Spatial Efficacy of Respiration Monitoring using Doppler Radars for Personalized Thermal Comfort Assessment

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Abstract –

Recent research efforts have shown that human thermophysiological features could play a crucial role in inferring occupants' thermal comfort, which is required for comfort-aware heating, ventilation, and air conditioning (HVAC) operation. Our previous studies have demonstrated that variations of respiration, a representative human thermophysiological feature, can be non-intrusively quantified by a Doppler radar sensor (DRS). However, in pursuit of enabling human-aware rooms in buildings, in this study we have explored the impact of distance and position of the respiration monitoring system to investigate the potential of DRS systems as a ubiquitous apparatus in the real-world scenarios. Through experimental studies, respiration characteristics were evaluated in different locations and angles relative to the location of the measurement device. The measurements were carried out using a DRS system and a respiratory belt for ground truth data collection. The noise artifacts were reduced by applying the Savitzky-Golay method and Hann window, and respiration was identified by selecting the frequency component with the maximum amplitude in the typical breathing frequency range (0.1 to 0.5 Hz). Our analyses demonstrated that the signal from a cost-effective DRS technology without the use of external amplifiers could cover a range, within 1.0m longitudinally and 0.5m laterally, which is sufficient for an individual sensing given a normal office environment. It was also observed that the use of an external amplifier extends the range of the DRS sensing but at the same time accentuates the noise. Therefore, advanced noise removal methods are needed to increase the range of robust sensing. This study contributes to DRS deployment strategies for realization of comfort-aware systems.

Keywords –

Comfort-aware HVAC operation; Doppler radar; Respiration monitoring

1 Introduction

Studies have demonstrated that accounting for human dynamics in the control logic of Heating, Ventilation, and Air-Conditioning (HVAC) systems has potentials of creating satisfactory indoor environments and improving energy efficiency in buildings [1, 2]. Conventionally, the predicted mean vote (PMV) model, which has been recommended by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [3], has played such a role. However, it has been shown that the generalized human-related factors in the PMV model (the met and clo units for metabolic rate and clothing insulation) could misrepresent actual occupants' dynamics [4, 5] during the operations. For example, Humphreys and Hancock [6] have shown that occupants prefer diverse thermal sensations from cold to hot, which is different from the assumption of the PMV model for thermal satisfaction at neutral state. The objective of the PMV model is to provide thermal conditioning for an environment that majority of occupants find acceptable. Therefore, the predicted thermal comfort by the PMV model, especially when a small number of occupants are present in a space, could deviate from the actual thermal comfort [7]. Hence, recent research efforts have been dedicated to proposing novel methods of adapting actual thermal perception and preferences of occupants to address the aforesaid limitations.

Motivated by the prevalence of the information and communication technologies (ICT), the starting point was the use of electronic surveys [8, 9] to digitize the process of distributing, collecting, and analysing questionnaires and facilitate the data collection process. Hence, large scale occupant comfort voting data have been conveniently collected (e.g., over 10,000 votes were collected within one year [10]), which has contributed to context-aware HVAC operational strategies. This strategy aims to offer personalized comfort zones based on occupants' thermal preferences (hereinafter, this operation is called comfort-aware HVAC operation in this study).

The difficulty of this survey-based approach comes from two aspects: (1) the need for user dedications, and (2) direct comfort quantification. Jazizadeh and Becerik-Gerber [11] have evaluated the participants' dedications in the first data collection process and through a stratified sample selection focused on users that had consistency in providing thermal feedback. Similarly, Kim, et al. [5], have emphasized on the need for users' dedications to create their comfort profiles. It has been also shown that the direct comfort quantification might not fully represent the cause and effect given that occupants' preferences vary under the same thermal conditions [12]. Therefore, when it comes to comfort inference, moderate accuracies (up to 75.0%) have been reported [5, 13]. Accordingly, the integration of physiological attributes in thermal comfort inference has gained attention [14].

Current research efforts are searching for physiological sensing systems (PSS) that can be used in practice to collect human contextual data not only for developing high-performance comfort profiles, but also for realization of comfort-aware HVAC operation. For example, Li, et al. [15] and Ranjan and Scott [16] used an infrared imaging technology for this purpose. Our previous studies have shown that Doppler Radar Sensors (DRSs) have potentials of measuring human thermoregulation states as a non-intrusive apparatus for quantification of respiration [17-19]. However, practical application of this technology calls for investigating the feasibility of the technology under realistic environmental conditions including the distance from the sensor and the direction of signal communication.

Therefore, in this study, we have explored the potential of DRS systems as a ubiquitous measurement method for thermal comfort assessment. In addition to non-intrusiveness, applicability, and sensitivity, ubiquity is one of the core attributes needed for PSS methods to be applied in control loops. Further details on these attributes could be found in the study by Jung and Jazizadeh [20]. In doing so, we conducted two experimental studies. The first focuses on assessing the effective range of a DRS system. To this end, we used two sensing set ups; (1) a minimal DRS setting (without an external amplifier) and (2) a DRS setting with an external amplifier. The subjects were sitting at multiple locations and changed the angle with respect to the DRS, and then their pulmonary activities were measured by the DRS and respiratory belt (the latter for the ground truth). By comparing the respiration extracted by two devices, we assessed the range of a DRS sensor with regard to pulmonary activity measurement. The second experimental study focuses on multi-occupant sensing. As a preliminary attempt, we sought to measure the respiration activity of two occupants in front of a single DRS.

The structure of this paper is as follows. The following section reviews the previous studies that have revealed the potentials of using respiration as a PSS methodology for thermal comfort quantification. Section 3 explains the methodology of this study, and Section 4 presents the results. The paper is concluded with contributions and limitations of this study in Section 6.

2 Previous studies

Thermal comfort is the outcome of diverse mechanisms in the human body and human thermoregulation state demonstrates the response to the ambient environment [21]. Hence, in the indoor comfort research domain, the association between human thermophysiological response and ambient temperature has been investigated for decades.

One of the main contributing mechanisms is the skin blood flow adjustment for heat dissipation regulation. The expansion of blood vessels (i.e., vasodilation) increases the heat dissipation and vice versa (i.e., vasoconstriction). These variations contribute to the skin temperature, that has been used as a well-known physiological parameter for thermal comfort quantification. To this end, given its non-intrusive nature, the infrared imaging technology has been used as a potential apparatus [15, 16]. Moreover, the feasibility of using RGB video images by employing the photoplethysmography (PPG) has been also explored [20, 22].

Another thermophysiological feature that represent thermoregulation mechanism is breathing. ASHRAE [21] mentions that metabolic rate – a collective response of the human body to the ambient environment – can be most accurately quantified by respiration. The inspired air is at ambient temperature and expired air is near the core temperature. In other words, the human body exchange heat with the surrounding environment through respiration. Despite this substantial contribution to the heat exchange between the human body and ambient environment, respiration has not been widely utilized as an attribute in thermal comfort assessment due to the difficulties, associated with its measurements. For example, a spirometer, which is a commonly used apparatus for respiration measurement, requires subjects to blow their breaths into the device, which is not a practical approach for building level measurements.

Leveraging the Doppler effect, a physical phenomenon that causes variation of frequency or wavelength, when the location of wave source or observer is moving, DRSs have been employed as a non-intrusive approach of measuring cardiopulmonary activity (i.e., periodic movements of chest and abdomen area, induced by heart rate and respiration) in the clinical domain [23]. A DRS transmits a signal and receives a modulated signal representing the frequency and the displacement of the motion which causes the modulation. Motivated by its non-intrusiveness, we have investigated the potentials of using a DRS system as a means of quantifying human thermoregulation states. The implication of this approach is to employ this physiological response as input parameters to operate HVAC systems. The applicability and sensitivity have been demonstrated with two experimental studies for (1) two opposite temperatures (20 and 30ºC) with a 20-min acclimation time [17] and (2) transient thermal conditions (from 20 to 30ºC with no acclimation time) [18]. However, as noted the ubiquity is another critical attribute for practical use of DRS systems. Therefore, in this study, we have sought to explore whether we could use limited sensing nodes to cover a larger area in an indoor space (the primary objective) and multi-occupancy cases (the secondary objective).

These research questions have not been addressed by the previous studies, which focused on cardiopulmonary activity extraction by DRSs at a static location (0.5 m away from a DRS vertically) [24]. The data collection, respiration extraction process, and reason of having the simplest DRS setting are presented in the next section.

3 Methodology

3.1 Non-intrusive respiration extraction by Doppler radar sensors

Using the linear relationship between air volume variations and human chest and abdomen area [25], our thermoregulation state assessment approach extracts the features of pulmonary activities by using DRS systems [17]. The frequency and amplitude of DRS signals represent rates and intensity of breathing. Therefore, in our respiration quantification approach, we could infer thermoregulation states by quantifying the respiration leveraging the aforementioned features. Figure 1 shows the signal characteristics and the resultant breathing index. However, since we are interested in assessing the ubiquity attribute of the DRS systems in this study, we have solely focused on the frequency of respiration in evaluating the feasible range of measurement in quantifying the respiration activities. In doing so, four steps of post-processing methods have been utilized in analyzing the raw DRS signals: (1) applying the Savitzky-Golay smoothing filtering, (2) applying the Hanning window, (3) applying the fast Fourier transform, and (4) identifying the respiration component on the signal. The variations, derived from each step, is presented in Figure 2. The rationale behind using each step is as follows.

- The first step reduces noise and redundancy while preserving the shape and height of waveforms by the local least-squares polynomial approximations [26].
- The second step reduces the amplitude of discontinuities, caused by the digitization, by multiplying an amplitude that changes smoothly and gradually toward zero at the edges (Figure 3). Therefore, the process could result in better frequency resolution. Upon observing such discontinuities in the collected DRS datasets, we chose the Hanning window in consideration of its high applicability to different problems [27].
- The fast Fourier transform (FFT) is applied to convert a time-domain signal into the frequency-domain signal. This process helps the fourth step because the typical frequency range of respiration is often observed with a frequency less than 0.5 Hz [28]. Hence, the respiration activity can be extracted by identifying the signal that has the maximum amplitude within the aforesaid range of frequency [29].

3.2 Experimental setup

We have conducted an experimental study with three male human subjects. Their ages were 26, 31, and 33 and heights were 172, 182, and 183 cm. They declared no cardiopulmonary-related illnesses at the time of the experiment. This study was conducted upon receiving the approval of Virginia Tech's Internal Review Board (IRB) and informed consent was obtained. We used a number of experimental configurations:

1. A basic DRS sensing setup that does not use signal amplification with the first subject
2. A DRS setup that uses signal amplifier with the second subject.
3. The third configuration was focused on multi-occupant sensing, for which the second and third human subjects participated. In this configuration, we used the DRS sensing with signal amplification.

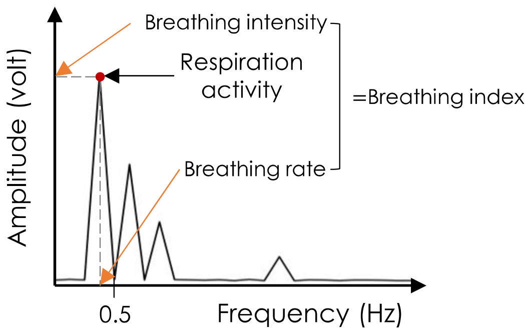

Figure 1. Features of the respiration activity

captured by DRS system.

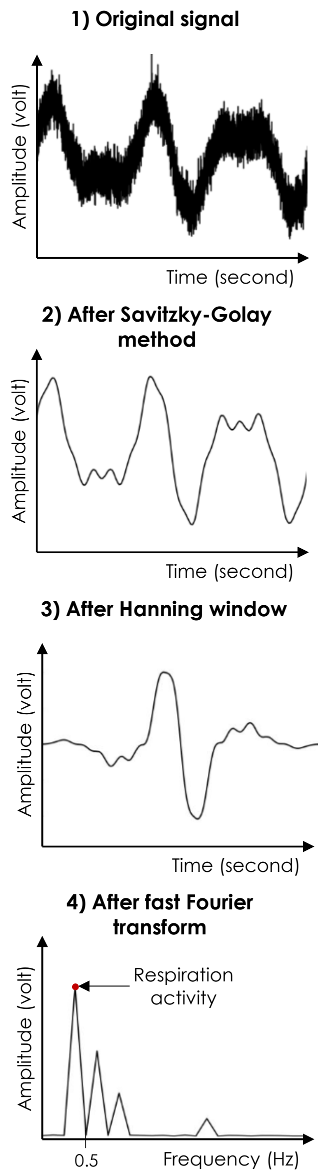

Figure 2. Respiration activity detection by using Doppler radar sensor signal (the signals are schematic representations)

For the sensing set up, we have used an RFBeam K-LC5 product as the DRS sensing system. This senor is a wide-angle sensing system – 34º vertical and 80º of horizontal beamwidths (Figure 4) – with a frequency of 24 GHz in the K-band, which is less occupied by other communication technologies. The sensing system is sensitive to subtle displacement and uses small antenna. As shown in Figure 5, the sensor dimensions are 25×25×6mm^3 [30]. This product includes a built-in low noise amplifier with 10dB gain and needs 5 voltage to power on. For the external amplifier, in the second and third configuration, we used a low-noise preamplifier, SR560. We used 30dB for the amplification factor, which was empirically selected after a tuning process. We also employed a low-band pass filter with the pre-amplifier to reduce the noises caused by higher frequency components. Considering the aforesaid typical frequency of human respiration activities, we employed 3Hz for the low-band pass filtering. For data acquisition, we used a generic data acquisition card from National Instruments (NI6001) and the LabView software with a sampling rate of 1,000 per second.

We placed a DRS on a table as shown in Figure 4. The height was 0.7m (a typical table height) and the subject was sitting naturally and wearing the MLT1132 respiratory belt by ADInstrument. The belt is a transducer that produces a voltage proportional to variations in length of the belt and was used for ground truth data collection.

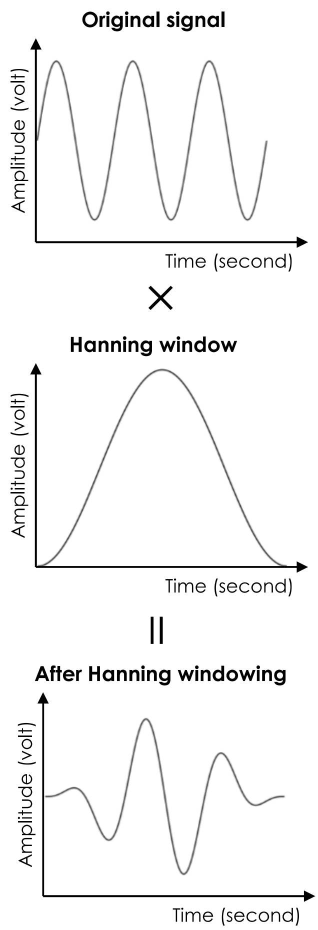

Figure 3. Applying Hanning window

For the first experimental configuration, the subject sat at multiple locations with respect to the location of the sensing system (Figure 6). With the use of external preamplifier, we presumed that a longer distance can be attempted. more distant points were examined: (1) 1.50m longitudinal and 0.50m lateral distance from the sensor and (2) 2.0m longitudinal distance from the sensor at the centreline. These locations have been highlighted with red circles in Figure 6. In each position, the subject faced different angles (from +45, +22.5, 0, –22.5 to –45º). Considering the symmetry of the sensing system, the data collection was conducted only on one side of the sensing system. Considering that DRS measures respiration activity by capturing the periodic movement of chest and abdomen area (moving back and forth), we did not consider the angle beyond ±45º. At each position and angle, we measured the subject's respiration activities for four times (each was 30 seconds of measurement – two minutes in total).

For the multi-occupancy case, which was the third configuration, two subjects were sitting in front of a DRS at 0.50m from the sensor and breathed naturally for 30 seconds.

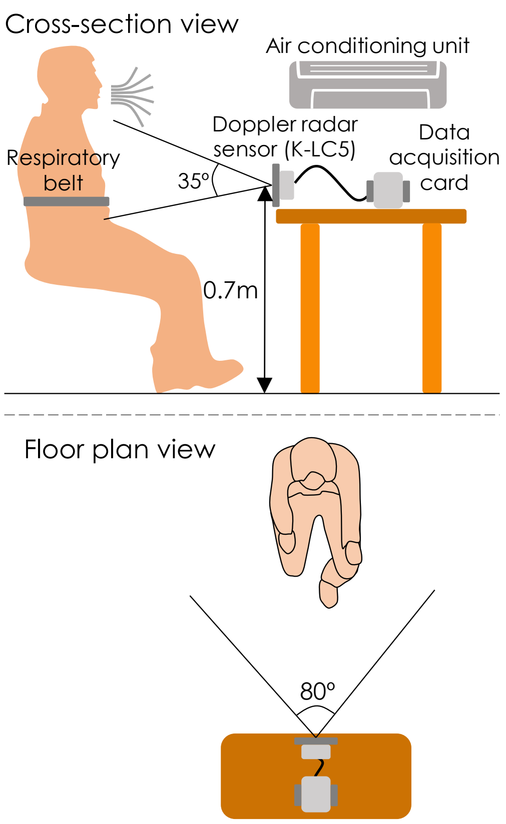

Figure 4. Cross-section and floor-plan view of the experimental set-up

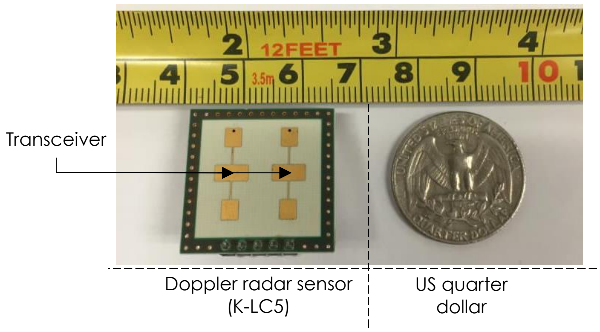

Figure 5. Doppler radar sensor used in this study

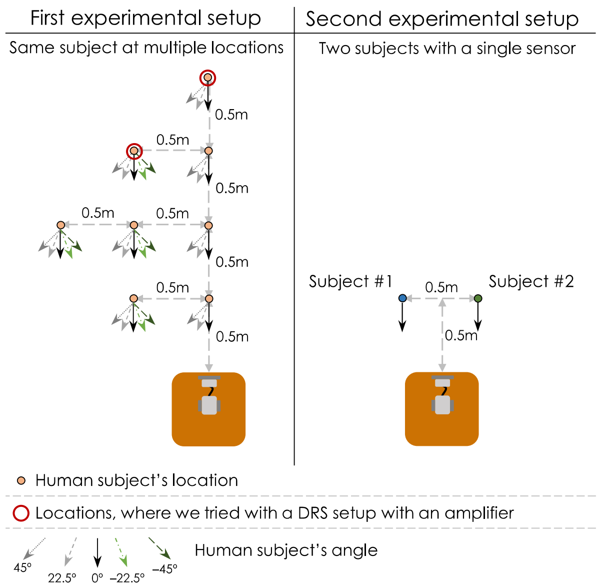

Figure 6. Subjects' locations and angles with respect to the DRS

4 Result

After collecting the raw DRS and respiratory belt data, we employed the aforesaid four steps to extract respiration activities from raw DRS data. Given that the data from belt does not contain noise we only employed the third and fourth steps on the data from that sensor. Due to the use of 30 seconds of measurements (N) with a sampling rate of 1,000 per second (F_s), the frequency resolution of FFT was $0.033Hz$ (F_s/N = 1000/30000 = 2 breathing per minute (BPM)). We compared the respiration rate from the DRS and respiratory belt data and interpreted the results using three indices: (1) there is no gap between the DRS and belt data (good), (2) the gap is equal to or below 4 BPM (moderate), and (3) the gap is more than 4 BPM (poor).

The results are shown in Table 1. Without the use of an external amplifier, the best performance was observed when the subject was facing the DRS at a distance of 0.5m. In this position, even when the subject's position was shifted at 45 degrees, correct measurements were observed in three out of four cases. In general, as anticipated, in cases the subject was facing the DRS system sitting parallel with the radar antenna plane, the returned signal captures more pronounced movements of the chest and abdomen areas, resulting in a better performance. In addition, in cases that the subject was sitting within the 0.5 m range (both longitudinal and lateral) away from the DRS, the accuracies were fairly acceptable. The discrepancy between the DRS measurements and the ground truth data increases as the range of measurement increases. The cells with light orange color represent the poor performances.

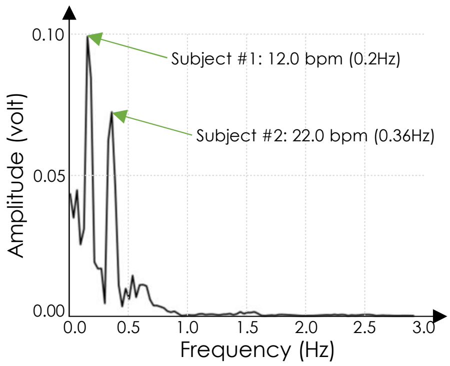

Figure 7. Results from the second experimental study

When the external amplifier was used, we could observe that the accuracy for farther ranges (or longer distances) is improved. For example, the case that the human subject was sitting in 1.0 m range (both longitudinal and lateral) away from the DRS, this DRS setup could identify breathing with fair accuracies, while the first setup fails. Even with the farthest ranges (1.5m longitudinal and 0.5m lateral, and 2.0m longitudinal), respiration activities could be quantified with fair accuracies. However, it has been observed that amplifying the DRS signal might result in lowering the overall accuracy. This is because the amplifier also amplifies the noise in the environment, often caused by subjects' subtle and spontaneous (e.g., yawning) movements.

Lastly, Figure 7 illustrates FFT output of the DRS signal for the third experimental configuration. As this graph shows, within the typical respiration frequencies two peaks are clearly located. Although limited observation, it shows that multi-occupant sensing could be potentially feasible using a single DRS system. However, more experimental studies are required for significant conclusions on multi-occupancy conditions.

5 Conclusion

This study has sought to investigate the ubiquity attribute of a non-intrusive respiration monitoring system, which has the potentials to be integrated into comfort-aware HVAC system operation. Given the recent research trends of exploring potential apparatuses of measuring human-related contextual data, this study provides insight into the feasibility of utilizing DRSs as a cost-effective and ubiquitous measurement system. The results demonstrated that, even by using a simple sensing and data processing set-up, respiration activities could be reasonably captured within the range of 1.0 m longitudinally and 0.5 m laterally. Considering the normal office environments, where occupants normally sit in a distance of 1.0 meter vertically from the computer monitor, this range can sufficiently cover an occupant. Moreover, the size of this sensor is small enough to be placed in a desk without interfering with occupants' activities. It is also noted that having an amplifier could expand the range of a DRS, but the set-up requires more advanced noise cancellation processes for precise respiration activity quantification. We have also preliminarily assessed the potential of sensing multiple people with a DRS with promising result.

One of the requirements for use of DRSs for thermoregulation state quantification is the duration of data acquisition, required for measurements. Due to the low frequency of respiration by nature, its precise measurement requires longer data collection durations. In this study, we used 30 seconds of measurements and, as a consequence, a 2-BPM resolution could be achieved with FFT. For a higher frequency resolution, a longer measurement time is necessary. As noted before, users' unintentional motions could add noise to the DRS signal and having a long measurement time increases a possibility of having noises.

Although this study used a specific product to evaluate the ubiquity attribute of a DRS, it can be used as a baseline for the future studies as we used a minimal hardware and software set-up. Accordingly, as future research, more diverse DRS set-ups can be explored with several scenarios such as expanding the testing area or having multiple DRS systems. Furthermore, the signal processing framework could be further developed. For example, in case of multi-occupancy conditions, a signal separation technique, such as independent component analysis, could be tried when similar breathing rates are captured by multiple occupants. As the results show, the proposed DRS system can also be used in vehicle air-conditioning operations considering its vicinity to the drivers. Accordingly, the outcome of this study will contribute to realization of comfort-aware HVAC operation, assisted with physiological sensing system. Another potential application includes monitoring of construction equipment operators.

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Table 1. Subject's location, angle, the experimental configurations, and the three evaluation criteria: (1) BPMs from the DRS and respiratory belt are equal, (2) the gap is equal to or below 4 BPM, and (3) the gap is more than 4 BPM.

Location (m)		Angle (º)	Number of monitored cases: Differences between the breathing rate from ground truth and DRS-based respiration monitoring					
			Without an external amplifier			With an external amplifier		
Longitudinal	Lateral		Equal (Good)	≤4 (Moderate)	>4 (Poor)	Equal (Good)	≤4 (Moderate)	>4 (Poor)
0.5	0.0	0.0	4	0	0	0	0	4
		22.5	4	0	0	2	0	2
		45.0	3	1	0	1	2	1
0.5	0.5	–45.0	2	2	0	1	3	0
		–22.5	2	2	0	2	1	1
		0.0	3	1	0	1	2	1
		22.5	2	2	0	0	2	2
		45.0	2	1	1	0	3	1
1.0	0.0	0.0	3	1	0	1	3	0
		22.5	1	2	1	0	3	1
		45.0	1	1	2	0	2	2
1.0	0.5	–45.0	2	0	2	0	3	1
		–22.5	1	1	2	0	2	2
		0.0	0	0	4	2	1	1
		22.5	2	0	2	1	1	2
		45.0	1	0	3	0	2	2
1.0	1.0	–45.0	0	4	0	0	1	3
		–22.5	0	0	4	2	1	1
		0.0	0	0	4	1	3	0
		22.5	0	0	4	2	1	1
		45.0	0	0	4	0	2	2
1.5	0.0	0.0	1	2	1	1	2	1
		22.5	0	0	4	2	2	0
		45.0	2	0	2	0	2	2
1.5	0.5	–45.0	-	-	-	2	1	1
		–22.5	-	-	-	0	2	2
		0.0	-	-	-	1	3	0
		22.5	-	-	-	1	1	2
		45.0	-	-	-	1	1	2
2.0	0.0	0.0	-	-	-	2	1	1
		22.5	-	-	-	1	1	2
		45.0	-	-	-	0	3	1

The cells with the light orange color have the bad cases more than 3 times (75%)

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