{\pi}{k})] \\ =& A_R sin \frac{4\pi x_R(t)}{\lambda} \end{aligned} \quad (3)$$

The delay in abdominal motion results in a phase offset denoted by k, while the difference in amplitude between the thorax and abdomen is represented by n [11]. A_R and $x_R(t)$ represent the amplitude of the respiratory effort and the chest wall displacement defined in (1), respectively. The total phase delay between the two components will determine how they add to produce a signal measured by radar.

Using (2) and (3) simulation was run in Matlab to examine how the two components contribute to the radar signal. It was assumed that x_1/x_2 is 2, A_1/A_2 is 3, and the total phase difference between the abdomen and thorax is about 20^o degrees. Fig. 1 shows the IQ plot of the abdomen, thorax, and combined signals. In this case, the resulting radius A_R for the radar signal falls in between A_1 and A_2, with the corresponding total phase change of 122^o degrees also in between the values simulated for the abdomen and thorax.

Fig. 1. shows the IQ plots obtained through simulation. It can be seen that, when a phase difference of 23^o degrees is present between the abdomen and thorax, then the abdomen has the highest radius and the highest total phase change.

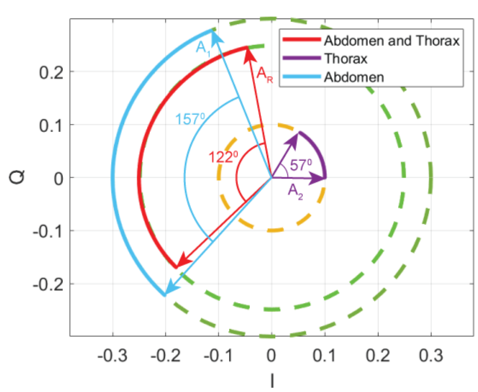

Fig. 1. Circle fitted IQ plot showing the phase angles and radii when only abdomen or thorax contribution is considered compared to that when both are considered. When these two areas contribute to the overall radar cross-section, it is hypothesized that A_R is the resulting radius from the radar output.

III. Experimental Methods

Human testing data were collected concurrently with Doppler radar and infrared cameras, following protocol number 14884 approved by the Committee on Human Studies (CHS) at the University of Hawaii. Fig. 2. shows the measurement setup including infrared cameras and 2.4 GHz quadrature Doppler radar [5]. A human subject was tested while seated still with an upright posture and back against the chair to reduce motion artifacts at 2 meters from the radar. Data was collected for approximately one minute during normal and deep breathing.

To map torso respiratory motion, Advanced Realtime Tracking GmbH (ARTTRACK2) infrared (IR) cameras with a DTrack central PC with Sync-card and proprietary processing software are used. This infrared motion capture system consists of two infrared cameras that form a stereo vision, enabling the tracking of three-dimensional coordinates of markers within their field of view. The y-axis, which is horizontal and perpendicular to the subject's frontal plane, is used to calculate the average displacement from the marker data. A 13 IR marker configuration is tested with two concentric circles of IR markers around the thorax marker [1]. The subset in Fig 2. shows the 13 IR marker configurations. Four bottom markers were placed below the diaphragm to mostly assess abdominal motion.

A 2.4 GHz continuous wave (CW) Doppler radar with a quadrature receiver is used in this study. The generated signal having a power of 10dBm is sent through the 0^0 degree splitter which gives the local oscillator (LO) signal and the transmitted signal. The received in-phase (I) and quadrature (Q) signals are further passed through the low noise amplifier having a gain of 200 V/V. A 10Hz low pass filter and DC coupling were used to further obtain a clean vital sign measurement from the I and Q signals. The outputs were then sent to a data acquisition program through a DAQ and recorded at a sampling rate of 1kHz using LabVIEW software. The IQ imbalance is estimated using a metallic rectangular flat plate measured at a range of 2 meters and with a displacement of 40mm and then compensated using the Gram-Schmidt method [7].

IV. Results

Four markers shown by the red box in Fig 2. represent the abdominal displacement caused by the diaphragm motion due to respiratory effort. The rest of the markers represent the thorax displacement due to rib cage motion during respiration [2]. These two groups of markers form two different clusters of displacements. Hence, to simplify the processing of data from the markers, two of the markers with the greatest displacement difference were chosen to compare to radar estimates.

For the subject's normal breathing test, Fig. 3(a) shows the comparison between the markers' displacement and the radar displacement estimated from the phase angle, θ calculated from the average radius of the fitted circle of the data for the overall test time. Fig. 3(b) depicts the case with deep

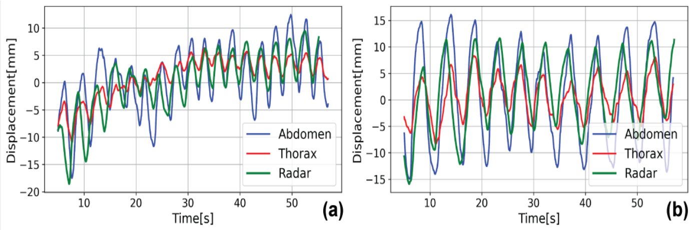

Fig. 2. Displacement results comparing thorax marker and abdomen marker for (a) normal breathing and (b) deep breathing with radar-estimated displacement.

breathing. The thorax marker had a much smaller displacement than the lowest marker on the abdomen. For both cases, the displacement measured by the radar is observed to be in between the displacement of the abdomen and the thorax. These results confirm the hypothesis that radar-measured respiratory displacement is composed of abdomen and thorax contributions with some phase delay between the two (Fig. 1).

V. Conclusions

This paper analyzed the respiratory dynamics produced by thoracic and abdominal motion measured by Doppler radar. Contributions of thorax and abdomen motion were modeled as two surfaces of different effective radar cross sections, moving with different displacements, and with some phase delay between the two sources. Simulation results indicate that with a small phase delay, the two signals combine to produce an ERCS in between the values assumed for the abdomen and thorax, with associated displacement also in between the displacements of the two sources. Experimental results carried out with 2.4 GHz Doppler radar, and an IR camera system with 13 markers attached to the torso, confirm this hypothesis. This is the first experimental validation of respiratory displacement measurement with Doppler radar taking into account thorax and abdomen motion during normal breathing. Future work will include the decomposition of radar signals into thorax and abdomen components.

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