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Experimental investigation of the reliability of reception of ultrasound signals in fire conditions

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ABSTRACT

We are concerned with the reliability of ultrasound location through beams reflected or propagating along the line of sight in fire conditions. For this purpose, we experimentally investigate the propagation of ultrasounds under hot air and fire environment, in a laboratory setting, in view of assessing the reliability of ultrasound-based safety devices and equipment for use in fire combat, and the limits of the ultrasounds in this type of application. Effects of hot air flows and fires on the ultrasound attenuation and on the attenuation variability are determined. The main finding is that hot air and fire induce strong (up to two orders of magnitude, 10–40 dB), highly variable attenuations of the ultrasounds, with variations of less than 1 ms, while the amplitude of the transmitted pulses through fire environment has a power-type law distribution. The main conclusion is that low frequency ultrasounds can be dependably used for localization and for robot guidance in fire environments for distances of a few meters, provided that a minimum of 40 dB attenuation is allowed due to fire and that appropriate detection methods, as time diversity, are used. We derive the probability distribution for the amplitude of the transmitted ultrasound pulses and develop design equations for ultrasound equipment for fire environments.

1. Introduction

Helping firefighters find a colleague trapped in the fire, a victim, or their own way out of a dangerous blaze are vital tasks in the firefighting profession. Personnel localization and view under smoke and fire conditions are essential in rescue and firefighting operations. To help fulfilling these tasks, several tools based on a variety of physical effects have been proposed recently. Strong particle emission (smoke), air turbulence, and high temperatures make difficult or impossible the use of direct vision through intense fires and limit the use of IR (thermal) [1,2]. Extensive testing of IR cameras for visualization in fire conditions has been reported by [1] and [2], who nevertheless emphasizes the limits of the extant standards for determining IR devices performance for fire and flame conditions. Ultrasound are not significantly attenuated or refracted by smoke, which makes them a potential candidate in localization and vision under smoke and fire conditions. However, other processes subsequently discussed affect ultrasound propagation, which must be thoroughly investigated and experimentally assessed.

Several authors proposed the use of and evaluated ultrasounds for the localization and rescue of firefighters [3–6], for guiding firefighting robots for rescuing people in fire sites [7,8], and for sensor networks for fire monitoring [9]. Ultrasound, radio, and light beacons in conjunction are proposed by [4] to overcome the limited reliability of each of these technologies under various conditions.

Also, proposals have been made for the use of ultrasound in sensor networks [10,4], localization means [3], monitoring [9] and communication [4] for the use by firefighters, rescue personnel, and fire monitoring. While several authors indicate benefits when using ultrasounds, as the ultrasounds with larger wavelengths are little attenuated in air and are able to propagate around and beyond obstacles [4,9], there are few data in the literature on ultrasound propagation under fire conditions, e.g. [5]. The use of ultrasounds under fire conditions was found only partly satisfactory, with disadvantages including limited range of operation [3] and limited reliability of communication [4]. However, ultrasound systems remain a strong candidate [9], because other systems have their own limitations [11] and because ultrasounds are easily produced with high intensities (e.g., 140 dB) to ensure high

Abbreviations: dB, decibels; IR, infra-red (electromagnetic radiation); RH, relative humidity (%); S/N, SNR, signal-to-noise ratio; STDV, standard deviation; n_{eff}, is the effective value of the noise (measured during the pauses between the pulses)

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signal-to-noise ratios for the reflected signals. The use of two different types of waves, e.g. ultrasounds and electromagnetic waves, combined with data fusion, would further increase the performance of communication and detection systems in fires conditions.

In this paper, we are concerned with the processes affecting the amplitude of the ultrasound signals reflected from surfaces beyond fires – a case of interest in firefighting robots and personnel detection. We do not deal with the effects of fire conditions on time propagation, as used in distance measurements.

The purpose of this research is to determine the usability of ultrasound beams for objects detection and ultrasound communication and visualization under fire conditions, based on measurements. For this purpose, we seek to provide experimental data and to derive the statistics of the received signal in order to establish foundations for assessing the reliability of ultrasound-based devices in fire environments and for the design of such devices. Specifically, we measure and analyze the attenuation process of ultrasounds reflected from cold surfaces after traversing hot air currents and zones with fire. We also determine the changes of the waveform of the emitted signal and characterize the equivalent fluctuation process and noise. We found that, due to fire conditions, for narrow ultrasound beams, attenuations of 40 dB (decibels) and higher must be expected even for small fires, with fast changes in attenuations occurring at time intervals as small as 1 ms. Yet, the variability of the attenuations allows attenuation compensation by appropriate designs of the ultrasound equipment using techniques such as time diversity, self-correlation, and signature detection in the received signals. This study is a first step of a research dealing with the experimental evaluation of ultrasound signals attenuation in fire conditions in view of developing guidance- and search-devices for firefighters.

The organization of the paper is as follows: In the next section, we revise the literature on ultrasound propagation and the involved processes. The third section presents the measuring method. The results are summarized and analyzed in the fourth section. We discuss the results and derive conclusions in the last section.

2. Sound propagation through spatially variable and unsteady atmosphere

The attenuation of the ultrasound under fire environment can be explained by a set of phenomena including refraction, reflection and variable air density scattering due to air temperature gradients, local air change of composition, including humidity, and wavefront change due to air flows induced by fire and by related air currents. The effects of thermal gradients and related air flows on sound propagation was intensively studied in meteorology [12,13,14], and biology [15,16]. Turbulence should be expected at least in parts of the fire region and always under violent fires. Turbulence may compound with other phenomena inducing stronger and irregular local gradients of the above propagation parameters and thus produce a higher variability in the ultrasound propagation. The unpredictability of the strength of the received signal (nonstationarity) in fire environments is explained by the variability of thermal gradients and by the variability of the air velocity under fire conditions. While the turbulence, when present, adds to the effect, it is not a necessary condition for explaining the observed signal variability. Indeed, laminar flows and even an almost stationary atmosphere, when accompanied by large thermal gradients, may 'bend" the sound waves, producing effects of apparent attenuation and heat haze, as extensively analyzed in [14–16], or sound focusing in an unexpected direction, similar to the optic illusions (Morgana mirage).

The direct consequences of the changes in atmospheric composition, in its density, and in its local movements are the change of sound velocity, refractions, reflections, beam defocalization and spot displacement in ultrasound communication systems operating in fire environment. As a result, strong variations of the ultrasound equivalent attenuation of the received signal are expected for communications through highly inhomogeneous medium.

Fires are dynamic processes with fast evolutions and nonstationary characteristics, accompanied by continuously changing temperature, composition, and local gas speed inside the fire zone and in the adjacent regions. Fire induced turbulence manifests in apparently random variations of all these gradients [17]. While there are good models for specific conditions of combustion [18–27], the modeling of fires occurring in nature or in buildings is less developed; in addition, various theoretical models, as [28], wait for experimental validation.

Ultrasounds have been proposed for measuring and visualizing atmospheric turbulence [19,20,23,24,29], determination of flame front position and fire front characteristics [30,31], and combustion processes [21]. The dynamics of small fires, under controlled conditions have been studied recently using light intensity measurements [22], but not tested for natural or model scale fires.

It is known that natural, domestic and artificially produced fires may be characterized by high variability of conditions in the fire and adjacent space, by strong air flows [25,32], nonstationarity [33], and by turbulence [33]. Finding under these conditions the relationship between the generated and the received signals requires in the framework of geometrical optics the use of the concept of eigenrays, the rays connecting two specified points (generating and receiving), respectively the determination of caustic, that is the envelope of the rays reflected from a specified surface. The use of the geometrical optics is however limited to the case where the non-uniformities (domains created by turbulence, regions where the temperature is approximately constant) induced by the fire have dimensions much larger than the wavelength [34]. For ultrasounds of 43 kHz, as used in this research, the wavelength is of the order of 1 cm. Consequently, only inside large fires, far from the fire front, the propagation may be assumed to obey the geometric optics rules. Beyond the density non-uniformities, other effects, as gas ionization [35], changes in the gas chemical composition [36], and the noise generation by the fire [37] affect the propagation and the characteristics of the received ultrasound signal. In Section 4, we deal with further theoretical approaches related to this topic.

3. Measuring method

3.1. Method and experimental equipment

All reported results fall in the class of reflected signal measurements. We chose reflectance instead of direct (line-of-sight) transmission because the later corresponds to the passive localization and to visualization, which are more sensitive to fire conditions. Indeed, the waves have to cross twice the fire under reflectance mode, while in direct reception the waves pass only once the fire.

We performed measurements with ultrasonic generators and receivers built by us to satisfy specific requirements, namely narrow lobe in the radiation diagram (narrow beams), long ultrasound bursts allowing the measurement of variation during single bursts, and large enough silence periods (0.9 s) for determining the change of propagation condition between bursts. The narrow lobe is needed to confine the direction of reception into a small solid angle and allow measurement in the fire regions produced by small, laboratory fires. At the same time, narrow beams are required to model the behavior of localization and