

Doppler radar assessment of environmental noise effect on cardiovascular and respiratory activity

Jannatun Noor Sameera
Dept. of Electrical and Computer Eng.
University of Hawaii at Manoa
Honolulu, Hawaii, USA
jsameera@hawaii.edu

Ksenia Sherstyuk
Dept. of Mechanical Eng.
Boston University
Boston, Massachusetts, USA
ksneia@bu.edu

Mohammad Shadman Ishrak
Dept. of Electrical and Computer Eng.
University of Hawaii at Manoa
Honolulu, Hawaii, USA
ishrak@hawaii.edu

Victor M. Lubecke
Dept. of Electrical and Computer Eng.
University of Hawaii at Manoa
Honolulu, Hawaii, USA
lubecke@hawaii.edu

Olga Boric-Lubecke
Dept. of Electrical and Computer Eng.
University of Hawaii at Manoa
Honolulu, Hawaii, USA
olga@hawaii.edu

Abstract—The significant impact of environmental noise on cardiovascular health is becoming more widely recognized. However, detailed studies related to environmental noise and human physiology are very limited. This study provides a detailed evaluation of heart rate and respiratory responses to different noise levels in a controlled experimental environment using Doppler radar. The findings indicate that while respiratory rates show notable variations, heart rates remain largely unchanged with alterations in noise levels. This non-invasive approach to assessing the effects of environmental noise using Doppler radar could help improve indoor environmental quality by adapting conditions to enhance acoustic comfort and reduce stress for occupants.

Index Terms—Doppler radar, environmental noise, heart rate, respiratory rate.

I. INTRODUCTION

The impact of noise pollution on health is becoming more acknowledged, affecting beyond auditory disturbances to include sleep disruption, cognitive impairment, and a greater risk of arterial hypertension, heart attacks, and strokes as evidenced by epidemiological research [1]. Previous research has demonstrated that indoor environmental quality (IEQ) which includes acoustic comfort as a primary element, can significantly affect health, comfort, cognitive capacity, and productivity [2]. A study used contact sensors to associate an increased sound level with an increase in average heart rate and heart rate variability parameters. It stated this association depends on the location and mobility contexts [3]. Although the effect of different locations was considered, the noise levels were not varied throughout the study. Furthermore, previous works on a detailed study of the effect of noise on cardiovascular activity are very limited. In this study, we have presented a comprehensive assessment of the effect of environmental noise on cardiovascular activity and quantified it in terms of heart rate and respiration rate. Continuous

monitoring is of paramount importance as it can help the prognosis of any underlying health condition. Additionally, it can also be employed to realize an adaptive IEQ mentioned earlier. However, most cardiovascular monitoring studies involve contact sensors, which are unsuitable due to disadvantages such as skin irritation, limited mobility, etc. [4], [5]. Although Hurtado et. al. presented using a non-invasive temperature respiratory monitoring system, heart rate monitoring was not demonstrated [6]. Hence, we have employed a 24 GHz quadrature channel continuous wave (CW) Doppler radar that presents a novel and holistic approach for continuous and non-invasive monitoring of the effect of environmental noise on both heart and respiration rates. For this purpose, we have introduced two types of noise into the anechoic chamber where the experiments were conducted. Section II. describes the experimental setup in detail along with the theoretical background. Furthermore, this study explores the possibility of using Doppler radar for a more comprehensive approach to assessing acoustic comfort. The results using data from the radar are quantified and presented in Section III. Finally, the paper concludes with a brief discussion on future research directions planned to be built upon these findings.

II. BACKGROUND

A. Theory

A continuous wave (CW) Doppler radar sends a directional, single-frequency signal whose phase is modulated after reflecting off a moving target. This phase shift corresponds to the movement of the target. The outputs from a CW Doppler radar can be expressed as,

$$B_I(t) = A_I \cos\left(\theta + \frac{4\pi x(t)}{\lambda} + \phi_I\right) \quad (1)$$

$$B_Q(t) = A_Q \sin\left(\theta + \frac{4\pi x(t)}{\lambda} + \phi_Q\right) \quad (2)$$

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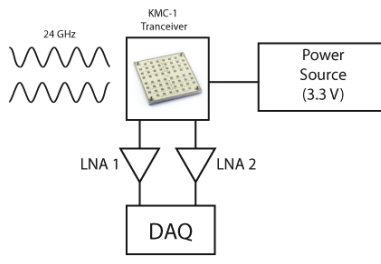


Fig. 1. Block Diagram of the Quadrature Radar Setup

where, A_I and A_Q represent the amplitude of the received waves in the I and Q channel respectively, ϕ_I and ϕ_Q represent the phase offsets produced by initial calibration conditions in the system. $x(t)$ represents the displacement due to the target's motion and the constant phase shift due to phase change at the surface of the target and between mixer and antenna is given by θ .

Having two orthonormal outputs on a quadrature setup ensures that when one of the channels is at a "null point", the other channel is at an "optimum point", thereby neutralizing the distance-dependence of SNR of the signal. In an ideal quadrature radar system, the mixer properties, namely the attenuation factors A_I and A_Q and the phase delays ϕ_I and ϕ_Q are considered equal. Practically, the values differ due to the inherent characteristics of the mixer. The imbalance created by these inequalities is compensated by using Gram-Schmidt imbalance correction [7].

Following the imbalance correction, the data is demodulated using the arctangent demodulation, which is expressed as,

$$\phi(t) = \arctan\left(\frac{V_Q + B_Q(t)}{V_I + B_I(t)}\right) \quad (3)$$

where V_I and V_Q represent the DC offset values in the received signal caused primarily by the static object reflections in the environment [8]. The presence of these offsets reduces the resolution of θ and also prevents the amplification due to voltage limitations in the DAQ. Using the Levenberg-Marquardt circle fitting algorithm, the DC offset part of the signal was removed while preserving the DC information [9].

B. Experimental Setup

In this work, a commercial off-the-shelf RFbeam Microwave K-MC1 transceiver module containing a 24GHz K-band antenna array was used as the CW Doppler radar (Fig. 1). The module contains IQ mixers and IF-preamplifiers. The IQ outputs are low-pass filtered at 10 Hz and amplified 20 times using SR560 low-noise amplifiers. A chest belt (UFI Model 1132 Pneumotrace II) and piezoelectric finger pulse sensor are used to collect the reference respiratory and heart signals. Data from all the sensors are recorded using an 18-bit NI DAQ at 100 Hz sampling rate.

Data is collected from six subjects following protocol number 14884 approved by the Committee on Human Studies (CHS) of the University of Hawaii system. The subjects were

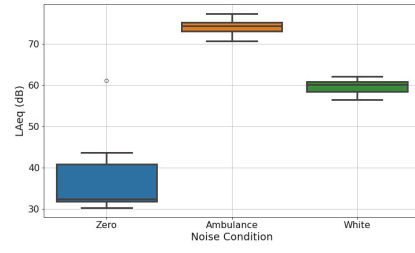


Fig. 2. LAeq Levels Across Different Noise Conditions

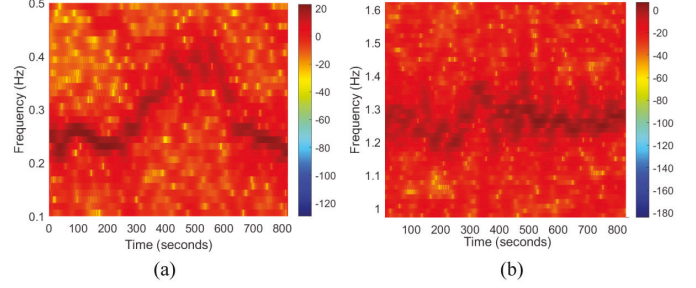


Fig. 3. Spectrogram of (a) respiration (chest belt) and (b) heart (finger pulse) signals obtained through STFT for Subject 5.

instructed to sit still in an anechoic chamber and breathe normally during the 15-minute duration of data collection. To monitor the effect of environmental noise, ambulance noise was introduced after 5 minutes in the chamber. The ambulance noise persisted for another 5 minutes. For the last 5 minutes, a 256Hz white noise containing a static-like hum was introduced in the anechoic chamber. To quantify the noise levels during these 3 stages of the experiment, the NIOSH Sound Level Meter mobile application was used and the equivalent continuous sound level, LAeq (dB) was noted for each stage. Fig 2. shows a boxplot of LAeq (dB) values reported for each stage of all the datasets. As can be seen, the LAeq (dB) shows a lower spread when the ambulance and white noise are introduced in the anechoic chamber. However, the LAeq(dB) shows higher variation during the first 5 minutes of the recording when no noise is introduced.

III. RESULTS

To assess the effect of environmental noise on human physiology, the subjects' respiration rate (RR) and heart rate (HR) were extracted during each 5-minute segment containing different noise levels. For extracting the respiration signal from the demodulated radar signal, a multiresolution analysis using maximal overlap discrete wavelet transform (MODWT) was performed after FIR bandpass filtering the signal from 0.01-0.5 Hz [8]. MODWT is a linear filtering operation that decomposes an original signal into detailed and approximate fields without sampling down in the filtering process to extract the desired frequency components. This method was also used on the reference unfiltered signals to remove the baseline wandering in the collected data.

At first, we investigated whether sufficient change in noise level has been introduced in our experiment that causes changes in physiology. Short-time Fourier transform (STFT) was applied to obtain the spectrogram used for observing the continuous change in respiration and heart rates. Fig 3. shows the respiration and heart rate spectrogram for Subject 5 at different noise levels using data from reference sensors. The average of the change of all subjects does not reflect significant results. Hence, the spectrogram of a single subject is shown in Fig 3. The LAeq increases by 41.1 dB when ambulance noise is introduced after the first 5 minutes. As can be seen from Fig 3(a). the respiration rate starts to increase as well. Next, the LAeq gets decreased by 14.7 dB when the white noise is introduced into the anechoic chamber instead of the ambulance noise. Although the respiration rate of the subject remains constant at the start of the final stage, it starts to decrease slowly at approximately 12 minutes. While changes in noise levels affect the respiration rate, the heart rate does not show significant change throughout the whole 15-minute duration (Fig 3 (b).). It is to be noted that since the LAeq measured is the average of the whole 5 minutes, it accounts for any unwanted external noise that occurred outside the anechoic chamber during this experiment. Hence, the LAeq for zero noise level is almost at the same level as while noise level for Subject 1.

Next, we investigated whether Doppler radar can reflect this change in human physiology with the change in noise level. Our previous study demonstrated the accuracy of heart rate extraction using Doppler radar with mean average error (MAE) as low as 1.67 bpm [10]. The MAE for the extracted respiration rate using Doppler radar was within 1.21 b/m. Table I shows the change in respiration rate and heart rate with a change in noise level. For clarity, we have named the noise level of the first 5 minutes of the study as zero. The heart rate is extracted from the FFT of the heart signal obtained by performing MODWT on the FIR bandpass-filtered demodulated radar signal. In this case, the demodulated signal is filtered from 0.85-5Hz with an order of 600 [10]. Similar to reference sensor measurements, Doppler radar signals can manifest the effect of environmental noise on the physiology of the subject under test. The respiration rate shows an increase when the ambulance noise is introduced in the anechoic chamber. During the last 5 minutes with white noise, the respiration rate is decreased. It can also be seen that, in most cases, an increase in LAeq is associated with a corresponding rise in the respiration rate. While the respiration rate exhibits notable variations under different noise conditions, the heart rate remains largely unchanged in the majority of cases. Subject 6 shows the highest increase in heart rate by 16 bpm when the noise condition is changed by 44.2 dB.

IV. CONCLUSIONS

This work presented a comprehensive assessment of the effect of environmental noise on the cardiovascular system. The potential of Doppler radar for non-contact environmental noise assessment was also demonstrated. The noise level was

TABLE I
HEART AND RESPIRATION RATE ACROSS DIFFERENT NOISE CONDITIONS.

Subject	Noise Condition: LAeq (dB)	HR (bpm)	RR (b/m)
1	Zero: 61.2	67.2	7.8
	Ambulance: 77.3	69.6	10.8
	White: 62.2	68.4	9.6
2	Zero: 32.7	76.8	13.2
	Ambulance: 74.1	69.6	21.6
	White: 59.9	70.8	17.4
3	Zero: 43.7	58.8	14.4
	Ambulance: 75.5	61.2	18.6
	White: 61.1	58.2	12.6
4	Zero: 32.3	61.8	15
	Ambulance: 70.8	63.6	16.8
	White: 56.5	62.4	15.6
5	Zero: 31.7	69.6	13.8
	Ambulance: 72.8	63	17.4
	White: 58.1	66	14.4
6	Zero: 30.4	56.4	15.6
	Ambulance: 74.6	72.6	20.4
	White: 60.5	61.8	19.8

varied by introducing ambulance and white noise into the measurement environment at different stages of the experiment. It was found that although the respiration rate varies significantly, the heart rate does not show significant changes with the change in noise level. 24 GHz Doppler radar has been popularly used for studying heart rate variability (HRV), which is an important feature in stress assessment [11]–[13]. Hence, in our future work, we will study the effect of different noise levels on HRV parameters to establish an association between noise and stress levels.

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