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by

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In recent years new methods based on signal processing technical have been developed to measure the normal acoustic impedance of materials. These methods proved to be considerably faster easier to implement than the SRW method they replace. Mathematical, hardware and software aspects of these techniques are discussed and results obtained over a frequency range of 200-4000 Hz for several architectural materials are presented.

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NEW METHODS OF MEASURING NORMAL ACOUSTIC IMPEDANCE

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INTRODUCTION

About three years ago, owing to our work in computer simulation of sound fields in enclosures, we developed the need for closely spaced, broad-band measurements of normal acoustic impedance for a variety of architectural materials. Through text books and student laboratories I was well aware of the Standing-Wave-Ratio technique and the tedium of its application. Given our problem and the extreme numbers of data points we needed to collect, a technique orders of magnitude faster was clearly required. An answer was found in a 1977 paper by A.F. Seybert and D.F. Ross (Ref.5). During the course of our research with the Seybert/Ross technique, another related method was published in the Journal by J.Y. Chung and D.F. Blaser (Ref.2). We found the Chung/Blaser technique to be as easy to implement and as accurate, but to compute in a much shorter time than the Seybert/Ross method. The purpose of this paper will be to discuss and compare the implementation of these two related methods.

THE HISTORY OF DUAL, FIXED-MICROPHONE MEASURING TECHNIQUES

It surprised me to learn that dual, fixed-microphone techniques for measuring the normal acoustic impedance of materials are not new, but date back as far perhaps as 1932. The first mention in the literature was a 1941 paper by Clapp and Firestone on acoustic wattmeters (Ref.3). They recognized that their device could be used to measure the absorption coefficients of materials. Then at the 28th meeting of the Acoustical Society in 1943 R.H. Bolt and A.A. Petrauskas delivered a paper titled "An Acoustic Meter for Rapid Field Measurements" (Ref.1). Some years later, Dr. Ted Schultz wrote his Ph.D. thesis and published a paper on the acoustic wattmeter and discussed its application to the measurement of absorption coefficients (Ref.6). These methods all used analog circuitry and sinusodial sound sources. Perhaps one of the reasons that use of the acoustic wattmeter for impedance measurements has beneclipsed by the Standing-Wave-Ratio apparatus has been the complexity of the wattmeters circuitry.

Recently S.J. Elliott has published a description of a low-cost, simple system of this type (Ref.4) so perhaps the use of dual, microphone analog techniques for impedance measurement will gain popularity in the future.

DIGITAL TECHNIQUES

Both the Seybert/Ross and the Chung/Blaser techniques to be discussed today are digital methods and consequently require digital signal processing equipment. Figure 1 is a schematic diagram of the necessary equipment. The core pieces of equipment are a tube, a desktop computer, and a signal analyzer. A speaker one end of the tube is excited by white noise and, with an unknown impedance at the other end of the tube, the auto- and cross-spectra of the the signal at the two microphone locations is measured. From these values and the knowledge of the microphone spacings, the acoustic impedance of the material at the end of the tube can be calculated. Unlike the Standing-Wave-Ratio method, these techniques do not require that the sample material be placed inside the tube. Rather, the tube is placed against the sample, thus allowing *in situ* measurements.

THE SEYBERT/ROSS METHOD

Let's look first at the principles of the Seybert/Ross method because mathematically, this is the simplier of the two. The frequency dependent absorption coefficient $\alpha(f)$ of a material is unity minus the ratio of reflected sound power to the incident sound power. This can be given by

$$\alpha(f) = 1 - \frac{S_{rr}(f)}{S_{ii}(f)}$$

where $S_{rr}(f)$ and $S_{ii}(f)$ are the frequency dependent auto-power spectral values of the reflected and incident waves. Similarly, the phase change upon reflection can be given by

$$\phi(f) = \tan^{-1}\left[\frac{Q_{ir}(f)}{C_{ir}(f)}\right]$$

where Q_{ir} and C_{ir} are the imaginary and real parts of the cross-power spectrum of the incident to reflected waves.

Note that we cannot measure $S_{ii}(f)$, $S_{rr}(f)$, $C_{ir}(f)$ and $Q_{ir}(f)$ directly, but we can measure $S_{11}(f)$, $S_{22}(f)$, $C_{12}(f)$ and $Q_{12}(f)$, the auto- and cross-power spectra of the signals at microphones 1 and 2. The signals at microphones 1 and 2 contain both incident and reflected waves. Can $S_{11}(f)$ etc. be decomposed to yield $S_{ii}(f)$ etc.?

The answer is "yes" and quite readily in fact. The mathematics is marvelously simple, requiring only the definition of a finite Fourier transform, Euler's relations and elementary complex algebra. I'll spare you the details (they're contained in Ref.5), but with an additional ten minutes, I'm sure I could convince you that

$$S_{11}(f) = S_{ii}(f) + S_{rr}(f) + 2 \cos 2kx_1 \, C_{ir}(f) + 2 \sin 2kx_1 \, Q_{ir}$$

where k is the wave number and x_1 is the distance between microphone 1 and the sample end of the tube. Note that $S_{11}(f)$ is a linear function of $S_{ii}(f)$, $S_{rr}(f)$, $C_{ir}(f)$ and $Q_{ir}(f)$. $S_{22}(f)$, $C_{12}(f)$ and $Q_{12}(f)$ are as well. Thus we can write

$$\begin{bmatrix} S_{11}(f) \\ S_{22}(f) \\ C_{12}(f) \\ Q_{12}(f) \end{bmatrix} = \begin{bmatrix} A \end{bmatrix} \begin{bmatrix} S_{ii}(f) \\ S_{rr}(f) \\ C_{ir}(f) \\ Q_{ir}(f) \end{bmatrix}$$

where $[A]$ is the coefficient matrix. The good news is that $[A]$ is, in general, invertable. The bad news is that the coefficients are functions of the wave number k , making $[A]$ frequency dependent. Consequently, $[A]$ must be inverted at each frequency of interest and multiplied by the vector on the left-hand side to yield the auto- and cross-power spectral values for the incident and reflected waves. From these values, then, the absorption coefficients and the phase change can be computed as previously mentioned.

If our orginal goal had been to find the complex acoustic impedance rather that the absorption coefficient and phase change, we would have started with the relation

$$Z(f) = \frac{C_{pu}(f) + iQ_{pu}(f)}{S_{uu}(f)}$$

where Z is the complex acoustic impedance, p is the acoustic pressure, u is the particle velocity, and the other symbols are defined as before. Using standard acoustic relationships, we could find Z(f) in terms of

$S_{ii}(f)$, $S_{rr}(f)$, $C_{ir}(f)$ and $Q_{ir}(f)$.

THE CONSTRUCTION OF THE TUBE

Before we consider the Chung/Blaser technique, let's consider the details of the impedance tube. We wanted to make our first tube as quickly and as cheaply as possible. Essentially we took a 3" round speaker and bolted it to one end of a 3" diameter, 12" long piece of PVC pipe. Two holes were drilled into the tube wall and some Tygon tubing inserted to hold the 7/8" diameter microphones in place.

The HP-5420 signal analyzer has its own low-pass filtered white noise source. The noise must be filtered to remove frequencies above those we are measuring, and thereby prevent aliasing phenomena. The noise was amplified and sent to the speaker. The microphone signals were preamplified and sent to the HP-5420 where auto- and cross-spectral data was averaged over 30 samples and resolved into 256 frequency bins. This data was dumped into an HP-85 controller where it was multiplied by the inverted coefficient matrix calculated at each frequency as discussed above. Results were plotted from the HP-85. The entire process of data collection, calculation and plotting took roughly 18 minutes. We were able to obtain data from about 200 Hz to 2500 Hz. The lower limit seems regulated by our ability to measure phase differences between the microphone signals for very large wavelength. The upper limit is controlled either by the microphone spacing, which must be less than ½ wavelength, or by the first "sloshing" mode of the tube, above which our assumptions of plane waves travelling down the tube and reflecting break down.

MICROPHONE CALIBRATION

We must mention here the phase and amplitude calibration of the two microphone/preamplifier sections. There are basically two techniques available (and perhaps some creative combinations of the two). We could stop the data collection half way through and switch microphone systems, or we could place the microphones in identical sound fields before we start and record any frequency-dependent phase and amplitude differences. Test data could then be preconditioned in the controller by this record before multiplication by the inverted matrices. Both methods are discussed in the literature. We found that the latter method was superior as it allowed for imbalances in the A/D converter sections of the signal processor, whereas the microphone switching method did not. The identical sound fields were obtained by placing the microphones in a plate mounted at the sample end of the tube, assuming the sound field to be radially symmetric at frequencies below sloshing.

VALIDATION OF TUBE PERFORMANCE

The performance of the tube was then validated against a known system. As suggested in the Seybert/Ross paper, we used a piece of pipe,the same diameter as the impedance tube, with a reflective cap to provide a purely reactive impedance. We would expect a absorption coefficient of 0 and a phase change equal to

$$\frac{2L}{\lambda} \cdot {}^{-}2\pi$$

Good results were obtained out to 2500 Hz.

THE CHUNG/BLASER METHOD

We wanted to improve the system in two ways: we wanted a higher frequency range and we wanted to cut down the 18 minute running time. We changed the system controller to a faster HP-87, built a fancy aluminum tube of 1½" diameter and used ½" diameter microphones with a closer spacing. Simultaneously, we discovered the 1981 Chung/Blaser paper. The system described by Chung and Blaser is the same, but the mathematical formulation is different.

Chung and Blaser show that the complex reflection coefficient can be expressed in terms of acoustic transfer functions between the two microphones as

$$R(f)= \frac{H_{12}(f) - H_i(f)}{H_r(f) - H_{12}(f)}$$

where $H_{12}(f)$ is the acoustic transfer function between microphone 1 and 2 and is expressible by $\frac{C_{12}+iQ_{12}}{S_{11}(f)}$

and H_i is the transfer function of the incident wave between the two microphone locations and $H_r(f)$ is the transfer function of the reflected wave between the microphone locations. The transfer functions of the incident and reflected waves between the microphones are simply the phase delays associated with the microphone spacing e^{-iks} and e^{iks}

where s is the microphone spacing. Be careful to note that the microphones in the Chung/Blaser paper are numbered oppositely from the Seybert/Ross work.

The acoustic impedance, absorption coefficient, and phase change can all be readily computed from the complex reflection coefficient. The above equations showed that the complex reflection coefficient could be calculated from the cross-power spectra of the two microphones and the auto-power spectra of microphone 1 alone, without matrix inversion. Therefore, this method should save us time in both data transfer from the signal processor and in calculation time. Using this new system, in fact, running time was cut to about 12 minutes.

RESULTS USING THE NEW SYSTEM

The system was again validated against a capped tube. Results showing experimental and theoretical results are attached. Good agreement is obtained out to about 4000 Hz. Also attached are results obtained for several other architectural materials.

COMPARISON OF SEYBERT/ROSS AND CHUNG/BLASER RESULTS

We wondered if there were any computational differences affecting accuracy between the two methods. Both methods were put to work on the same auto- and cross-spectra data sets. The results, which are attached, appear identical, although the Seybert/Ross system required 240 seconds of computing time versus 100 seconds for the Chung/Blaser method.

CONCLUSIONS

We have been very pleased with our two systems, but now use the Chung/Blaser method exclusively because of its faster processing time. Output of the method can be stored in magnetic form for other uses, which is extremely helpful. We are building an even smaller tube, using smaller microphones with still closer spacing, hoping to push our measurement capability to 6400 Hz and beyond.

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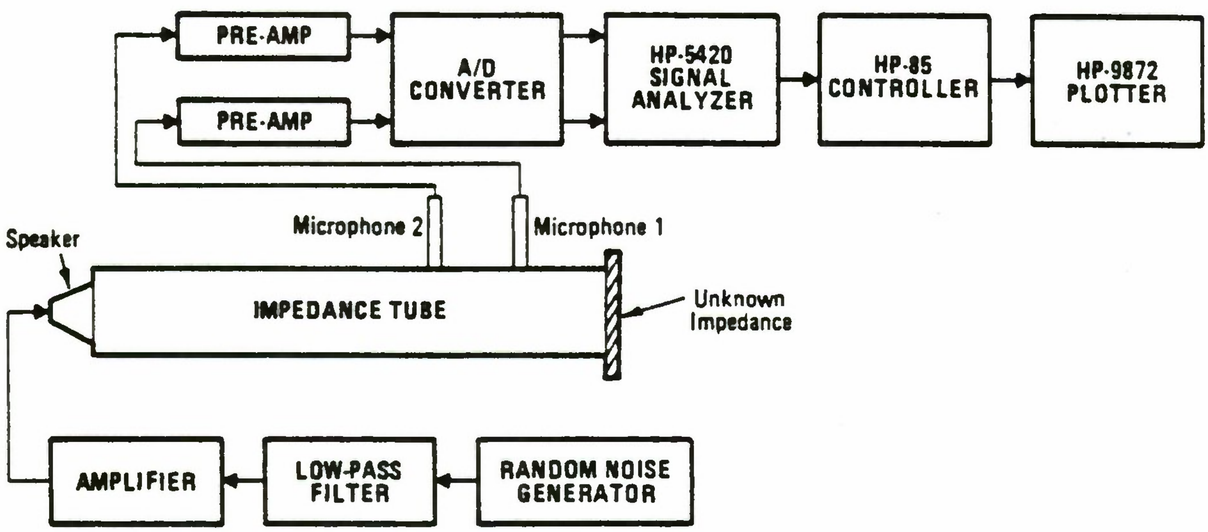
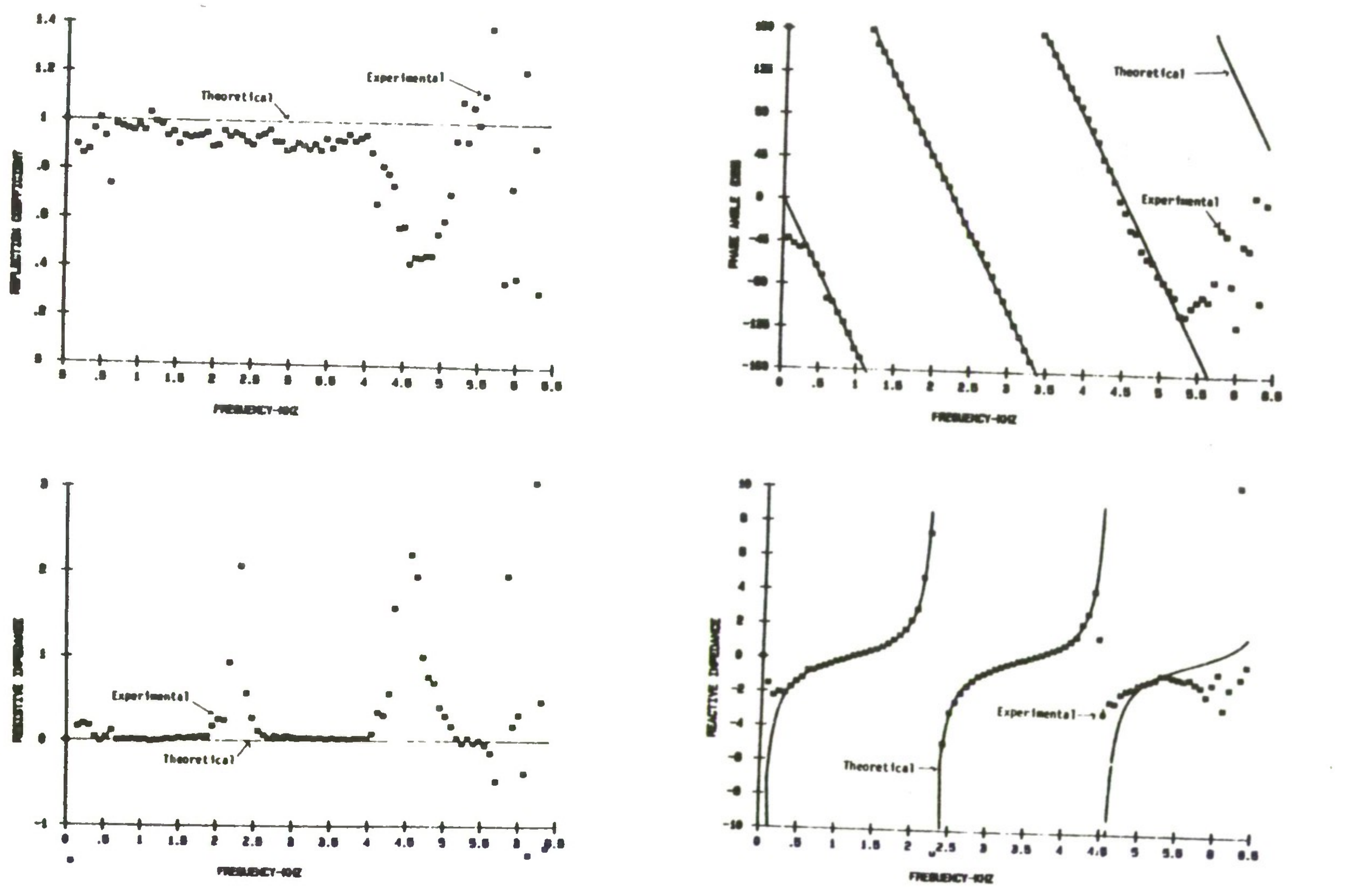
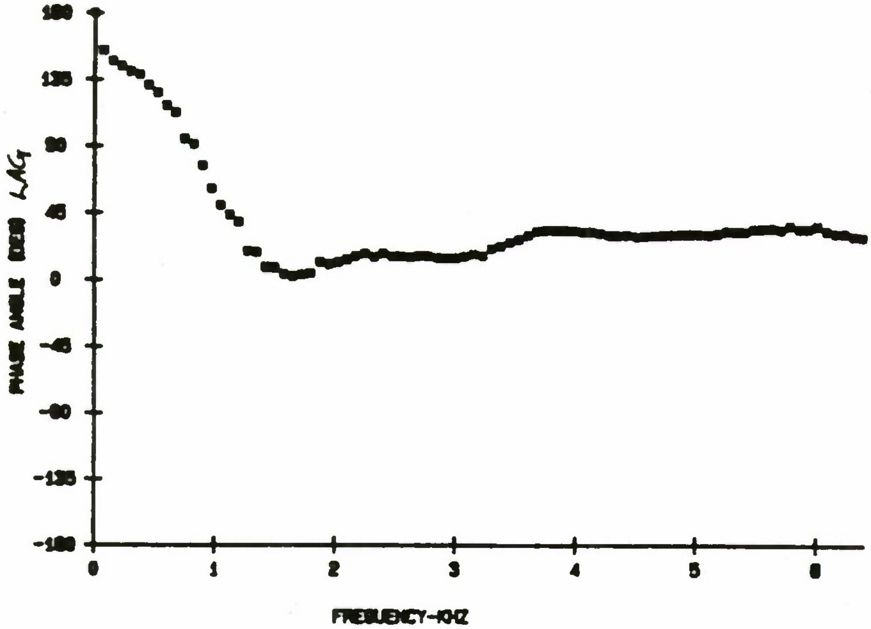


Figure 1. Experimental Set-up Simplified Block Diagram

3" Capped Pipe Reactive System



1 cm Thick Seat Cushion on Sheet Metal



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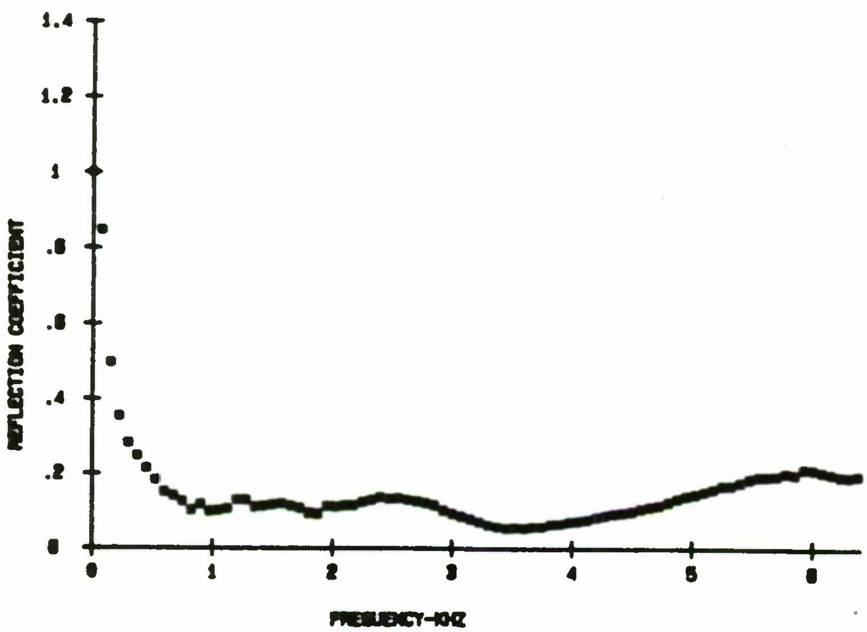
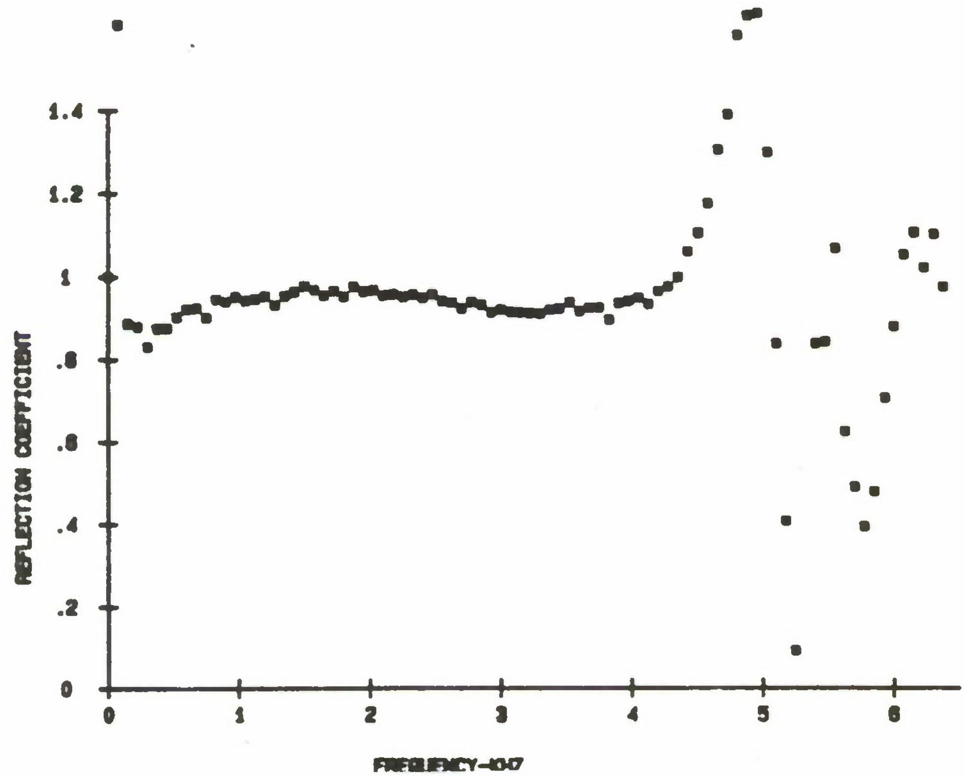
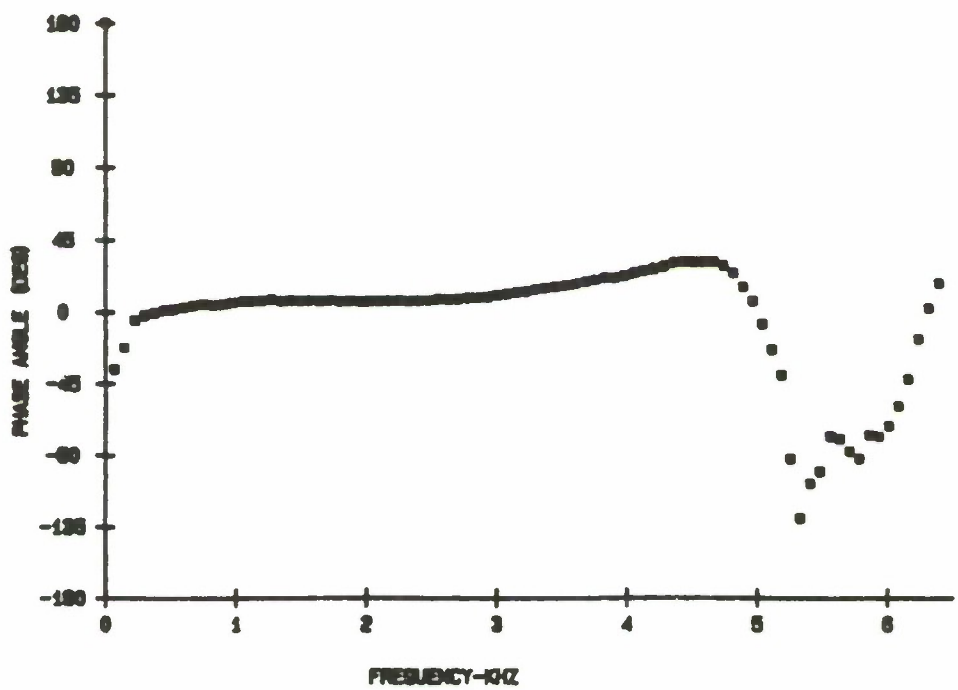


COMMERCIALLY AVAILABLE ACOUSTIC TILE - TYPE 1





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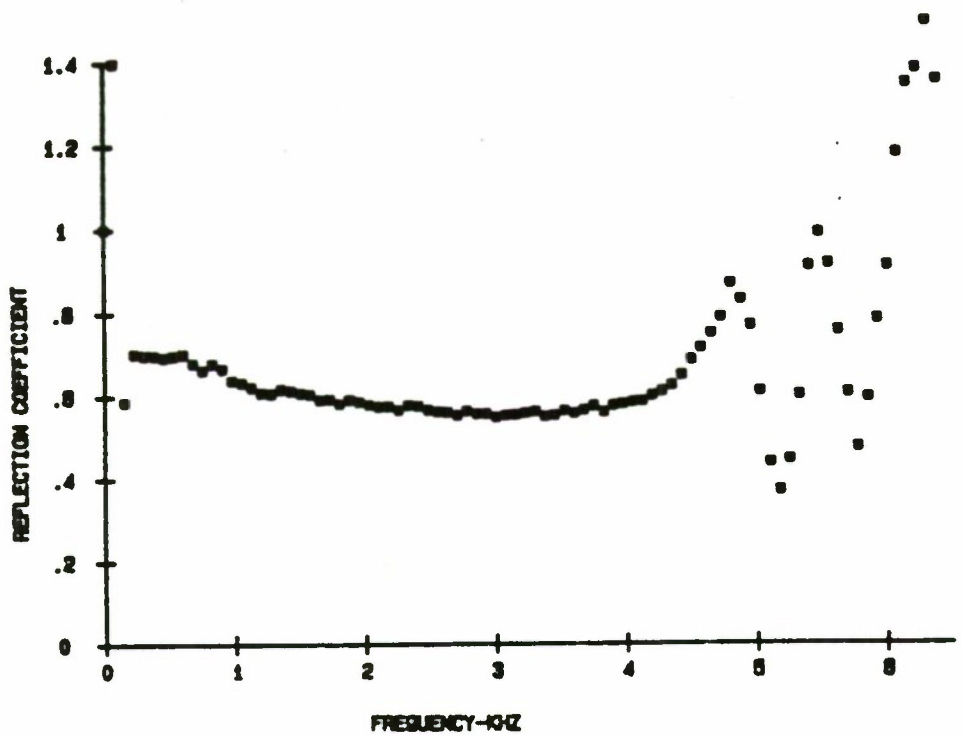
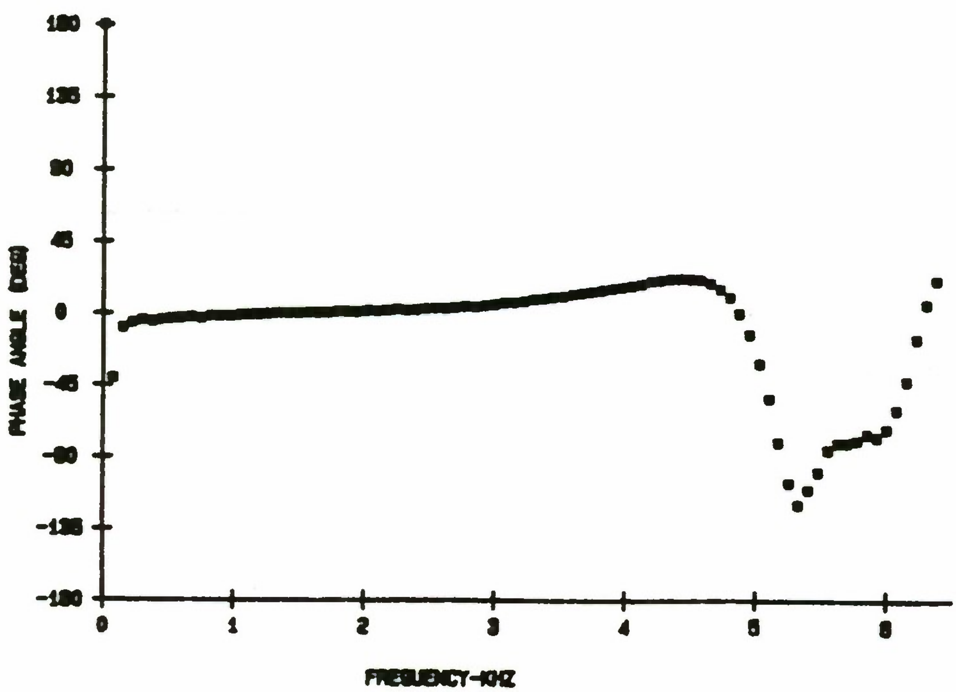
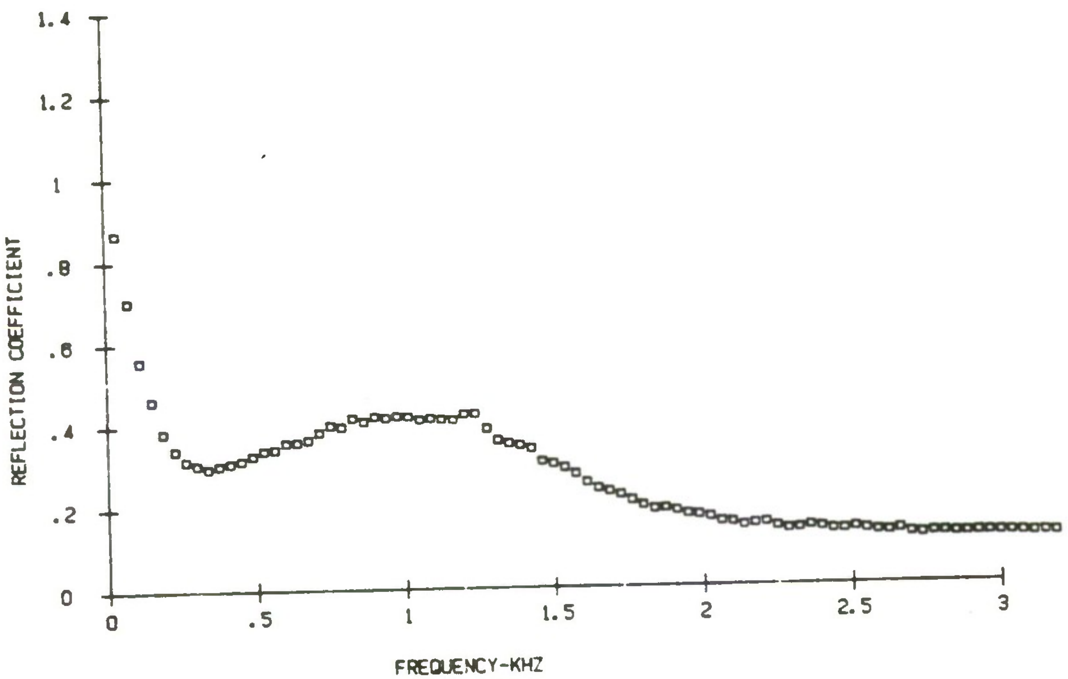
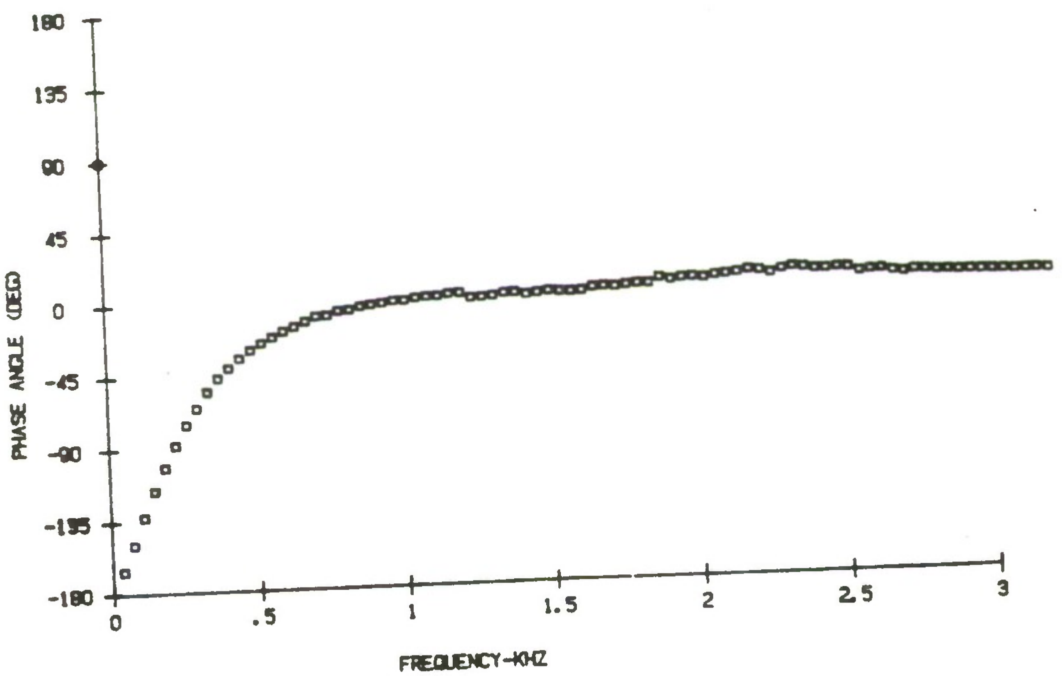


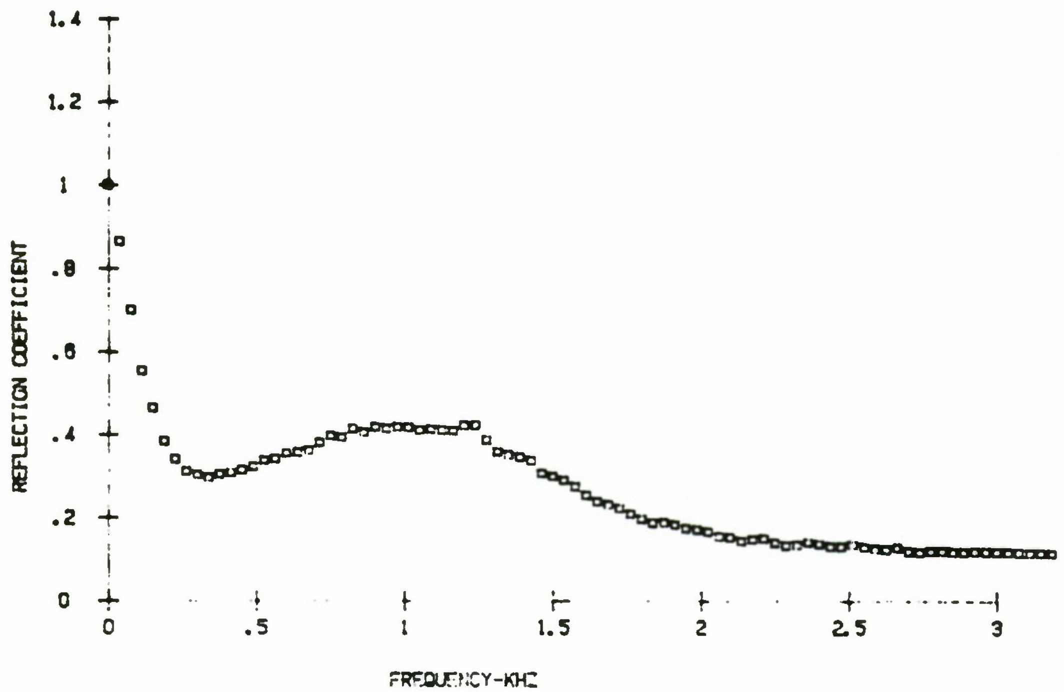


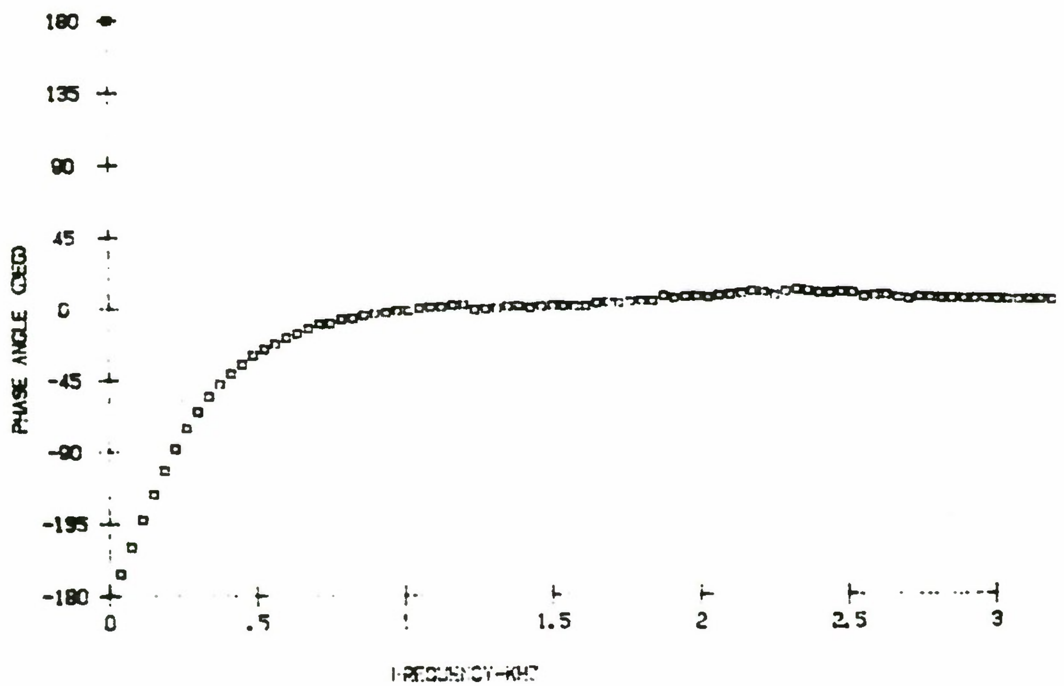
SEAT CUSHION DATA PROCESSED USING SEYBERT/ROSS
ALGORITHM





SEAT CUSHION DATA PROCESSED USING CHUNG/BLASER ALGORITHM





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