Analysis of Active Sounds for Fire Localization

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Abstract: Localization of fire in smoke environments enables fire-fighters to perform fire-fighting operations safely in a short time, and it is also required to develop autonomous fire-fighting robots. This paper provides a sound property available for fire localization by investigating sound transmission through flame-air interfaces, sound transmission across a gas flow whose gas density is different from the air, and sound transmission in smoke. Sound analysis is performed for several sound frequencies, heat release rates and concentrations of smoke. It is shown that sound through flame fluctuates, and the fluctuation range does not depend on the sound frequency, the heat release rate, or the combustion process. Sound through flame can be distinguished from sound through gas-flow or smoke. The sound property shown in this paper informs the existence of flame in the sound path.

Key Words: fire-fighting, fire safety science, disaster response robotics, sound analysis.

1. Introduction

If a fire breaks out in an indoor environment, the fire is usually detected by a fire alarm system. The alarm indicates the existence of a fire around the alarm, however the system does not provide the detailed location of the fire. Therefore, fire-fighters at a fire scene have to search for the fire source and people in need of rescue by direct eye observation. The search operation is difficult and fraught with hazards since fire scenes in indoor environments are often filled with smoke. If the location of fire in smoke is found by a fire localization sensor, then fire-fighters can perform the search operation safely in a short time.

Another motivation for fire localization comes from development of fire-fighting robots [1]–[3]. Fire localization sensors are required to make fire-fighting robots autonomous. Here, autonomous fire-fighting robots are desired by practical agencies such as the Fire and Disaster Management Agency of Japan [4].

Fire localization can be performed by color cameras, infrared cameras, and thermal cameras [5],[6]. They are based on electromagnetic waves, and their performance depends on the wavelength. Short wavelength devices, such as color cameras, infrared cameras and short wavelength thermal cameras, are not available in smoke environments [7]. Although long wavelength thermal cameras work well in smoke environments [7], it is required for fire localization to distinguish fire and other hot objects from thermal images. In a fire scene, there exist several hot objects, for example, fire, smoke, and objects heated by fire. A supervised machine learning technique has been proposed for classifications of fire and smoke from thermal images [8]. However, fire temperature varies depending on burning materials and combustion processes, and it is not reasonable to recognize fire in a huge variety of fire scenes by using only thermal images.

Fire can be also found by sound as follows [9]. A speaker emits a sound in a room, the sound is reflected by a wall, and the sound is received by a microphone. When the sound passes through fire, then the sound decays. The decrease of the sound magnitude informs the presence of fire in the sound path. This is available only if the magnitude of sound through no flame is known. The assumption does not hold in practical situations. The magnitude of the reflected sound depends on the length of the sound path and the reflecting object, and they are unknown in general.

In order to realize fire localization in smoke environments by using other than thermal distribution, this paper focuses on sound since sound has potential for transmission in dense smoke. The following three aspects of sound transmission are investigated in this paper: sound transmission through flame-air interfaces, that across a gas flow whose gas density is different from the air, and that in smoke; each of them is simply called sound transmission through flame, gas-flow, or smoke. Sound analysis is performed for several sound frequencies, heat release rates, and concentrations of smoke. It is shown that sound through flame fluctuates rather than decays. In particular, the following three are demonstrated in this paper: (1) sound through flame fluctuates, and the fluctuation range does not depend on the sound frequency, the heat release rate, or the combustion process, (2) sound through gas-flow also fluctuates, and the fluctuation range depends on the sound frequency, and (3) sound through smoke does not fluctuate. Sound through flame can be distinguished from sound through gas-flow or smoke. The sound property shown in this paper informs the existence of flame in the sound path, and it is available for fire localization.

2. Experimental Setup

This paper introduces two experimental systems described below. Devices and materials used in the experimental systems are listed in Table 1.

Each experimental system contains a speaker/microphone unit, and the unit is the same in all experiments. It consists of a speaker, a microphone, a computer, a microcomputer, an amplifier, and an AD converter. The devices are connected over a wired network. The sound frequency emitted by the speaker is
set to 10 kHz, 30 kHz, or 45 kHz since the effective frequency range of the speaker is from 2.5 kHz to 45 kHz and one of the microphones is from 10 kHz to 65 kHz.

The speaker/microphone unit works as follows. The computer sends a trigger signal to the microcomputer every 0.1 s, and 100 trigger signals are sent for each experimental setting. When a trigger signal is received by the microcomputer, the microcomputer with the amplifier applies a rectangular voltage of 18.0 V with a specified frequency to the speaker for 1.0 ms. Then the speaker emits a sound. Sounds are received by the microphone, and they are sampled by the AD converter at 100 kHz. The sampled data are stored by the computer. In total, 100 trial data are recorded for each experimental setting.

Sound transmission through flame or gas-flow is investigated in an environment, called the burner environment, shown in Fig. 1. A diffusion flame with a uniform velocity distribution can be established on a burner with a porous disk whose diameter and thickness are 100 mm and 10 mm, respectively. The fuel gas is methane, and it is supplied from a bomb to the burner. The volumetric flow rate of the fuel gas is measured with a flow meter, and it can be regulated with a needle valve manually. The flow rate has a linear relationship with the heat release rate of the flame on the burner, and the heat release rate can be controlled manually. The flow rate also has influences on the height and the combustion process of the burner flame. In fact, the burner flame grows as the flow rate increases as shown in Fig. 2. In addition, it is seen that a blue flame is established on the burner at a flow rate of 2.0 L/min, a blue/yellowish flame appears at 4.0 L/min, and a yellowish flame is generated at 6.0 L/min or higher.

The burner environment generates a combustion field that has a non-uniform and time-varying acoustic impedance density in the sound path. Its density variations produce sound refraction and reflection, and they give some effect on the received sound wave [9]. Actual fires at fire scenes come from combustion of hydrocarbon materials, and methane has the simplest chemical structure in hydrocarbon materials. Therefore, the burner environment is suitable for investigation of fundamental characteristics of sound through a combustion field, although its combustion conditions may differ from actual fire scenes. In particular, burner systems with methane fuels are commonly used to investigate fundamental combustion characteristics as can be seen in [10],[11].

In the burner environments, the speaker and the microphone are placed in a vertical line as illustrated in Fig. 1. A sound emitted from the speaker is reflected by a wall located 1.0 m away from the speaker. Then the reflected sound is received by the microphone. Trial data for sound transmission through flame are obtained when a diffusion flame is established on the burner. Trial data for sound transmission through gas-flow are collected when the fuel gas is supplied to the burner without flame. The path length that the sound travels in flame or gas-flow is determined by the burner diameter.

Sound transmission through smoke is investigated in a 1.0 m cardboard cube, called the box environment, shown in Fig. 3. Smoke is supplied from a fog machine with a fog liquid. A
projector and a light meter are placed as illustrated in Fig. 3. They are required to measure the smoke concentration calculated from

\[ k = \frac{1}{L} \log \frac{I_0}{I} \tag{1} \]

where \( L \) is the length of the light path, \( I_0 \) is the intensity of the light through no smoke, and \( I \) is the intensity of the light through smoke [12]. The larger the value of \( k \) is, the less visibility the environment has. The speaker and the microphone are placed at opposite walls as illustrated in Fig. 3. The microphone receives the direct sound emitted from the speaker, and the received sound is not affected by sounds reverberated in the narrow cube for some time.

Actual smoke at fire scenes is a collection of liquid particles and solid particles, and its diameter is of the order of micrometers [13]. The fog machine in the box environment generates liquid particles of the order of micrometers [14], and the wavelength of 10 kHz–45 kHz sound is of the order of millimeters. They mean that the machine-generated particles have the almost same diameter as actual smoke. Therefore, the box environment is available for investigation of fundamental characteristics of sound through smoke although it is filled with only liquid particles. In particular, machine-generated particles are sometimes used as simulant smoke [15].

In summary, sound transmission through flame, gas-flow, and smoke investigated in this paper denotes, respectively, sound transmission across a combustion-gas flow in a reactive field at high temperatures, that across a methane-gas flow in a non-reactive field at ordinary temperatures, and that in the air with a liquid-mist in a non-reactive field at ordinary temperatures.

3. Results and Discussions

3.1 Time Series of the Power Spectral Density

For each trial data, a time series of the power spectral density at a specified frequency is computed by the short time Fourier transform. Figure 4 shows three samples obtained when the speaker emitted 45 kHz sound in the burner environment. In the top of Fig. 4, no fuel gas was supplied to the burner, and there existed no flame or gas-flow in the environment. In the bottom two of Fig. 4, a diffusion flame was established at a flow rate of 2.0 L/min. The time when the peak of the direct sound arrived is set to 0 in the three samples.

When there exists no flame or gas-flow in the environment, two large peaks can be found in each time series of the power spectral density as marked by A and B in Fig. 4. The peak A is observed soon after sound emission, and it is from the direct sound emitted from the speaker, not any reflected sound. The peak B is from the sound reflected by the wall since it travels about 2.0 m. A small peak between the peaks A and B is from a sound reflected by the burner.

In the bottom two of Fig. 4, the direct sound and the burner-reflected sound remain almost unchanged from the top of Fig. 4 since their paths are unchanged. On the other hand, the wall-reflected sound passes through flame, and its sound path is changed. Its peak significantly decreases as can be seen from the middle of Fig. 4 or vanishes as confirmed in the bottom of Fig. 4. The sound through flame is variable even if the experimental conditions are fixed.

3.2 Fluctuations of Sound

Resulting peak values of the power spectral density are summarized in Fig. 5, where the peak values for the sound through flame or gas-flow were obtained from the wall-reflected sound, and those through smoke were given from the direct sound. Technically, each peak of the wall-reflected sound is determined as a maximum between 4.59 ms and 6.59 ms after the time when the peak of the direct sound arrives, since the peaks are sometimes not clear as shown in the bottom of Fig. 4. The time of 5.59 ms is the average time when the peaks of the wall-reflected sound at 10 kHz through no flame or gas-flow are received. The number of peak values are 100 for each experimental setting.

It is clear from Fig. 5 that the peak values become constant when there exists no flame, gas-flow, or smoke.

The following two about the sound through flame can be confirmed in Fig. 5: (1) The peak values fluctuate when the sound passes through flame. The fluctuation ranges do not significantly depend on the frequency of the emitted sound. They also do not significantly depend on the flow rate of gas, or equivalently, the heat release rate or the combustion process. (2) The peak values of the sound through flame are less than those through no flame. Their decrements do not depend on the flow rate. Its frequency dependence is not clear from Fig. 5.

In contrast to the sound through flame, the peaks of the sound through gas-flow depend on the frequency of the emitted sound as follows: (1) The peak values at 10 kHz fluctuate very little while the peak values at 30 kHz or 45 kHz fluctuate large. The fluctuation ranges at 30 kHz and 45 kHz are not so different from each other, and they do not depend on the flow rate. In addition, the fluctuation ranges are similar to those of sound through flame. (2) The peak values at 10 kHz do not depend on the flow rate of gas. On the other hand, the peak values at 30 kHz and 45 kHz depend on the flow rate of gas, and they decrease when the flow rate is larger than 4.0 L/min.

Sound transmission through smoke is summarized as follows: (1) The peak values at any frequency and any smoke

![Fig. 4 Three samples of time series of the power spectral density at a frequency of 45 kHz.](image-url)
Fig. 5 Left and middle: box plots of peak values of the sound reflected by the wall through flame and gas-flow. Right: box plots of peak values of the direct sound emitted from the speaker through smoke.

Fig. 6 Scatter plots of peak values versus arrival times of the peaks of the wall-reflected sound. The flow rate of methane was 2.0 L/min.

concentration fluctuate very little. (2) The peak values monotonically decrease as the smoke concentration increases. The decrease rate is large at 45 kHz and small at 10 kHz.

Not only the peak values but also the arrival times of the peaks fluctuate when the wall-reflected sound passes through flame as shown in Fig. 6. The peak values of the sound through flame do not correlate with the arrival times of the peaks. Note that even if the 10 kHz sound passes through gas-flow, both the peak values and the arrival times remain constant.

3.3 Scenario for Fire Localization

If the reflected sound at 45 kHz fluctuates, then the following three possibilities arise: (1) the sound passes through flame, (2) the sound passes through gas-flow, and (3) the reflecting object is moving or changing. In the first case, the arrival times of the peaks at 10 kHz are uncorrelated with the peak values. In the second case, the arrival times of the peaks at 10 kHz are almost constant. In the third case, the arrival times of the peaks at 10 kHz are correlated highly with the peak values as discussed below. In summary, the three cases can be distinguished by the fluctuation characteristics of sound with 10 kHz and 45 kHz components.

Let us now discuss the above third case, and consider a swinging pendulum as a special case. It is assumed that a tangent line of the swing circle is equal to the sound path (see also Fig. 7). If the pendulum is always in the sound path, then only the length of the sound path is changed. If the pendulum is sometimes outside of the sound path, then the reflecting material is changed. The magnitude of the reflected sound depends on the length of the sound path and the material of the reflecting object. Then, the arrival times of the peaks are correlated highly with the peak values for each reflecting object in both the two cases. The authors suppose that large, uncorrelated and frequent fluctuations other than flame do not occur at actual fire scenes such as residential fires, factory fires, or forest fires.

Smoke affects sound transmission little. In particular, the magnitude of sound does not fluctuate very little in smoke. Although the magnitude decreases little in dense smoke, the decrease may be compensated by power increase of the speaker. The presence of smoke is not so serious for fire localization.

Fire localization sensor based on sound has the potential to work well in actual fire scenes. This follows from the following two facts. (1) The sound property shown in this paper derives from a non-uniform and time-varying acoustic impedance density in the combustion field. It is independent of the heat release...
rate or the combustion process as can be seen in Figs. 2 and 5. (2) Sound-based sensors are available if the sound speed is significantly faster than the flowing speed of sound transmitting media. This is valid even if measurement environments are not steady, silent, or clean. For example, ultrasonic range sensors are usually installed on the bottom of unmanned helicopters so as to measure the altitudes [16]. Strong winds caused by helicopter rotors blow in their measurement environments. The ultrasonic range sensors work correctly in such disturbed, noisy, and sometimes dirty measurement environments.

4. Conclusion

Fire localization is useful for both fire-fighters and firefighting robots to perform fire-fighting operations safely in a short time. As a step towards realizing a fire localization sensor, this paper has investigated three aspects of sound transmission; sound transmission through flame-air interfaces, that across a gas flow whose gas density is different from the air, and that in smoke. This paper has demonstrated that sound through flame fluctuated and the fluctuation range is independent of the sound frequency, the heat release rate, and the combustion process. Sound through flame can be distinguished from that through gas-flow or smoke. The result in this paper is available for fire localization, and it provides fire information other than thermal distribution.

The sound property shown in this paper informs the existence of flame in the sound path. The result combined with 2D or 3D sonar scanning generates depth images with information of indoor environments and fire locations. To this end, it is required to establish a concrete algorithm for fire localization and a framework for the combination. This issue needs further research and is remained as future work.

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