ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Engineering Acoustics
Session 4aEAb: Acoustics for Navigation

4aEAb4. Measuring the acoustic response of a compartment fire

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Rescue teams have a small window of time to locate a downed firefighter. Their task is made more difficult due to low visibility, smoke, toxic gases, and high temperatures. In the United States, most firefighters are equipped with a Personal Alarm Safety System (PASS) device that emits an alarm sound, when the firefighter becomes incapacitated. Rescue teams can then follow this sound to the source to locate the downed firefighter. While the PASS device has been enormously successful, anecdotal evidence has shown it fails in some interesting scenarios. For example cases have been recorded where firefighters inside the building were unable to hear the signal, whereas those outside heard it clearly. To explain these cases, and to improve the signal used by the PASS device, it is necessary to understand sound propagation in the fireground environment. This paper will present acoustic transfer measurements inside a laboratory compartment fire, simulating a fire in a residential structure. The research aims to understand how the developing temperature gradient and smoke layer influences sound propagation. A secondary goal is the development and validation of finite element models of fireground acoustics. [Work supported by U.S. Department of Homeland Security Assistance to Firefighters Grants Program.]

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

Rescue teams have a small window of time to locate a downed firefighter. Their task is made more difficult due to low visibility, smoke, toxic gases, and high temperatures found on the fireground. In the United States, most firefighters are equipped with a Personal Alarm Safety System (PASS) device, that emits an alarm sound when the firefighter becomes incapacitated. Rescue teams can then follow this sound to the source in order to locate the downed firefighter. However, anecdotal evidence has been building that the PASS device, while effective, can be improved in certain situations. Cases have been found where rescue teams inside a structure were unable to hear the alarm, whereas those outside heard the alarm [1]. These anomalies have motivated research to understand sound propagation in compartment fires. This paper will present early efforts towards the modeling and validation of acoustics in compartment fires, with an end goal of guiding the development of the National Fire Protection Association (NFPA) 1982 standard that governs the PASS alarm [2].

NUMERICAL SIMULATION

Experimental acoustic measurements can be expensive and difficult to conduct. A fire magnifies these difficulties, because of the harsh environment. Toxic gasses, high temperatures, potential health and safety risks, and the material losses caused by the fire present a considerable challenge to conducting full scale acoustic experiments in compartment fires. This research attempts to model the sound propagation under realistically evolving fires, and to validate these models using large-scale laboratory experiments.

The evolution of the fire and the associated temperature field is modeled using the computational fluid dynamics package Fire Dynamic Simulator (FDS) and visualized using the package Smokeview. FDS solves a form of the Navier-Stokes equations appropriate for low-speed thermally driven flow [3, 4]. FDS and Smokeview were developed under the leadership of National Institute of Standards and Technology (NIST) and VTT Technical Research Center of Finland, with developers from USA, Finland, France, and Germany.

COMSOL® (a commercially available multi-physics simulation software) was used to model the sound propagation in the temperature field calculated by FDS. COMSOL Livelink™ for MATLAB® was used as the interface between the two programs.

EXPERIMENTAL ACOUSTIC MEASUREMENTS

Full scale compartment fire testing was conducted in the University of Texas burn facility. The facility plan view is shown in Figure 1. The total floor area is 5.6 m x 4.6 m. A 0.2 second, 100–5000 Hz log-frequency modulated signal was generated by an NI-9263 analog output module with a 100 kHz sample rate. This signal was amplified by a QSC MX-700 Power Amplifier, and transmitted to a Fisher SB80555 acoustic driver, mounted in 19.05 mm gypsum board. The response of the room was recorded by two PCB Peizotronics U130D20 microphones placed in the room. Both microphones were wrapped in 5 cm think Kaowool (ceramic fiber insulation) to prevent thermal damage. The microphones were connected to a PCB Piezotronics model 480E09 ICP Sensor Signal Conditioner. Simultaneous digitization at 16.6 kHz was performed using an NI-9215 Analog Input Module (BNC). Both the NI-9215 and the NI-9178 were installed in a NI-cDAQ 9178 CompactDAQ chassis. The chassis interfaced with a MATLAB® based data acquisition script over a USB-2.0 bus.

The fire was created using a 0.093 m², square profile propane sand burner. A Dwyer gas flow-meter was used to control the propane into the burner, and this allows control of the heat release rate (HRR). For this experiment, a 150 kW HRR was chosen.
**FIGURE 1:** The experimental setup is presented in this figure. Figure (a) presents the geometry of the experiment, and figure (b) presents a block diagram displaying the flow of material (propane) and information (acoustic signals) for this experiment.
FIGURE 2: A model of the room used to conduct the experiment outlined in Section 3. This model is developed in Fire Dynamic Simulator (FDS) in order to calculate the temperature field produced by a fire inside the room. In this model, a burner is used to create a 150 kW fire inside this room. FDS calculates the temperature at every assigned mesh point, however for visualization purposes a single slice of data is presented. The slice presented above is 31 seconds after ignition, and already the temperature at the ceiling is $>300^\circ$ Celsius. Eventually, fire and acoustics models will be combined to simulate sound propagation in real fire scenarios.

For each ping (transmit/receive cycle) the system was considered stationary, because the time scale of heat transfer in this system was much slower than the speed of sound. However, between pings this assumption might not be true, and time domain averaging may not be appropriate.

Raw time series data from the microphones was recorded and post-processed under MATLAB®. Each ping was processed independently of the others. All analysis was done using raw, unfiltered time series data.

**Preliminary Fire Dynamic Simulator Model**

A proof of concept fire simulation was developed to understand the qualitative temperature distribution in the room, as the fire progresses. A 3D FDS model of the experimental burn facility is shown in Figure 2. A model 150 kW fire was created inside the model burn structure, with no ventilation provided. At the time of writing, the leakage conditions inside this facility had not been measured, therefore this simulation was not intended to be a full model of the experiment. However, the evolution of the temperature profile provides a qualitative description of the conditions inside the room.

The colored slice shown in Figure 2 is the temperature profile on that plane, as calculated by FDS. The 3D temperature field is calculated at each point in the mesh, however for visualization purposes only 1 plane is shown here.

The most dominant effect is the stratification of the room into a hot layer at the top and the bottom layer. The 2 layers could change the acoustics of the room significantly, for example the hot-cold boundary could act as a reflector, and the gradient could bend the acoustic path and create multi-paths.
FIGURE 3: Magnitude squared coherence plots for microphone 1 and microphone 2 as compared to the transmit signal. Magnitude-squared coherence can be a measure of the signal to noise. Unity indicates perfect coherence, and 0 indicates no coherence. The coherent frequencies change as the fire evolves, and higher frequencies are affected by this more than lower frequencies.

RESULTS

In order to understand the signal to noise relationship, the magnitude-squared coherence was calculated for each microphone compared to the transmitted signal. The magnitude-squared coherence can be considered a frequency domain analog of the cross-correlation function. It is normalized between 0 (no correlation) and 1 (perfect correlation) [5, 6].

Figure 3 shows color plots of the coherence for every ping. Each row corresponds to 1 ping, and the columns represent frequency. The elapsed time since the beginning of the experiment is on the y-axis, increasing down. Frequency appears on the x-axis increasing to the right. The two horizontal black lines indicate the times of fire ignition and extinction.

It appears that the higher order room resonance frequencies correspond with the highest coherence. We see significant deviation of these frequencies as the fire evolves. Microphone 1 is more coherent than microphone 2, however both show a degradation in coherence at the higher frequencies as time passes. This means that as the compartment is getting hotter, high frequencies are attenuated more.
The high values of the coherence within the transmit frequency band gives confidence in the validity of the data. In order to further understand the response of the room, frequency-domain transfer functions between the source and the microphones were calculated. Presented in Figure 4 is the magnitude in dB of the transfer functions. As before, the black horizontal lines indicate the ignition and extinction of the fire, and photographic images from within the burn structure at these two times is shown in Figure 4 (b) and (c).

For both microphones significant spectral changes are seen as the fire evolves. Microphone 1 shows these effect more clearly than microphone 2. Lower frequency modes are not as affected as high frequency modes. There is also significant attenuation of the high frequency modes very early in the fire (most likely because it was still developing and not in a state of equilibrium), and as time increases in the experiment.

Microphone 2, which is behind the internal wall, is even more interesting. This could simulate a firefighter down in a room, and a potential rescuer looking for him entering a hallway. The shift and attenuation of the high frequencies is a significant concern, because the current NFPA 1982 standard [2] specifies a frequency component in the 1 kHz–4 kHz range. This data indicated that a searching firefighter might not be able to hear this high frequency component.

**FUTURE WORK**

Presented in this paper is the 1st stage of development of a numerical model to simulate sound propagation in compartment fires, and the experimental techniques that will be used to validate this model. In the future more experiments will be conducted to ensure repeatability, as well as to explore different configurations, for example varying the location of the source and receivers, and using different fires. The experiments will develop an empirical knowledge of the acoustics in compartment fires, and lead to more accurate models.

**CONCLUSIONS**

The PASS device is used by firefighters to alert rescue teams and other firefighters, if they are disabled. This paper presented experimental and numerical tools under development to study the alarm signal produced by the PASS device. Section 2 presented the computational tools to model sound propagation in a compartment fire, and Section 3 presented an experimental study of sound propagation in this environment. One of the key future goals is to measure actual temperature during compartment fire experiments. This will allow better validation of the numerical model. We hope to use the numerical tools developed and validated using these procedures for modeling sound propagation in single-family housing, or other common structural fires. Those results combined with measurements of fireground noise and the effect of firefighter gear will be used to make recommendations regarding the PASS alarm signal.

**ACKNOWLEDGMENTS**

This project is funded by DHS/FEMA (United States Department of Homeland Security / Federal Emergency Management Agency) under grant # EMW-2010-FP-00885, in collaboration with the Fire Protection Research Foundation, NFPA's research affiliate.
(a) Acoustic transfer function of a compartment fire for microphone 1. The black lines indicate ignition (top) and extinction (bottom) of the fire.

(b) Acoustic transfer function of a compartment fire for microphone 2

(c) Photograph of the inside of the compartment, at the moment of ignition (top black line in a. and b.)

(d) Photograph of the inside of the room, at the moment of extinction (bottom black line in a. and b.). The room appears dark due to the presence of smoke

**Figure 4:** Received/source signal transfer functions for microphone 1, shown in (a), and microphone 2, shown in (b), and the conditions inside the room at ignition (c) and extinction (d) are shown here. The frequency response of the microphones indicated that high frequencies were affected more by the evolving fire.
REFERENCES


