Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

The use of a two channel Doppler radar sensor for the characterization of heart motion phases

J. Muehlsteff, J.A.J. Thijs, R. Pinter
{jens.muehlsteff, jeroen.thijs, r.pinter} @philips.com
Philips Research, Weisshausstrasse 2, 52066 Aachen, Germany

Abstract— **This paper investigates a two-channel Doppler radar sensor that can provide information on the direction of movement. The radar sensor has the advantage of non-invasive, contactless measurements, compared to ultrasound. From theoretical considerations and a working model, we deduce a criterion for extracting points of no movement in a heart cycle. We propose to use this criterion to characterize the heart motion phases, beyond looking at signal morphology only. In contrast to the ECG, this technique provides easy and comfortable access to information about the mechanical activity of the heart.**

Keywords---CW Doppler radar, heart monitoring, mechanical heart activity, continuous monitoring, arterial dilatation

I. Introduction

THERE is an increasing demand for long term continuous monitoring of a patient's vital signs like the ECG [1]. It has been shown [2] that it is possible to characterize the mechanical activity of the heart using a Doppler radar sensor and provide information about the mechanical function of the heart that is comparable to impedance cardiography. Compared to standard ECG measurement, the mechanical activity of the heart provides additional information, for example for the determination of stroke volume and cardiac output for congestive heart failure patients. Two channel Doppler radar sensors are available on the market. The speed and the direction of movement as well as a change of direction can be measured with these sensors. Using this for heart measurements will provide additional information about timing of heart phases. Thorough analysis of the two-channel sensor provides an insight of the additional opportunities a two-channel sensor can provide. A radar sensor has the advantage that no direct skin contact is required and, compared to ultrasound, does not need any coupling gel. Additionally, it does not have the disadvantage of ultrasound measurements which is restricted to certain viewing windows.

II. Experimental Setup

A. CW Doppler radar module

The Doppler radar module is based on the commercially available microwave motion sensor KMY24 (Micro Systems Engineering GmbH, Germany). It contains a 2.45 GHz oscillator and a receiver in the same housing. The sensor works in continuous wave mode. For the intended use, a front-end module for the sensor was designed. This module contains the filter structure as depicted in the block diagram in Fig. 1.

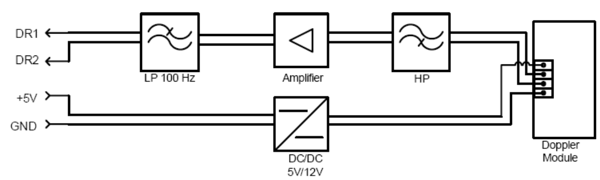

Fig. 1. Block diagram of the Doppler radar front-end

The high-pass filter removes the DC component from the signal and the low-pass filter removes high frequency noise before sampling. The amplifier's gain can be adjusted.

B. In-vivo measurement positions on the body

Several in-vivo measurements have been performed using the radar sensor. In one measurement the radar sensor was used in parallel with an ECG measurement for comparison of the electrical and mechanical heart activity as well as the segmentation of the different heart phases. The radar sensor was positioned directly on the thorax in the sternum area. The ECG was measured using a standard one-lead (Einthoven I) measurement. In another application the radar sensor was used for an extremity measurement of vasodilatation in combination with a photo-plethysmography (PPG) measurement. The radar sensor was positioned at the femoral artery whereas the PPG measurement was done using a standard finger clip.

C. Single plate reflector

We verified our theoretical considerations with a setup, which is shown schematically in the following figure.

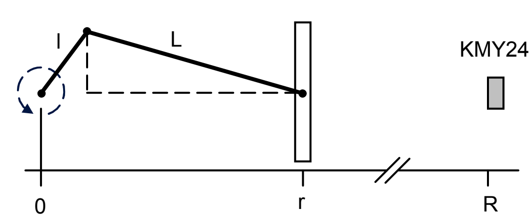

Fig. 2. Schematic of the setup used for verifying the theoretical consideration

It consisted of a metal plate as reflector, the movement amplitude and velocity of which were adjustable. The reflector distance r(t) is given by:

$$r(t) = l \cdot \cos(\omega t) + \sqrt{L^2 - (l \cdot \sin(\omega t))^2} \tag{1}$$

III. ANALYSIS

A. Sensor description

A characteristic feature of the KMY24 is the use of two mixer diodes, i.e. two receivers. The mixer diodes are driven by the same oscillator, but with a defined phase difference. This makes it possible to recognize the direction of movement, i.e. if the target is receding or approaching the sensor.

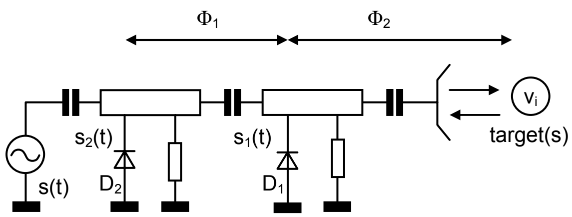

Fig 3. Internal structure of the KMY24

The oscillator signal s(t) and the signals at the two mixer diodes $s_1(t)$ and $s_2(t)$ can be described as follows.

$$s(t) = \sin(\omega_0 \cdot t) \tag{2}$$

$$s_1(t) = A_1 \cdot \sin(\omega_0 t + \Phi_1) \cdot \sum_{i=0}^{N-1} A_{1i} \sin(\omega_0 t \pm \tfrac{2v_i}{c}\omega_0 t + \Phi_1 + 2\Phi_{2i}) \tag{3}$$

$$s_2(t) = A_2 \cdot \sin(\omega_0 t) \cdot \sum_{i=0}^{N-1} A_{2i} \sin(\omega_0 t \pm \tfrac{2v_i}{c}\omega_0 t + 2\Phi_1 + 2\Phi_{2i}) \tag{4}$$

Multiple targets are considered here, resulting in $s_1(t)$ and $s_2(t)$ being the superposition of all target reflections that are Doppler-shifted according to the individual target velocities v_i. Internal to the KMY24 the signals $s_1(t)$ and $s_2(t)$ undergo a low-pass filtering. It can be shown that for the spectra of the filtered signals the following applies in the frequency domain:

$$S_{2LP}(f) = k \cdot e^{-j\left[\mp\frac{c}{2v_i}-1\right]2\cdot\Phi_1} \cdot S_{1LP}(f) \tag{5}$$

where k is a constant. Since the velocities $v_i << c$ the phase shift between the two channels is either $2\Phi_1$ or $-2\Phi_1$, while $|S_{1LP}(f)|$ and $|S_{2LP}(f)|$ are proportional to each other. In the KMY24, $2\Phi_1$ is an odd multiple of $\pi/2$.

B. Working Model

This section deals with a working model describing the expected Doppler radar sensor signals coming from periodically moving reflectors with amplitudes that are small compared to the wavelength, and discusses strategies for the signal interpretation. Our analysis extends the considerations presented in [2-4].

In the following we use the low-pass filtered sensor signals x_1 and x_2 from equations (3) and (4) of a two-channel Doppler radar sensor, which are given by:

$$x_1(t) = a \cdot \sum_{k=1}^{N} \frac{1}{D_k(t)^\gamma} \cos(\Theta_k(t)) \tag{6}$$

$$x_2(t) = b \cdot \sum_{k=1}^{N} \frac{1}{D_k(t)^\gamma} \cos(\Theta_k(t) + 2\Phi_1) \tag{7}$$

The cosine factors represent the local amplitudes of the reflected EM-waves. The signal amplitudes a and b differ (property of KMY24). The influence of the changing sensor–target distances $D_k(t)$ is modeled by an exponential factor γ. The phase difference $2\Phi_1$ equals an odd multiple of $\pi/2$ for the KMY24, see section A. The timely varying phase $\Theta_k(t)$

$$\Theta_k(t) = \frac{4\pi}{\lambda}\left(\int_0^t v_k(t')dt' + \Xi_k\right) \tag{8}$$

is related with the Doppler-effect as a sum of signals from N reflectors moving with velocity components $v_k(t)$ relevant for the Doppler shift and the sensor-reflector distance Ξ_k for t=0. In the following we analyze a single moving reflector, so the function D(t) and $\Theta(t)$ are simplified. Sensor-reflector distance D(t) and phase $\Theta(t)$ are then linearly related by:

$$D(t) = \frac{\lambda}{4\pi}\Theta(t) - \Xi \tag{9}$$

For a single reflector moving with a constant velocity v, equation (8) is the well-known Doppler-Radar equation.

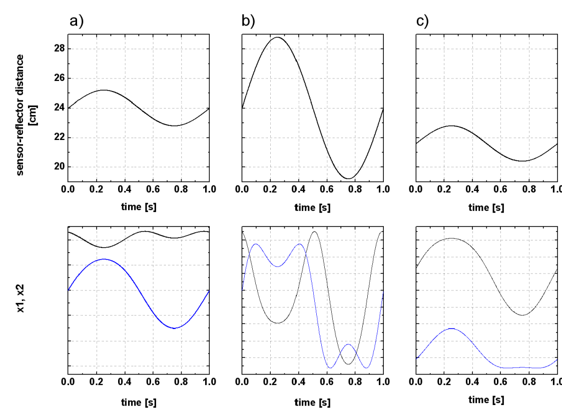

Fig. 4. Top row: variation of reflector motion amplitude (a and b) and sensor-reflector distance (c); bottom row: theoretical sensor-signals for cases a, b and c according to equations (6), (7) and (8)

Fig. 4 shows the theoretical signals for a single sinusoidally moving reflector with different parameters (Ξ, movement amplitude) calculated for a wavelength of λ=12 cm and γ=2. As can be seen the signal morphologies depend strongly on the chosen parameters and cannot be easily interpreted.

C. Data Analysis

This section addresses the questions, which kind of information can be extracted from the two-channel Doppler radar sensor for the specific use case of movements that are small compared to the wavelength λ.

Sensor – Reflector distance variation

If all relevant hardware-defined parameters like a, b, offsets, effective λ etc. are known, it is possible to derive the timely varying distance sensor-reflector from (6), (7) and (9) by combining the information of both channels. The distance is then given by:

$$D(t) + \Xi = \frac{\lambda}{4\pi} \arctan(\frac{ax_2}{bx_1}) \qquad (10)$$

In order to use equation (10) a calibration step is needed to determine the specific hardware-defined parameters.

Discriminative criterion for no reflector movement

Those points where the target does not move towards or away from the sensor (v=0) can be extracted if the time-derivatives of equation (3) and (4) are taken into account. At the point where both signals have a local extreme, the velocity of movement must be zero. In a plot of dx_2/dt over dx_1/dt both derivatives must be jointly zero and have a non-zero second derivative. Fig. 5 shows a plot of the time-derivatives of theoretical signals assuming a sinusoidal and a sum of two sinusoidal movements, which illustrates the mentioned criteria.

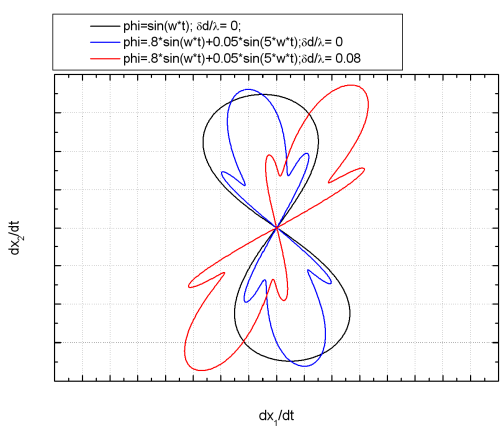

Fig. 5. Plot of the time-derivatives of signals x_2 vs. x_1; the point (0,0) marks the state of rest of the reflector and is the criterion for time measurements using a two channel Doppler radar

The advantage of this analysis is that a well-defined criterion which is also insensitive to signal offsets and the - often unknown - parameters a and b, enables the detection of resting states during a target movement. This is useful in medical application like detecting heart phases and artery dilatations.

IV. Results and Discussion

A. Results of verification with the model setup

According to the working model presented in section III B, changes of the signal morphology are expected for both a varying sensor-reflector distance and a varying motion amplitude. The following figure shows measurement results obtained while varying the distance. The measured signal fully agrees with the working model.

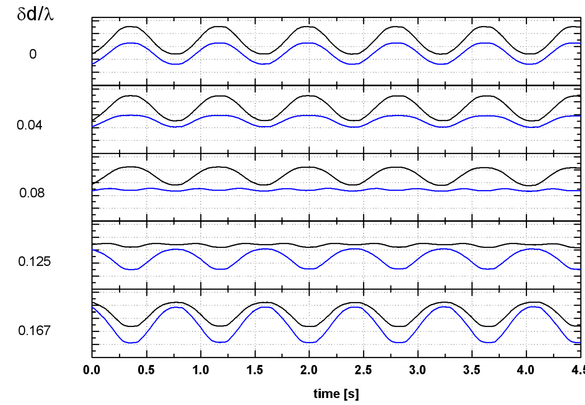

Fig. 6. Sensor-signals for different sensor-reflector distances (λ=12 cm)

In Fig. 7 a plot of dx_2/dt over dx_1/dt for different distances is shown. All signals exhibit a clear zero-crossing and a separation between the two regions of forward and backward movement.

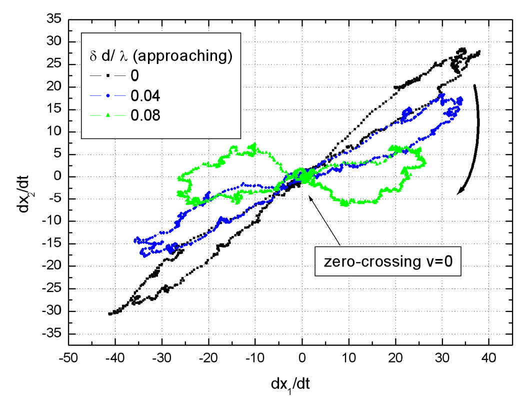

Fig. 7. Plot of the time-derivatives of signals x_2 vs. x_1 of the radar signals at different sensor reflector distances

The movement of the reflector was not perfectly smooth, because of limitations in the experimental setup. This causes irregularities in the curve that are similar to what is predicted in Fig. 5 under the assumption of higher harmonics.

B. In-vivo measurements from Doppler radar sensor

It should be noted that the wavelength at 2.45 GHz in air is about 12 cm whereas in tissue, the wavelength is about 3…5 cm [5]. The movement amplitude of the heart as well as vasodilatation is expected to be smaller than the wavelength.

Sternum measurement

In Fig. 8, the results of the measurement combination with the Doppler radar sensor positioned at the sternum and a standard 1 lead ECG is shown. The radar measurements show the two channels in the middle diagram. The lower part of Fig. 8 shows the time derivative of both radar signals. Using the criterion defined in section III it can be seen that there are several points per heart beat period for which both time derivatives have a simultaneous zero-crossing. These points are indicated by the numbers 1 to 5, where point 5 is the same as point 1 for another period. These zero-crossings indicate the point in time where the heart movement has a point of zero velocity, due to a change of direction or a pause in the movement. These points can be used to separate the different phases of the heart's pumping function.

- Atrial phase: From point 1 to point 2, the contraction of the atrium produces small velocity changes in both channels
- Contraction phase: Point 2 to point 3 defines the phase in which the ventricle contraction takes place. This is also reflected in the large velocity changes in this phase
- Point 3 to point 5 shows the filling phase where velocities decrease and the atria are filling again, the point 4 cannot be interpreted by a feature in the ECG.

Although there are several zero crossings in the time derivative of a single channel, only a limited number of points show a zero crossing in both derivatives simultaneously.

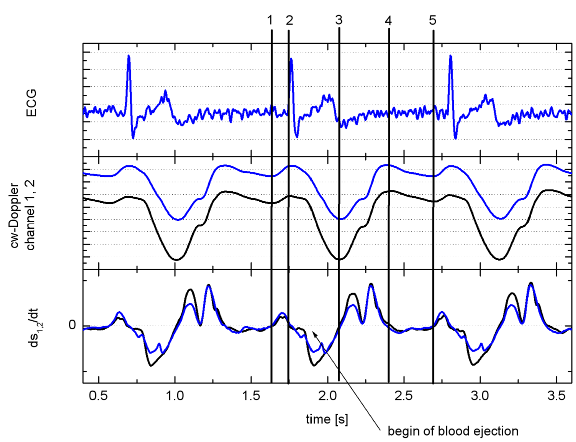

Fig. 8. Measurement of ECG and Doppler radar sensor

Right leg artery measurement

We have analyzed the signals of the two channel Doppler radar sensor from the right leg of a 33-year-old male. Fig. 9 shows the time derivatives of the measured Doppler signals synchronized with a finger photo-plethysmogram as reference. Obviously both Doppler radar signal derivatives have common zero-crossings at the points 1, 2, and 3 indicating states of no movement during a heart cycle, which coincide with the characteristic points of the PPG. The small time difference is due to the different propagation times to the leg and finger. The Doppler radar technique together with the presented signal analysis is therefore a promising approach to evaluate the dilatation and constriction of arteries or the comfortable extraction of pulse transit times.

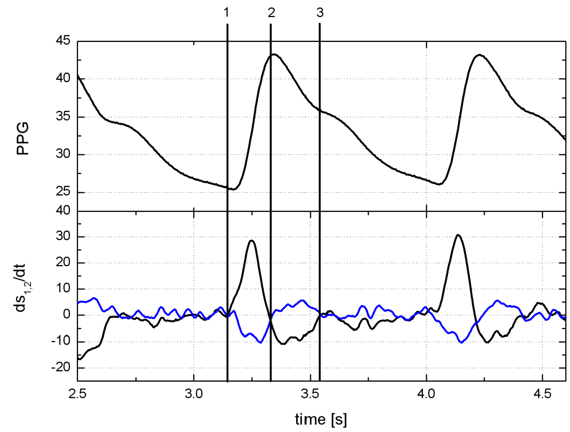

Fig. 9. Measurements of a 33 year old male; upper diagram: finger photo-plethysmogram, lower diagram: time derivative of both Doppler-Radar signals from the right leg artery

V. Conclusion and Next Steps

For a one channel Doppler radar sensor the morphology of the signal has been shown in [2] to be strongly dependent on the depth of the reflection. Making use of the morphology of the radar signal to extract information from the heart's activity is therefore complex and often not possible. We propose to look at fixed, easy to find points in the signal to extract this information. In this paper a clear criterion has been formulated to find typical points in the Doppler radar signal by using two channels. The criterion has been defined as follows. An extreme occuring in both channels at the same time marks a point in time when the observed target velocity components are zero. This indicates a change of direction or an instantaneous pause of the movement. Next steps will be to verify the points found in the radar signal by ultrasound measurements. Further research will also look at the possibility to combine multiple radar sensors for pulse wave measurements, continuing the work presented in this paper.

References

[1] American Heart Association, Heart and Stroke statistical update, 2005

[2] J.A.J. Thijs, J. Muehlsteff, O.Such, R. Pinter, R. Elfring, C.H. Igney, A comparison of continuous wave Doppler radar to impedance cardiography for analysis of mechanical heart activity, 2005, IEEE EMBC 2005, conference proceedings

[3] A. Thansandote, S. S. Stuchly, A. M. Smith, Monitoring variations of biological impedances using microwave Doppler radar, 1983, Phys. Med. Biol. 28 983-990

[4] A. Droitcour, V. Lubecke et.al., A microwave radio for Doppler radar sensing of vital signs, 2001, MTT-S Digest, 175-178

[5] D. Andreuccetti, Dielectric properties of body tissues, IFAC-CNR, Firenze, Italy, http://niremf.ifac.cnr.it/tissprop/, 2002