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Ultrasonic Methods for Human Motion Detection

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ABSTRACT

Methods of human detection utilizing low-frequency (typically below a few hundred Hertz) seismic signals from footsteps are well known. Human footsteps generate broadband frequency vibration and sound signals from a few Hertz up to ultrasonic frequencies. The authors investigated the physical mechanisms involved in the generation of high frequency signals and the possibility of their application for human footstep detection. Striking and sliding contacts between a foot and the ground/floor produce the high-frequency responses. The present paper introduces an approach for human motion detection using passive and active ultrasonic methods. The passive method employs an ultrasonic sensor that is sensitive to the sound from sliding contacts. The active method utilizes continuous wave ultrasonic Doppler sonar. Human motions have unique Doppler signatures and their combination with footstep vibration and sound signatures increases the probability of human presence detection and reduces false alarms. Test results for the detection of a walking person by the two methods, both indoors and outdoors, are presented and discussed. This work is supported by the Army Research Office under Grant W911NF-04-1-0190.

1.0 INTRODUCTION

Walking people generate unique footstep acoustic [1, 2] and Doppler signatures [3-6] that can be used in security systems for human detection and recognition to differentiate them from other moving objects. Human footstep acoustic signatures have broadband frequency response from a few Hertz up to ultrasonic frequencies and generate vibrations and sound by an interaction of the foot and the supporting surface. Doppler signatures utilize vibrations of human body parts due to motion.

There are two characteristic frequency bands in the vibration and sound responses of footstep signatures [1, 2]. The first frequency band is generated by a force normal to the supporting surface and is concentrated in a low-frequency range below 500 Hz. This frequency band is used for seismic security detectors. The second frequency band is generated by the tangential (friction) force and located in a high-frequency range, above 1 kHz up to ultrasonic frequencies. Different walking styles (regular, soft and stealthy [1, 2, 7]) result in different vibration signatures in the low-frequency range that determine the maximum ranges for this method of footstep detection. For example, the stealthy walking style was undetectable even a few meters from a seismic detector [2, 7]. In buildings, footstep vibration magnitudes in the high-frequency range are comparable and independent of walking styles at distances close to the detector (one meter) [1].

The high-frequency (above 1 kHz) footstep vibration response was detected on a building floor, but was not detected on the outdoor ground, even at one meter from a walker [2]. This result shows greater attenuation of vibrations in the ground than in a building floor. This article presents a method for measuring the high-frequency response in footstep signals on the ground. This method is based on sound pressure measurements because the sound attenuation in air is significantly less than vibration attenuation in the ground [8]. Low-frequency, ambient acoustic noise decreased the dynamic range of these

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measurements [1], so a microphone, which had maximum sensitivity in the ultrasonic frequency range and roll-offs in sensitivity in the low frequency range, was used in these tests.

Doppler signatures of walking people were investigated and the results have been presented in a number of publications [3-5]. Pulse and continuous wave (CW) radar systems were used in these investigations, mainly under laboratory conditions, and measurements were usually made at short distances (up to 20 meters). The radar beam cross-section and dynamic range of the electronics (usually not more than 14-bits) restricted the human motion analyses at greater distances. These publications showed the benefits of using the unique human Doppler signature for human motion recognition and for the practical applications in security systems, medicine, animation, etc.

The present article reports results of human motion investigations with help of CW ultrasonic Doppler sonar. Low-cost, low-power ultrasonic motion sensors have been used in a wide range of applications, including security systems, since the 1970's [9-11]. A number of different ultrasonic sensors have been developed for operation in air [10]. Benefits of using ultrasonic CW Doppler sonar included the low-cost, low-electric noise, small size and weight of ceramic transducers and receivers, and the usage of the low-cost, 16-24-bit data acquisition boards with a sampling rate of 96 kHz for signal processing, recording, and analysis. Additional advantages of using ultrasonic Doppler sonar in building hallways include the possibility of detecting a walker by secondary reflections of ultrasonic waves from walls (secondary backscattering). This allows observation of a walking person obscured by a hallway corner.

This article introduces an approach that utilizes passive and active ultrasonic methods exploiting unique human high-frequency footstep sound pressure and Doppler signatures for human motion detection and recognition. Ultrasonic sensors with different frequency bands for passive and active methods were assembled in a small enclosure. Test results for human detection at the distances up to 18 meters are presented and discussed.

2.0 SETUP FOR MEASUREMENTS OF HUMAN FOOTSTEP VIBRATION AND SOUND SIGNATURES ON THE GROUND

High-frequency bands (above 1 kHz up to ultrasonic frequencies) in the vibration and sound responses from human footsteps were observed experimentally in buildings [1, 2]. Outdoor tests showed only the low-frequency vibration responses (below 1 kHz) of the ground to footsteps [2].

Since sound has less attenuation in air than vibrations in the ground [8], a new concept was pursued for development of a setup for high-frequency measurement of footsteps in outdoor tests. A resonance ultrasonic ceramic transducer was used for the high-frequency sound measurements. The resonance receiver was chosen because of the high level of the ambient noise floor in the low frequency range when compared with ultrasonic frequencies [12]. This high noise level can decrease the dynamic range of measured signals from footsteps in the high frequencies. However, the resonance receiver naturally filters low frequencies.

Outdoor tests were conducted in a grassy area on the University of Mississippi campus. The test setup (which was a modification of the test setup described in references [1, 2]) consisted of a circular track marked on the ground with a constant distance from an accelerometer to the subject during the measurements as shown in Figure 1. In these experiments a person walked on the circular track, which was 0.2 meter wide. The median radius of the track was one meter and, depending on the length of person's stride, 9-11 steps were required to complete a full circle.

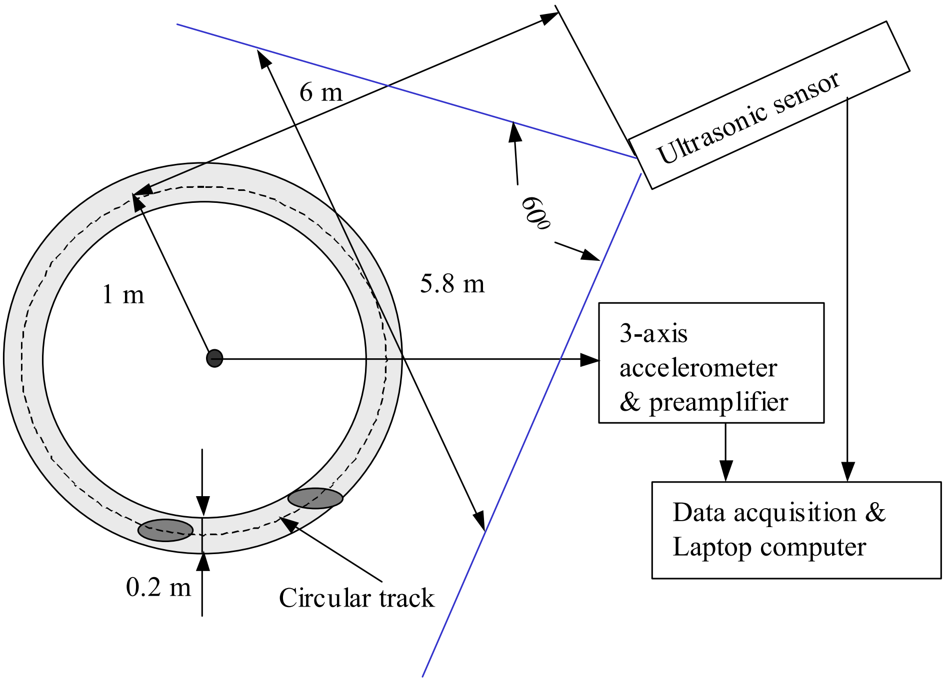

Figure 1. Setup for measurements of vibration and sound frequency response from footsteps on the ground.

A 3-axis accelerometer (PCB 356B18) was threaded into the top of a 10-centimeter spike hammered into the ground at the center of the circle as shown in Figure 1. The accelerometer was calibrated over the frequency range of 0.2 Hz-16.5 kHz and had a sensitivity of 1 V/g. A battery-powered signal conditioner (PCB model 480B21) amplified signals from the accelerometer. Only the component of acceleration normal to the ground surface is presented and discussed in this article. An ultrasonic ceramic sensor (25OSR) was attached to a tripod of 1.2 m height and placed 6 meters away from the center of the test track as shown in Figure 1. The ultrasonic ceramic sensor (UCS) had a resonance frequency of 25.5 kHz and typical bandwidth (at –6 dB) 1 kHz. The directivity (at -6 dB) was 60^0. The UCS was calibrated at the resonance frequency of 25.5 kHz and had a sensitivity of – 18 dB re 1 V/Pa. In the configuration presented in Figure 1, the beam pattern of the ultrasonic sensor covered all of the test area. A receiving preamplifier (not shown in Figure 1) amplified signals from the UCS. Data recording and processing were conducted using a two-channel, 16-bit data acquisition board (DAQ) (Echo Indigo IO) and a laptop computer with Sound Technology software (LAB432).

3.0 TEST RESULTS: FOOTSTEP VIBRATION AND SOUND SIGNATURES ON THE GROUND

Footstep acoustic signatures for regular, soft, and stealthy walking styles (described in reference [1]) of a man were measured using the setup shown in Figure 1. A man walked at constant speed for all test styles. A DAQ with a sampling rate of 64 kHz and a 32 kHz anti-aliasing filter acquired signals from the accelerometer and the UCS. The data (sound pressure and acceleration) for a full circle of ten footsteps for each walking style were taken and merged together in one data file. The results of processing are presented in Figures 2(a) - (c). The walking styles and each footstep on the test track are marked in these figures. Spectrograms of the sound and acceleration responses of the ground in the frequency band of 24.5 kHz – 26.5 kHz for the sound and of 20 Hz – 600 Hz for the acceleration are presented in Figures 2(a) and 2(b). The time domain signal of the acceleration is presented in Figure 2(c).

The high-frequency vibrations above 600 Hz were not detectable. All data are presented in the frequency range below 600 Hz. The fast Fourier transform (FFT) size was 8192, which corresponded to 7.81 Hz in the spectral line resolution and 128 ms in the time resolution. The qualitative comparison of the sound pressure and vibration responses of the walking styles shows the stable level of sound pressure signals for all walking styles in the distance range of 5-7 meters. The vibration response was less detectable for soft and stealthy styles even in one meter from detector.

In Figures 3 (a) and (b), the average spectra of ten footsteps for each walking style are presented for sound pressure and vibration signals, respectively. The sampling rate was 64 kHz and the FFT size was 32,768. The maxima of footsteps sound pressure responses have comparable magnitudes for all walking styles in high-frequency range. The signal to noise ratio is near 15 dB. This effect supports the conclusions reported in article [1] for footstep vibration signatures for different styles of walking in buildings.

The maxima of the ground vibration response to footsteps are in the frequency band near 19 Hz for all walking styles. The magnitudes of the sound pressure at 25.5 kHz and the acceleration at 19 Hz are presented in Table 1. A comparison of the walking styles and maxima of the vibration responses shows that the vibration maxima are related to the walking styles (see Table 1 and Fig. 3 (b)). Soft and stealthy walking reduced the vibration response of the ground by 7.5 dB and 12.5 dB, respectively, relative to regular walking. As a result, the range for footstep detection was reduced. The sound pressure response in the high-frequency range had no similar strong dependence on walking style (the dispersion of magnitudes is within of 1 dB).

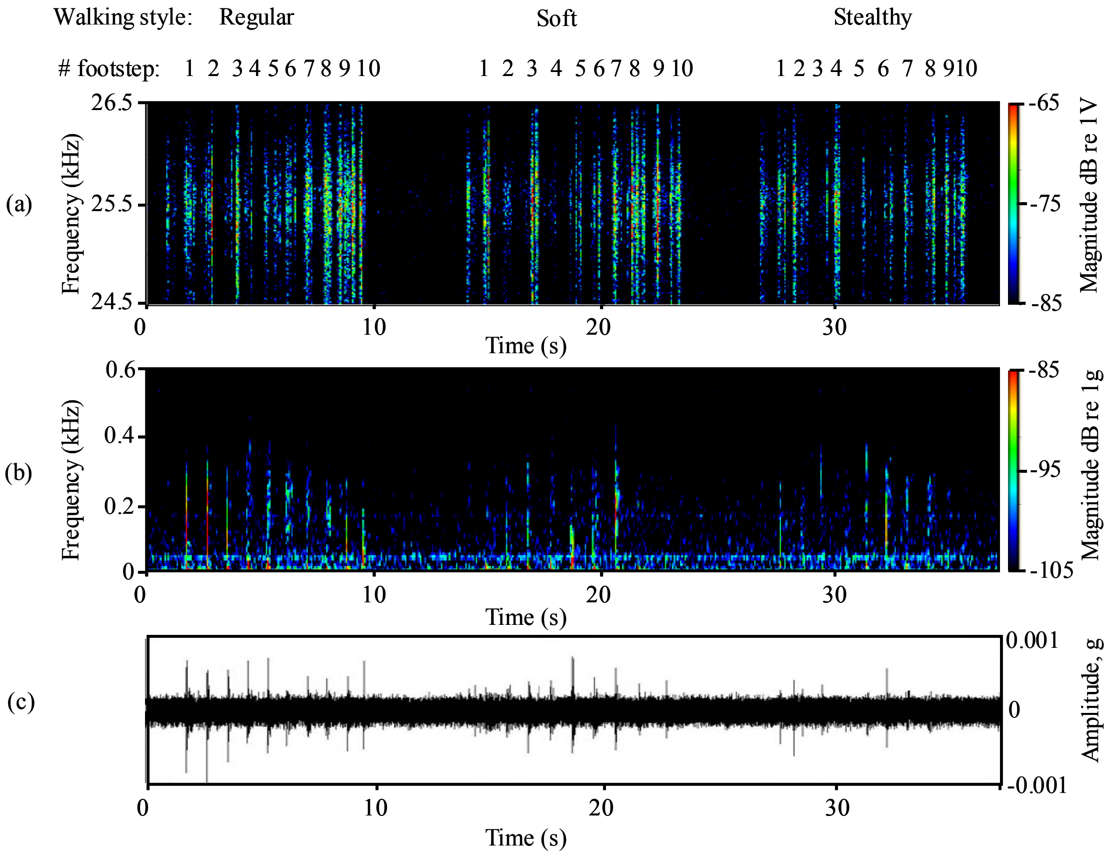

Figure 2. (a) and (b) are the spectrograms of sound pressure at a distance of 5-7 meters from a walker and acceleration at a distance of 1 meter from a walker, respectively, (c) is the time domain signal of acceleration of ten regular, soft, and stealthy footsteps on the ground. The sampling rate was 64 kHz and the FFT size was 8192.

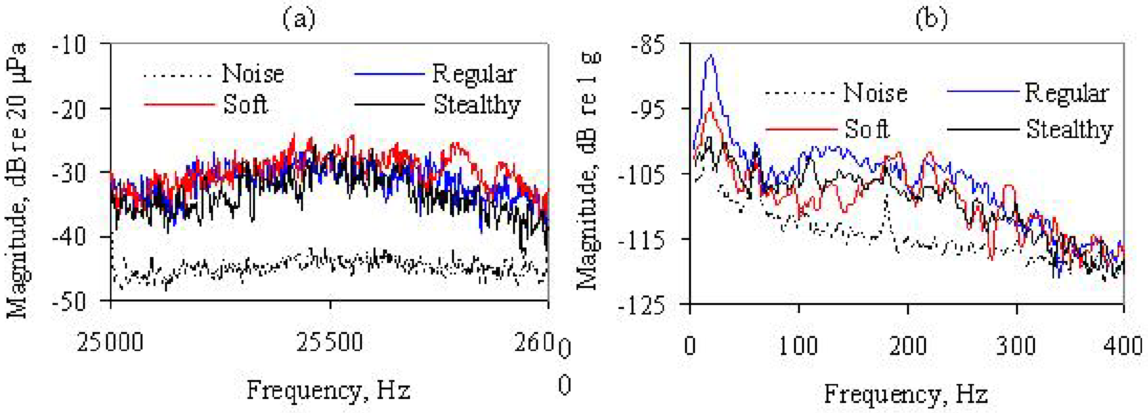

Figure 3. Average Fourier spectra of ten regular, soft, and stealthy footsteps on the ground. (a) is the sound pressure at 5-7 m from a walker and (b) is the acceleration at 1 m from a walker. The sampling rate was 64 kHz and the FFT size was 32,768.

Table 1. Walking styles

n	Walking style	Max. sound pressure response, dB re 20µPa @ 25.5 kHz	Max vibration response, dB re 1 g @ 19 Hz
1	Regular	-28	-86.5
2	Soft	-27	-94
3	Stealthy	-28	-99

4.0 MEASUREMENTS OF THE HUMAN MOTION DOPPLER SIGNATURE

A detailed investigation of the human body motion Doppler signature was conducted to study the problem of human recognition among other moving objects, for example, in a security system as the method of the false alarm reduction. There are a number of publications about results of measurements of the human motion Doppler signature by radar systems [3-6]. In general, this method involves the transmission of electromagnetic waves to the human body and registration of the back-scattered waves by the radar. The reflected waves are frequency-modulated by time-varying motions of human body parts, so the time-frequency analysis (spectrograms or dynamic spectra) is widely used in the investigation of the human motion Doppler signature [3-5]. The transmitted frequency typically is in the range of 2.4 – 100 GHz.

4.1 Application of the CW Ultrasonic Doppler Sonar for Measurements of Human Motion

An ultrasonic method can be applied for the study of the human motion Doppler signature. The physical principles (emitting and receiving the backscattered energy) and signal processing of ultrasonic and electromagnetic techniques are similar. The differences in the physical nature of waves (sound and electromagnetic waves) and in the speed of waves propagation (C_s = 343 m/s for the sound waves and C_e =300,000,000 m/s for the electromagnetic waves) make the ultrasonic measurements simpler and cheaper than electromagnetic measurements. For example, the wavelength of an ultrasonic wave at the frequency of f_s =40 kHz ($\lambda_u = C_s/f$ = (343,000 mm/s /40,000 s^{-1}) = 8.6 mm) is equal to the electromagnetic wavelength at the frequency of f_e = 35 GHz ($\lambda_e = C_e/f$ =(300,000,000,000 mm/s /35,000,000,000 s^{-1}) = 8.6 mm). These low-cost, ultrasonic sensors were developed for operation in air [10, 13].

Another advantage of measurement at ultrasonic frequencies is the application of low-cost, digital data acquisition boards (DAQ) that have broad dynamic ranges up to 24-bits in the frequency range up to 96 kHz for the signal processing and analysis. The extended dynamic range increases the accuracy of the human motion Doppler signature analysis. Potentially, it allows for the separation of reflected signals in the Doppler signature from individual human body parts (torso, legs, arms, etc.) that have different cross-sections.

Ultrasonic waves are almost fully reflected from rigid surfaces, for example, from walls in buildings. This property offers an opportunity to detect human motion by secondary reflected waves from walls (indirect method). Direct measurements of human motion involve:

Transmitted signal - human body - backscattered signal - receiver

Indirect measurements of human motion involve:

Transmitted signal - reflector - human body - backscattered signal - reflector – receiver

Ultrasonic and electromagnetic Doppler systems can both conduct direct measurements. Indirect measurements of the human motion Doppler signature using electromagnetic radar are only possible in the case where a fully-reflected surface for electromagnetic waves exists (metal walls, for example). Indirect measurements of a human motion (“vision” around the corner) are possible with ultrasonic Doppler sonar in buildings with the rigid walls that are typically used in constructions. This paper presents the test results of direct and indirect measurements with ultrasonic Doppler sonar in a modern building hallway.

4.2 Setup for the Measurements of Human Motion by the CW Ultrasonic Doppler Sonar

An ultrasonic Doppler sonar (UDS) was designed using two ultrasonic ceramic sensors (MATSU/PAN EFR-RCB40K 54). These sensors had a resonance frequency of 40 kHz, typical bandwidth (at –6 dB) 2 kHz, and directivity (at -6 dB) of 55^0. Both sensors were placed in a compact plastic enclosure as shown in Figures 4(a) and 5. One of the sensors emitted an ultrasonic wave and the other acted as a receiver. A HP 3314A signal generator applied a continuous wave electrical signal at 40 kHz to the transmitter. Signals from the receiver were amplified with a Stanford Research Systems SR 560 low-noise preamplifier (not shown in Figure 5). Data processing and recording were conducted using a two-channel, 16-bit DAQ (Echo Indigo IO) and a laptop computer with Sound Technology software (LAB432). Only the 40 kHz sensors shown in Figure 5 were used in these tests.

The human motion Doppler signatures were measured in the hallways of a modern university building. Direct and indirect measurements were conducted using the setups shown in Figures 4(b) and (c). These setups have straight tracks for walking and two different directions for the UDS beam pattern with respect to the tracks (parallel to walking track and orthogonal to walking track) as shown in Figures 4 (b) and (c).

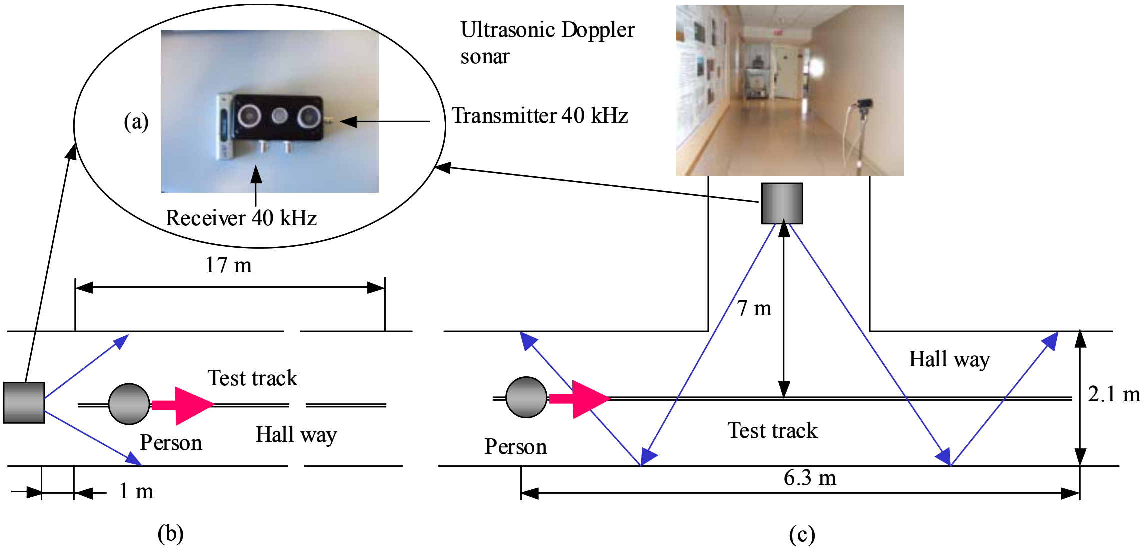

Figure 4. (a) Ultrasonic Doppler sonar; (b) Setup for direct measurements of human motion in which the UDS beam is parallel to the test track; (c) Setup for indirect measurement of human motion in which the UDS beam is orthogonal to the test track.

The UDS was placed on a tripod of 1.2 m height and located at the center of the width of hallway. In these experiments, a person walked on a straight track 0.3 meter wide. The length of the track was 17 meters for direct measurements and the distance from the UDS to the track beginning was 1 meter as shown in Figure 4 (b). The length of the track for indirect measurements was 6.3 meters and the minimum distance from the UDS to the track was 7 meters as shown in Figure 4(c).

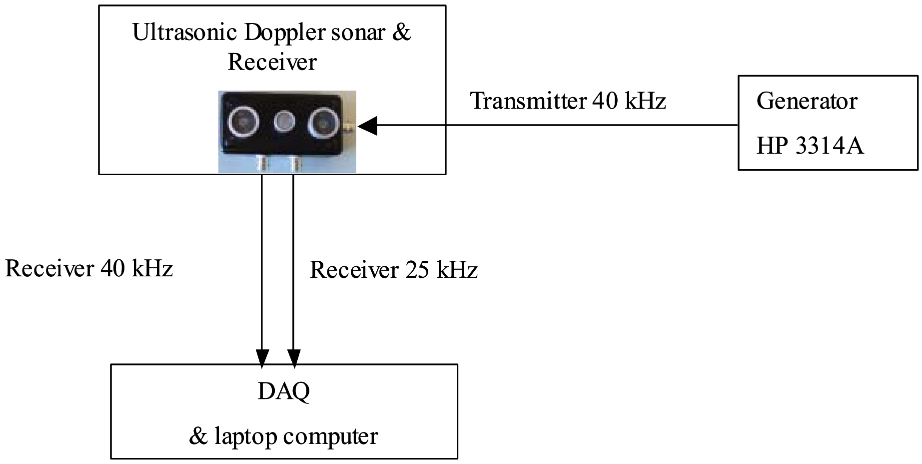

Figure 5. Block diagram of the measuring system.

5.0 TEST RESULTS: HUMAN DOPPLER SIGNATURE

Doppler signatures for the regular walking style of a walker were measured with the setup presented in Figures 4 (b) and (c). A DAQ with a sampling rate of 96 kHz and a 48 kHz anti-aliasing filter acquired signals from the UDS.

5.1 Direct Measurements of the Human Doppler Signature

The spectrogram of reflected waves in the frequency band of 38.5 kHz – 40.5 kHz from a person walking away from the UDS at a range of 1-18 meters is presented in Figure 6. A walker was standing one meter from the UDS (the start time of 0 s in the spectrogram) and then started walking with a constant speed of motion on the straight track as shown in Figure 4 (b), and stopped out off track range. Twenty-two steps were required to complete the distance of 17 meters. The average length of the person's stride was L = 17m/22 = 0.73 m. The FFT size was 16,384, which corresponded to 5.9 Hz in the spectral line resolution and 170 ms in the time resolution.

The spectrogram shows detectable values of Doppler shifts in reflected waves from a walking person at a distance of 1-18 meters on the test track. The horizontal red line (40 kHz) in the spectrogram is the sum of direct coupling between the transmitter and the receiver through the air and the common enclosure and the reflected signal from stationary objects. The strongest reflection from a walking person corresponded to the line fluctuated near the frequency of 39.7 kHz (marked by #1 in Figure 6). The Doppler shift Δf is proportional to the object speed V [14]:

$$\Delta f = \frac{2V}{C_S} f \ , \qquad (1)$$

where C_S is the sound speed, and f is the transmitted frequency.

In this case in which the frequency shift was –300 Hz (where C_S = 343 m/s was the sound speed in air, f = 40kHz, Δf = 300 Hz), the speed of the walker V follows from Equation (1):

$$V = \frac{\Delta f}{2 \times f} \times C_S = \frac{300}{2 \times 40000} \times 343 = 1.29[m/s] \ . \qquad (2)$$

The direct estimation of V from data presented on the spectrogram in Figure 6 gives the value of:

$$V = \frac{D}{t} = \frac{17}{13.8} = 1.23[m/s], \qquad (3)$$

where D of 17 meters was the track length, t =13.8 s was the time needed to traverse the track by the walker.

The speed V calculated from the Doppler shift (Eq. (2)) and from experimental geometry (Eq. (3)) is approximately the same, so the frequency shift of –300 Hz corresponds to the body part having the maximum value of the cross section, that is the torso [3].

The envelope of curves marked by #2 in Figure 6 corresponds to the motions of the legs and arms, which have smaller cross sections than the torso, so they are less detectable with distance. Leg and arm motions had larger Doppler shift values in comparison with the torso motion, which corresponded to the larger speeds of these body parts.

The comparison of relative phases of curves #1 and envelope #2 (Figure 6) shows that the minimum value (minimum Doppler shift) of the torso motion corresponded to the maximum value of leg and arm motions. The torso motion is in the opposite phase to one set of leg and arm motions and in phase to another set of leg and arm motions. The minimum value of the Doppler shift in envelope #2 ($\Delta f = 0$ Hz) corresponds to the zero speed of leg and arm (where one leg is in contact with the floor).

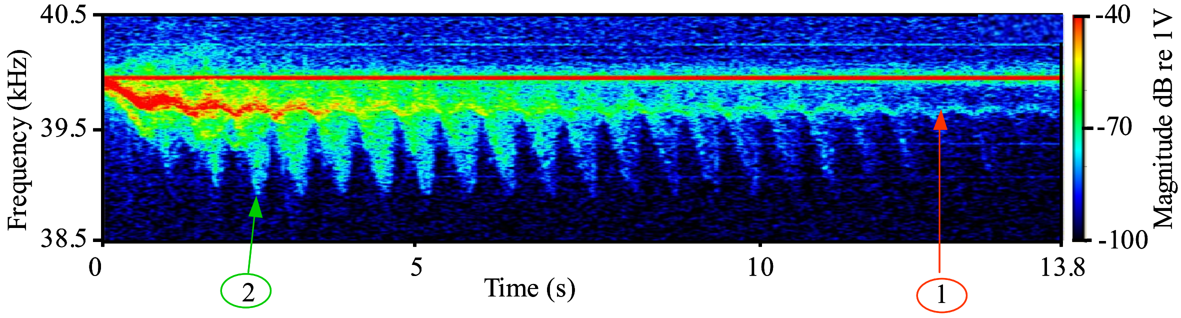

Figure 6. A spectrogram of the human Doppler signature at the distance range of 1-18 meters. A person was walking away from UDS. The sampling rate was 96 kHz and the FFT size was 16,384.

5.2 Indirect Measurements of the Human Motion Doppler Signature

There were two tests using indirect measurements of the human motion Doppler signatures versus speed of motion in the building hallway for the setup shown in Figure 4(c). In the first test, a person was walking and in the second test the same person was running. The spectrograms of reflected waves from the person walking/running in orthogonal direction to the ultrasonic beam of the UDS are presented in Figures 7(a) and (b) in the frequency ranges of 39.5 kHz - 40.5 kHz (for walking) and of 38 kHz – 42 kHz (for running). The hallway geometry corresponding to the track length and start/stop positions of the walking/running person are plotted on the top of Figures 7(a) and (b). The person was standing 2.1 meters from the hallway corner, then started walking/running on the straight track as shown in Figure 4 (c), and stopped 2.1 meters beyond the corner. Nine walking steps or five running steps were required to complete the distance of 6.3 meters. The average length of the person's stride was $L_1 = 6.3\text{m}/9 = 0.7\text{m}$ (for walking) and $L_2 = 6.3/5 = 1.26\text{m}$ (for running). The FFT size was 8192, which corresponded to 11.7 Hz in the spectral line resolution and 85.3 ms in the time resolution.

The spectrograms show detectable values of the Doppler shifts in the reflected waves from the walking/running person, including the motion in the space obscured by the hallway corner. Three walking and two running footsteps were detected beyond the corner as shown in Figures 7(a) and (b).

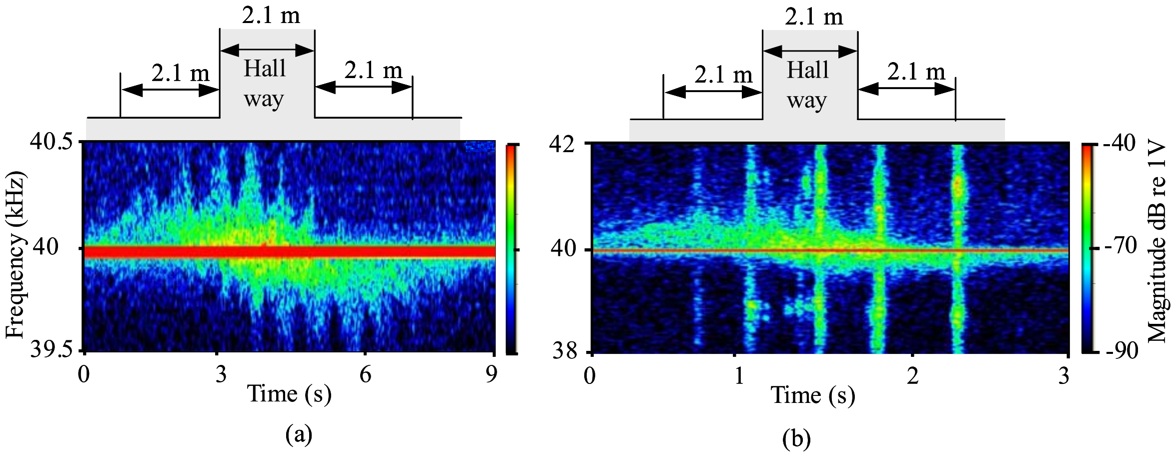

Figure 7. The spectrograms of the Doppler signatures of a walking (a) and running (b) person in the orthogonal directions to the ultrasonic beam of the UDS, placed 7 meters away from the test track. The sampling rate was 96 kHz and the FFT size was 8192.

6.0 COMBINED ULTRASONIC METHOD OF WALKING HUMAN DETECTION

The fusion of passive and active ultrasonic methods for human motion detection was conducted. UDS and ultrasonic ceramic sensors were placed in the same compact enclosure as shown in Figure 5. The UDS and UCS had different resonance frequencies of 40 kHz and of 25 kHz, respectively. This prevented electrical and acoustical interference between sensors.

6.1 Test Setup

An ultrasonic device (UD), including the UDS and UCS, was placed on a tripod of 1.2 m height and located at the center of the width of hallway. In these experiments, a person walked along a straight track of 0.3 meter width. The length of the track was 8 meters and the distance from the UD to the track edge was 1 meter as shown in Figure 4 (b). A block diagram of the measuring system is presented in Figure 5.

A HP 3314A signal generator was applied to the transmitter of the 40 kHz CW signal. Data recording and processing were conducted using a two-channel, 24-bit data acquisition board (DAQ) (Echo Indigo IO), and a laptop computer with Sound Technology software (LAB432) as shown in Figure 5. A driver for the DAQ was updated from 16-bit to 24-bit that decreased the electronic noise of the DAQ. A 24-bit DAQ allowed making tests without a preamplifier for the receivers. A DAQ with the sampling rate of 96 kHz and 48 kHz anti-aliasing filter acquired signals from the UDS and UCS.

6.2 Test Results

The spectrograms of the Doppler and sound pressure footstep signatures are presented in Figures 8(a) and (b) in the frequency range of 39 kHz-42 kHz (Doppler signature) and of 24.5 kHz - 26 kHz (footstep sound pressure signature) and for a distance range of 1-9 meters from a person walking toward to UD.

A person walked with constant speed of motion on the straight track, as shown in Figure 4 (b), and stopped at one meter from the UD. Eleven footsteps were required to complete the distance of eight meters. The FFT size was 16,384, which corresponded to 5.9 Hz in the spectral line resolution and 170 ms in the time resolution.

The spectrograms in Figures 8(a) and (b) show detectable values of footstep sound pressure and the Doppler signatures at tested distances. The spectrogram in Figure 8(a) shows two responses separated in time in a single footstep signature (11 sets of two close vertical lines in Figure 8(a) correspond to 11 footsteps) described in article [1]. These two responses (phases of footstep motion) were produced by the sliding contacts (friction) between a foot and a floor in the broadband frequency range. The first phase (heel strike) response included the deceleration stage of the leading foot. The second phase (toe slap and weight transfer) included the toe slap resulting from the deceleration stage of the leading foot and the weight transfer resulting from the acceleration stage of the trailing foot. The spectrogram in Figure 8(a) shows qualitatively different magnitudes in footstep signatures for the left and right legs of a walker (odd and even footsteps).

The second spectrogram in Figure 8(b) shows the motion of a person and the first spectrogram (Figure 8 (a)) provides information about the friction due to motion. Friction signals correspond the maximum speed (maximum Doppler shift) in the torso motion. Two separated-in-time responses in a single footstep signal allow identification of the type of moving object. These two combined ultrasonic methods and data analyses help to not only to detect but also identify the type of an object.

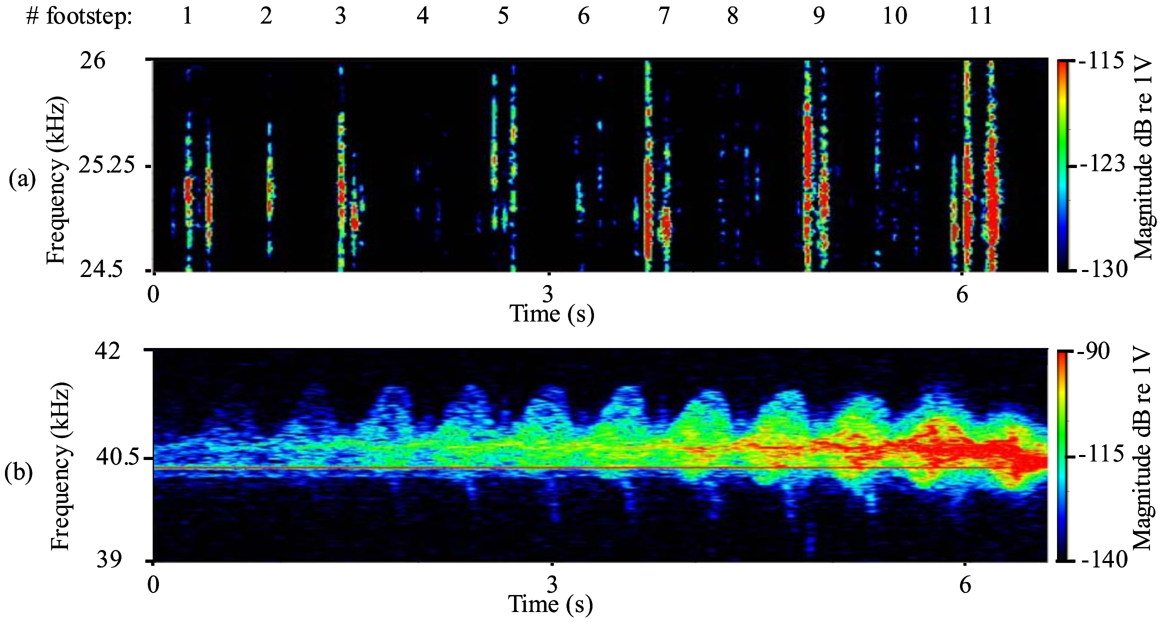

Figure 8. The spectrograms of footstep sound pressure signature (a) and the Doppler signature (b) of a person walking toward to UD in the distance range of 1-9 meters. The sampling rate was 96 kHz and the FFT size was 16,384.

7.0 SUMMARY

An ultrasonic method for human footstep detection, indoors and outdoors, was developed. This method had no strong dependence on the human footstep style (regular, soft, and stealthy), unlike the seismic method. Outdoor tests showed human footstep detection on a grassy ground at 7 meters from the ultrasonic detector with a signal to noise ratio near 15 dB.

The Doppler signature of a walking/running person was measured and analyzed in building hallways. The direct measurements were conducted at a distance range of 1-18 meters. It was experimentally shown that human motion could be detected in the space obscured by a hallway corner (“vision” around the corner). This method is based on measuring the secondary backscattered ultrasonic waves from hallway walls and from human motion.

The fusion of active and passive ultrasonic methods was proposed and tested for human motion detection in buildings. The two methods allow detection and recognition of the type of object by the analysis of the Doppler shift and unique high-frequency footstep signature.

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