A Short Water-filled Pulse Tube for the Measurement of the Acoustic Properties of Materials at Low Frequencies

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Abstract: This work describes a method for making complex sound speed measurements for a material sample in a pulse tube that is a fraction of a wavelength long (1). The method utilizes signal processing to separate incident from reflected sound and active sound cancellation to reduce reverberation and wall modes.

INTRODUCTION

A great deal of work is currently being done in acoustics using composite materials that act as underwater acoustic absorbers and decouplers. These materials have properties that can vary non-linearly with frequency, pressure and temperature. This work describes a method for making measurements of intrinsic complex sound speed as a function of frequency, temperature and pressure using a short acoustic pulse tube.

MEASUREMENT CONCEPT

The fundamental concept behind the measurement method is the acoustic impedance translation theorem for layers. If the complex acoustic impedance behind a layer is known, and the complex acoustic impedance of the layer plus what's behind it is known, the complex sound speed in the layer can be determined provided that the density and thickness of the layer are known. By measuring the complex reflection coefficient from a surface in a medium of known sound speed and density (i.e. the water in the tube), the complex impedance at that surface can be calculated. This method is applied experimentally by measuring the complex reflection coefficient from the end of the pulse tube with and without a sample placed at the end of the tube. The complex acoustic impedance of the front and back of the sample layer are calculated from these reflection coefficients, and the impedance translation theorem is applied to solve for the complex sound speed of the sample material. The impedance translation theorem applies only to infinite layers of finite thickness. The samples in the tube, however, are finite in diameter, and there is a water gap between the tube wall and the sample outer diameter. However, an analytical model such as the propagation model described below, can be used to calculate the intrinsic complex sound speed from experimental measurements made with a finite diameter sample.

In order to make complex reflection coefficient measurements at low frequencies in the laboratory, a short pulse tube was designed and built. A pulsed incident signal (as opposed to a cw signal) was used in order to minimize the problem of vibrations in the tube wall. A dual sensor system similar to that described by Suzuki (2) was employed to separate the incident pulse from the reflected pulse in the absence of temporal separation. Active sound cancellation at the end of the tube opposite from the sample was used to attenuate the reflections from that end.

ANALYTICAL AND EXPERIMENTAL DESIGN

Two analytical models (a propagation model and a simulation) were developed to aid in the experimental design. The propagation model examined wave propagation in an infinitely long, water-filled, elastic (steel) tube. A characteristic equation for the axial wavenumber was developed by imposing boundary conditions on the equations of motion for longitudinal and shear waves in the tube and longitudinal waves in the water. This model predicted the dispersion curves and mode shapes of the propagating modes.

The simulation model simulated the measurement method, assuming propagation of a plane wave mode in the fluid and in the tube wall, each at different speeds and amplitudes as calculated by the propagation model. The simulation was useful in evaluating the sensitivity of the measurement method to experimental design characteristics such as the impedance of the end behind the sample, and experimental errors such as noise, and
Figure 1 is a diagram of the short pulse tube as built. The entire tube was submerged horizontally in a tub of water so that samples could be removed and inserted underwater without introducing air into the tube. Three hydrophones were used so the data could be processed with two different hydrophone separation distances. The separated incident and reflected pulses were used to calculate the complex reflection coefficient and also to provide input to the active sound cancellation actuator at the end of the tube opposite from the sample. The purpose of the active sound cancellation actuator was to attenuate reflections from that end of the tube. Experimentally, the active sound cancellation worked well, providing up to 35 dB of attenuation.

FIGURE 1: Short Pulse Tube Configuration

RESULTS AND CONCLUSIONS

There were some experimental difficulties not anticipated when the system was built. One was a problem with the plane wave water mode exciting the tube endcap and consequently exciting the plane wave mode in the tube wall. This was significantly reduced by decoupling the endcaps from the water by inserting a pressure-release type layer in front of the endcaps. This configuration changed the impedance of the sample backing from a high to a low impedance, and also precluded experimental measurements from being made under pressure.

Measurements were made on a sample of natural rubber because it was readily available, and it's acoustic properties generally known. The experiment was able to calculate the correct sound speed above 1200 Hz, but below this frequency, the experimental results were poor. By using the simulation model, it was determined that the limiting error source below 1200 Hz was noise. The simulation was used to predict the experimental results with an improved signal to noise ratio, estimated by decreasing the background noise to a level similar to System K of NUWC-USRD, and increasing the signal level with a more robust source, such as a larger diameter PZT sphere, and an equally robust actuator. The simulation predicted good experimental results down to a frequency of 300 Hz.

After validating the simulation with the experiment, the simulation was used to vary the experimental configuration to minimize the sensitivity of the results to measurement errors. The simulation and the experiment showed that the thicker the sample, relative to a wavelength, the lower the sensitivity to measurement errors. Fortunately, many of the materials of interest in underwater acoustics are compliant materials with slower sound speeds than natural rubber, and consequently shorter wavelengths. The simulation also showed that with a high impedance backing behind the sample (instead of the low impedance backing used in the experiment), the sensitivity to measurement errors would be lower, and the low frequency results would improve.

The results of both the experiment and the simulation suggest that a short tube method could be useful for measuring the complex sound speed of compliant materials at frequencies down to 300 Hz or possibly even lower.

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REFERENCES