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Acoustic wave propagation in a sensor port: Experimental measurements and analytical model predictions

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ABSTRACT

In this paper, results from an experimental study on pressure fluctuations in a sensor port are presented. The sensor ports are attached to a large flat plate over which plane acoustic waves propagate. In addition, an analytical model is developed by solving the acoustic wave equation subject to rigid and pressure release boundary conditions. The experimental data is used as input to the model from one end of the sensor port in order to predict the pressure fluctuations at the other end of the sensor port. Two sensor ports are used; a short and a long one. The short sensor port resonates at 1000 Hz, whereas the long sensor port resonates at 245 Hz. The acoustic source generates harmonic and random plane acoustic waves, which can be modeled easily. Pressure fluctuation measurements are made both on the plate surface and inside the sensor ports for various plane wave inputs; harmonic and random. Power spectra, sound pressure levels and transfer functions are then obtained at the various microphone locations. The experimental results for the short sensor port show an amplification factor of 45 between the inlet and the rigid end of the sensor port at a frequency of 1000 Hz. For the long sensor port, the amplification is nearly 50 at a frequency of 245 Hz, with lower amplifications at higher frequencies. Using the measured power spectrum at the rigid end of the sensor port for a random plane wave input, the absorption coefficient is calculated using the half-power law. Using this absorption coefficient in our analytical model, predictions were made at both ends of the sensor port using experimental data as input. The model predictions for both sensor ports are in good agreement with experimental data.

1. Introduction

Using sensors to monitor various processes both in nature and in different applications has become a common engineering practice. This is driven by the desire to prevent catastrophic events such as a bridge collapse, a rocket engine explosion or an airplane engine failure, just to name few. In all these cases, the challenge is making sure that the sensors are protected and working properly. In the bridge case, this is not too difficult to achieve; however in other cases such as the rocket or airplane engines it is a lot harder to protect the sensors as the desired location can be in a very harsh environment characterized by high temperatures due to combustion. Rocket engine failure has been investigated extensively in the past [1] and one of the causes of failures has been linked to combustion instabilities [1] that result in very high amplitude pressure fluctuations. Therefore, having pressure sensors inside the combustion chamber is desirable; however, the harsh environments that exist inside the chamber prevent this. This has led to an extensive research and development effort to overcome this difficulty. Due to the applied nature of the problem, the results of the various research efforts have led to patents [2,3] rather than detailed technical papers.

Reshotko and Karchmer [4] measured the pressure fluctuations in a YF-102 engine as well as the far-field noise in an attempt to understand the contribution of internal combustion to the far-field noise. Instead of measuring the pressure fluctuations directly in the combustion chamber, they used a duct-component rig test facility and therefore they needed to establish a relationship between the pressure fluctuations in the duct-component facility and those in the chamber. Their measurements showed some differences in spectra but found that the internal dynamics of the combustor as an acoustic source were preserved in the duct-component facility.

Passaro et al. [5,6] measured the unsteady fluctuations of both pressure and temperature in the outflow from a gas turbine

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combustor. This is done in order to assess the turbulence level which has a direct impact on turbine blade heat transfer, therefore efficiency, life and safety of the turbine. This is particularly important for higher pressure and temperature applications and also for lean-flame combustors operating near the stability limits. To achieve their goal, they developed high frequency probes fitted on a rapid injection and cooling system to protect the probes from the harsh environment.

Wegner et al. [7] used short and infinite-line pressure probes to protect microphones when measuring sound in hostile environments. The probes used tubes to remove the microphones from the sensing location. Using coherence-based techniques, they separated the hydrodynamic fluctuations from those of the acoustic field in order to ascertain that the probe tubes replicated the flush microphone data. They presented the best way to make accurate in-duct measurements of the acoustic field using probe microphones. Recently Sohi [8] developed a fast-response multifunctional Micro-Electro Mechanical Systems (MEMS) sensor for the simultaneous measurement of in-cylinder pressure and temperature in an internal combustion engine. Their innovation is based on a new non-planar and flexible multifunctional membrane, which responds to both pressure and temperature variations at the same time.

On the analytical development side, Munjal [9] studied acoustic wave propagation in ducts and mufflers with rectangular and circular cross-section and with and without mean flow. His research concentrated on waves propagating in one direction with a focus on their dissipation. Tijdeman [10] also considered the effect of mean velocity profile on acoustic waves propagating in one direction in a tube. His focus was also on the attenuation of the waves in an infinitely long tube. Karthik et al. [11], and Kumar and Sujith [12] studied acoustic standing waves in fluid medium with temperature gradient and without mean flow. Howe [13] presented one-dimensional wave propagation through various junctions and used continuity of volume velocity and pressure at the interfaces to derive various results. On the computational side, Frendi et al. [14–16] studied several acoustic wave propagation problems over both flexible and rigid surfaces. When flexible surfaces were used, strong coupling was obtained between the acoustic waves and the flexible surfaces.

In the current paper, a study of acoustic wave propagation in a sensor port is carried-out both experimentally and analytically. This study is motivated by the desire to monitor pressure fluctuations in a harsh environment such as a rocket engine in order to enhance operational safety. A fully anechoic chamber, in ambient air conditions, is used to eliminate reflections from rigid surfaces, in addition, random and harmonic plane waves are propagated over a flat plate with a sensor port and other measurement ports. Pressure versus time data is collected from microphones located in the various ports. Parallel to the experimental work, an analytical model was developed by solving the acoustic wave equation in a circular port subject to rigid and pressure release boundary conditions at both ends. The developed model is then used to predict pressure fluctuations at both ends of the sensor port using measured data at the opposite end of the port as input.

The remainder of the paper is organized as follows; the experimental setup is described in Section 2, followed by the development of the analytical model in Section 3. The experimental results are presented in Section 4 for the two sensor ports used and the analytical model predictions follow in Section 5. The paper closes with some concluding remarks in Section 6.

2. Experimental setup

Acoustic measurements are difficult to make as they require a reflection free environment. In order to achieve that, a fully anechoic chamber is used. The chamber has a cut-off frequency of 150 Hz and all measurements are carried out for frequencies above this frequency. Another important component of the experiment is the acoustic excitation source. One requirement for the source to satisfy is ease of modeling using simple harmonic functions and not having concern with the phase. To this end, a plane wave speaker was identified, TOA PW-1230SB, that satisfied this requirements and able to cover frequencies of interest. A power amplifier was used to drive the plane wave speaker, OSD Audio PA90 Commercial 70 V Integrated Amplifier. The measurement devices used are ½ inch Bruel & Kjaer, B&K, vented microphones that have excellent response characteristics for frequencies up to 20 kHz. The temperature and humidity in the chamber were also measured for potential use in the analytical model. All the experiments were run using the B&K Pulse software that allows multiple input channels and also real-time monitoring of the experiment in addition to time capture and report generation features. Once all of these important components were identified, the design of the experiments started.

Fig. 1 shows the experimental setup used in the anechoic chamber. A large and thick aluminum plate whose surface was machined to be very smooth is shown suspended to the ceiling of the anechoic chamber. The plate dimensions are $101.6 \times 60.96 \times 1.27$ cm in length, width and thickness, respectively. Three holes were machined into the plate; one at the center of the plate used for the sensor port and two others used for additional flush pressure measurements, one 15.24 cm off-center at the same downstream location as the sensor port and the other on the centerline 25.5 cm downstream from the sensor port, Fig. 1(a). Also shown in Fig. 1(a) is the plane wave speaker, positioned flat on the wire mesh floor of the chamber and just below the plate. Fig. 1(b) shows the back side of the plate where three B&K microphones are shown, one attached to the base of a short sensor port and the others to the holes used for additional flush pressure measurements along the plate.

Fig. 2 shows, side-by-side, the two sensor ports used; 8.425 and 34.34 cm long for the short and long sensor port, respectively. Both ports are cylindrical, with 1.27 cm inner diameter, and machined from the same hexagonal aluminum bar. The hexagonal shape allowed sensors to be mounted with ease. A threaded end can be seen to the right end of each port. This end threads directly onto the plate at the center such that the center plate hole lines up perfectly with the port hole to form a smooth continuous cylindrical port. A 1.27 cm diameter side hole is shown on the long sensor port of Fig. 2 where a microphone will be placed. There is another 1.27 cm diameter hole on the opposite side near the threaded end of the long port where an additional microphone will be placed. A 1.27 cm diameter microphone is inserted 1.27 cm inside the ports from the back side of the plate, as shown in Fig. 1 for the short port. The total length available for the acoustic waves to travel inside the ports are; 7.60 and 33.64 cm for the short and long port, respectively.

Fig. 3(a) and (b) shows sketches of the panel together with the location and labeling of the various microphones used. Fig. 3(a) shows the microphone labeling for the short port, while Fig. 3(b) shows that for the long port. Two additional microphones are added when a long sensor port is used. Microphones 2 and 3 occupy the same position for both experimental setups. Microphone 1 is located at the end of the sensor ports, while microphones 4 and 5 are located along the length of the long port on opposite sides; one is 8.265 cm from the plate, Mic4, and the other is 8.74 cm from the port end, Mic5. The direction of propagation of the plane acoustic waves is also shown on the sketches. The sensor port and Mic2 are 50.8 cm from the leading edge of the plate, whereas Mic3 is 76.2 cm.