Imaging Sound Resonance in Gases with Stroboscopic Holography

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This file is to present essential documentation of the subject matter of this portion of Workshop 38 at the AAPT Summer Meeting in Portland, OR – July 18, 2010. This portion of the workshop will focus on the primary experimental challenges of this experiment first done at Bethel University in the mid-1990's and published in AJP **64** (9), September 1996. It has since been done several times by student projects within our Optics class – most recently in spring 2008. We use a student project, mini-research approach to this portion of our advanced laboratory, and thus there is no "lab manual" and detailed expectations vary each time students take on the experiment. Each time this challenging project is done, students work with the lab instructors to achieve in their own way a successful completion of the imaging of resonant sound waves in the closed tube resonator using stroboscopic real-time holographic techniques.

The current web-based version of the AJP issue noted above suffers in the archiving process since the crucial "shades of grey" figures that document the sound images from the experiment are effectively blackened out – and are useless. Consequently this document will include images from the student work immediately upon semester conclusion, and they are much more useful than Fig. 6 and Fig. 7 in the archived AJP reference. The originally distributed paper copy of AJP **64** (9), September 1996 also had good figures. In addition, in Workshop 38 I will be able to show the video clips that graphically show the standing waves in the resonator as slowed down by stroboscopic holography. We will go through all the acoustics and optical details of the system – including the operation and alignment of the acousto-optic (AO) cell and hands-on measurements of the resonances of the chamber with an air fill.

This is the **basic optical system** employed in the detailed descriptions to follow on the next pages.

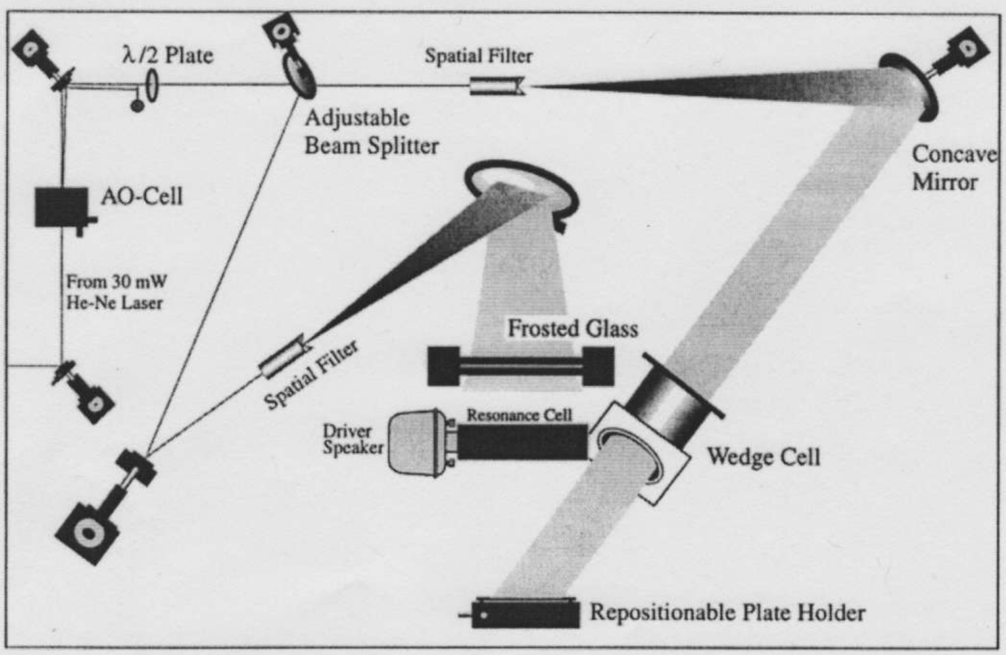
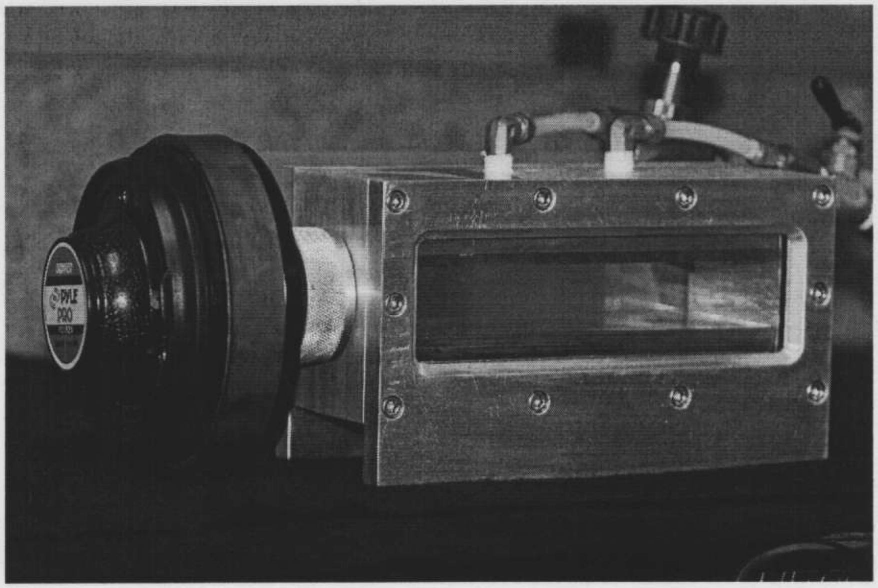
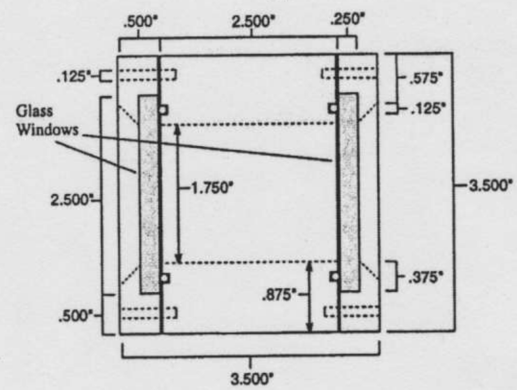


Figure 5: Real-time stroboscopic holography system for imaging standing sound waves.

We will also be describing in more detail the construction of one version of a sound resonance cell that can be driven up to 150 -160 dB with the attached speaker. Photo and line drawings are shown below:



(a)



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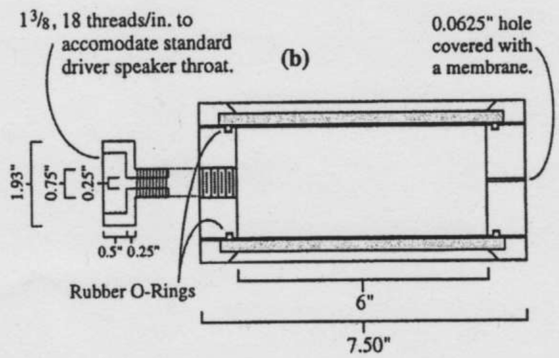

Holographic Real-Time Imaging of Standing Waves in Gases

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Stroboscopic holographic interferometry has been developed at an advanced undergraduate level allowing real-time imaging of standing sound waves in gas filled, closed tube resonators. A heterodyne Mach-Zehnder interferometer was first built by students to show the feasibility of interferometric detection of sound waves in a small cell. In the subsequent holographic study, the laser irradiance is modulated by an acousto-optic cell at frequencies near that of the standing wave, and a video camera records the fringe motion due to sound pressure changes. Fractional fringe shifts are observed for an air filled cell, and multiple fringe shifts are imaged for the case of freon. Sound reflections from the cell ends are easily observed, with non-sinusoidal waveforms dominating at high intensities due to superposition of resonator harmonics.

Introduction

Holographic techniques are widely used to carefully map out the amplitudes of vibration for mechanical structures ranging from musical instruments to aircraft engines[1,2]. Even though standing sound waves in gases are a central concern in many areas of acoustics, they have been difficult to image in any quantitative fashion. Indeed in teaching introductory physics a common approach is to present the height of flames or motions of cork dust as some indication of the location of nodes and antinodes, or a small microphone may be moved through the sound field to slowly map out a modal pattern. This project sought to interferometrically study and eventually holographically image the sound waves in a closed tube resonator. Imaging of the sound requires the production of localized background interference fringes which are shifted in position by the changing index of refraction caused by acoustically varying gas pressure. This end was accomplished in two phases within a project based junior/senior level optics laboratory, beginning with a dual beam interferometric probing of the resonant cell and culminating in real-time holographic imaging. The resultant real-time holographic images of the cell allow production of a dramatic stroboscopic videotape which maps out the oscillations of the pressure sound field for the first three standing wave modes.

Preliminary Calculations

The optical path length change Δ for a beam of light of wavelength λ and total geometrical path L is given by

$$(n-1)\mathrm{L} = \Delta = m\lambda$$

when a gas of index n is evacuated from the path, and m indicates the number of interference fringe shifts expected during the evacuation. In the case of air at atmospheric pressure evacuated from a cell of length 6 cm (using n = 1.0003) one obtains about 30 fringes, as may be easily demonstrated with a classroom Michelson interferometer. One can then estimate the interferometric effect of sound by first approximating the pressure changes due to a very loud sound (say 140 db) in the resonant cell and then comparing this to full atmosphere evacuation. If $\mathrm{L_p}$ represents the pressure level of the sound in dB, then

$$\mathrm{L_p} = 20\log_{10}(\Delta\mathrm{P}/\Delta\mathrm{P_o})$$

where ΔP represents the amplitude of the pressure oscillations and $\Delta\mathrm{P_o}$ (about 20 μPa) corresponds to the pressure amplitude at the threshold of hearing[3]. Thus pressure amplitudes of 200 Pa are expected at 140 dB, with total pressure changes at a given point given by 2ΔP or about 400 Pa at 140 dB.

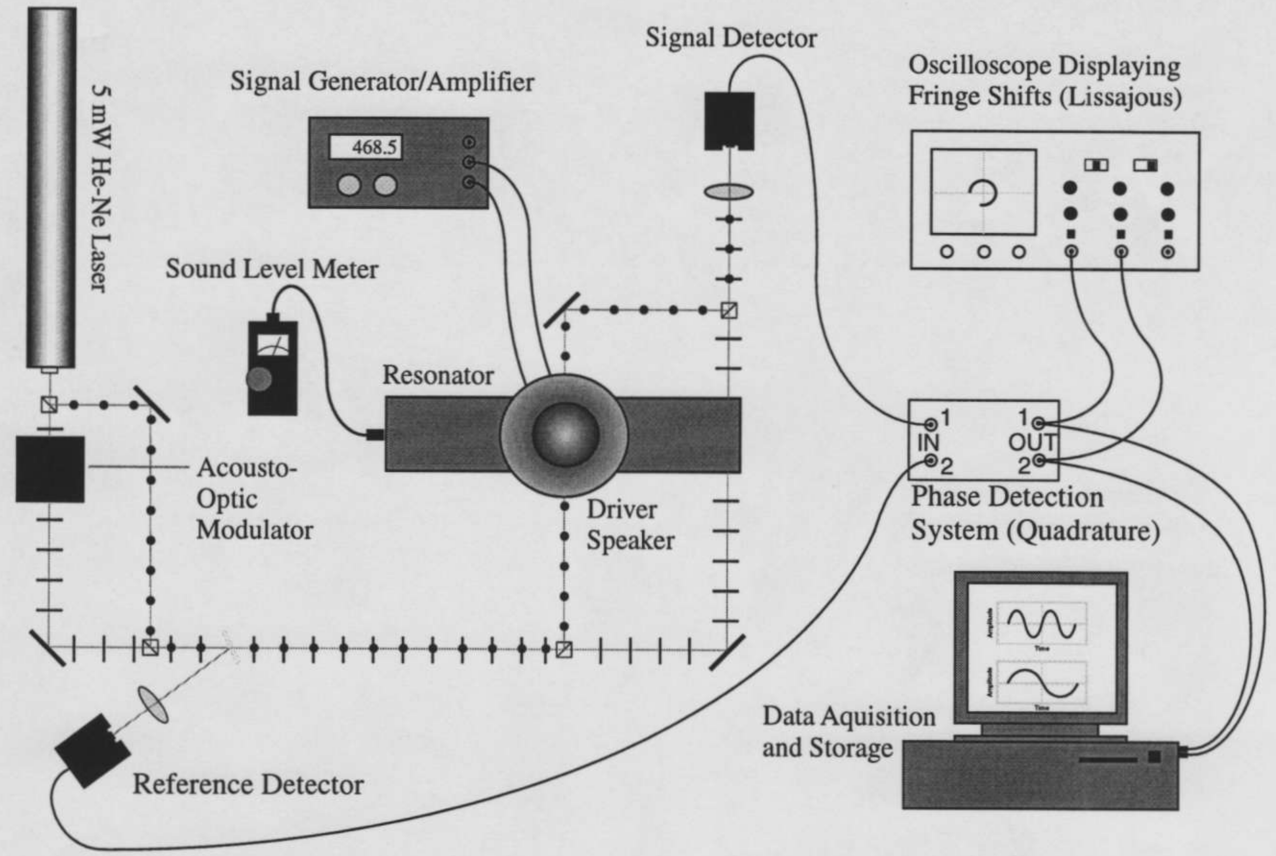

Figure 1: Mach-Zehnder system for probing the sound field at pressure antinodes of a closed tube resonator.

Mach-Zehnder Measurements

In a preliminary interferometry project to detect these small pressure changes, the optical system shown in Fig. 1 was constructed. A simple wood box resonator (of the type usually driven by a vibrating tuned bar mounted over the center hole) was placed in two optical probe beams. A 60-watt compression speaker driver was placed over the center hole, and sound entered the resonator through at 0.5 cm hole in a rubber stopper which covered the large center hole. To measure sound levels inside the resonator, a very small hole was drilled through one end of the box, and thus the pressure antinodes at that end could be monitored by a small external electret microphone connected to a sound level meter. The microphone was backed away from the hole until a 30 dB attenuation relative to internal intensity levels was achieved. Thus the sound level meter with a 120 dB range could approximate sound intensities in the resonator in excess of 150 dB. Since the box was driven at the center, the system greatly favored the f_2 mode shown in Figure 2, which has pressure antinodes at both the center and ends. A neon laser beam was split by a polarizing beam splitter, with the horizontal linear polarization passing through an acousto-optic (AO) modulator which shifts the optical frequency of the first order beam by 40 MHz, while the vertically polarized beam is unshifted. When recombined at a second beam splitter and carefully alligned to be collinear, the resultant beam is passed through an analyzer with its axis at 45° to bring the two components into superposition. They then produce a 40 MHz beat frequency which is measured by a reference detector. A similar scenario is played out downstream with the two beams passing through the resonator cell, except in this case the two interfering beams travel through different regions of the sound field in the cell. Thus in this case the 40 MHz beat frequency will be shifted in phase by the sound, with a 2π phase shift occuring if one path were to increase in path length by one wavelength at some particular time. Thus sound interference effects can be carefully followed in time by electronically measuring the phase shift between the reference detector and the signal de-

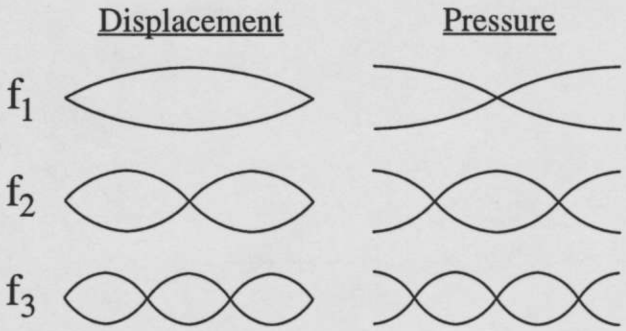

Figure 2: Longitudinal modes of first three harmonics of a closed tube.

tector. Note that the optical system as described is insensitive to vibration except as occuring when the two paths are separated while passing through the sound cell.

Fig. 3 shows the positions of the two beams in the standing wave pattern. To gain sensitivity to sound, the two beams are directed through the cell center and one end which correspond to pressure antinodes of opposite phase for the f_2 mode.

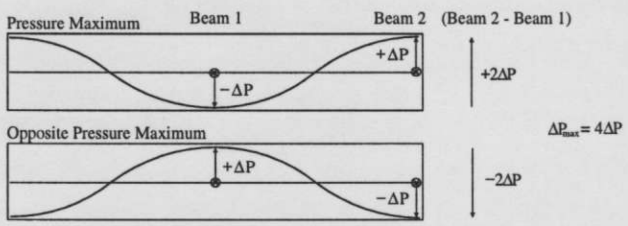

Figure 3: Pressure fluctuations expected at the beam positions in the f_2 sound field.

Thus the maximum phase shifts observed interferometrically are those due to $4\Delta P$ as the standing wave passes between the two extreme situations. The real-time phase shift is conveniently observed using an RF mixer system to generate $\sin(\phi)$ and $\cos(\phi)$, where ϕ is the phase shift between the two 40 MHz signals. These signals can be connected to an x-y oscilloscope which displays the phase shift in real time, going once around around a circle for each fringe. More information can also be gained by recording the two quadrature signals with a computer and then plotting out $\phi(t)$ after its calculation. Since the $4\Delta P$ pressure variation corresponds to about 800 Pa, and 30 fringes are observed from a full atmosphere evacuation (10^5 Pa) in a 6 cm cell, one would expect about one-fourth fringe of rapidly fluctuating phase for 140 dB. Indeed this is what is observed with the system described above within a 10% uncertainty due to our estimates of sound intensity level and some vibrational noise. These results encouraged our hypothesis that it should be possible to holographically image standing waves in gases.

Stroboscopic Holography

The optical components for the holographic experiment were mounted on a 4' x 6' optics table and are shown in Fig. 5. The 30 mW neon laser beam passes through an acousto-optic (AO) cell which in this case may be used to chop the beam, effectively strobing it on and off. The AO cell is driven by a pulse generator which allows control over pulse width, frequency, and phase.

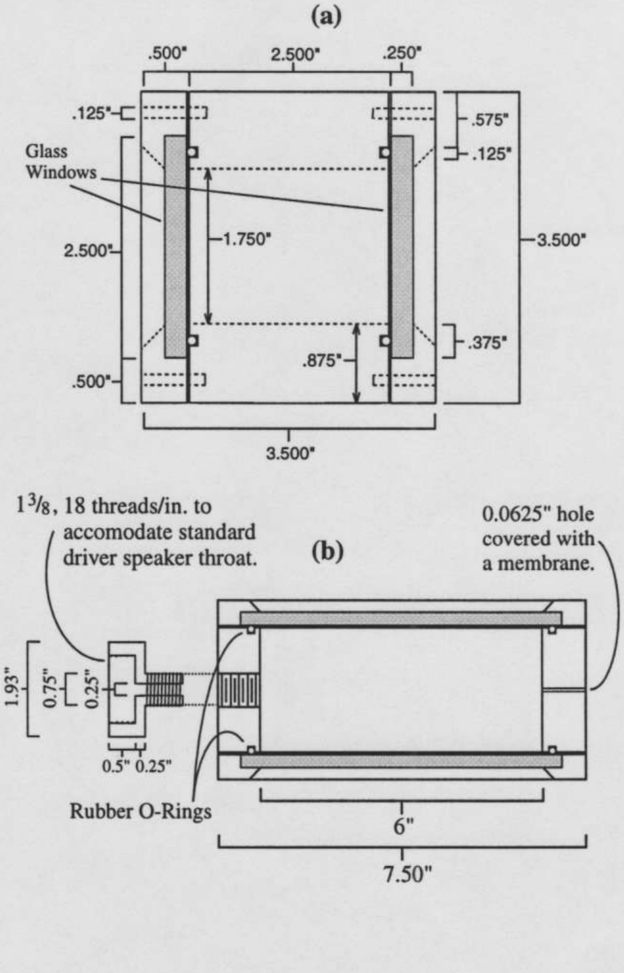

Figure 4: (a) Side view and dimensions (in inches) of aluminum cell. (b) Top view of cell.

The zero-order beam through the AO cell is

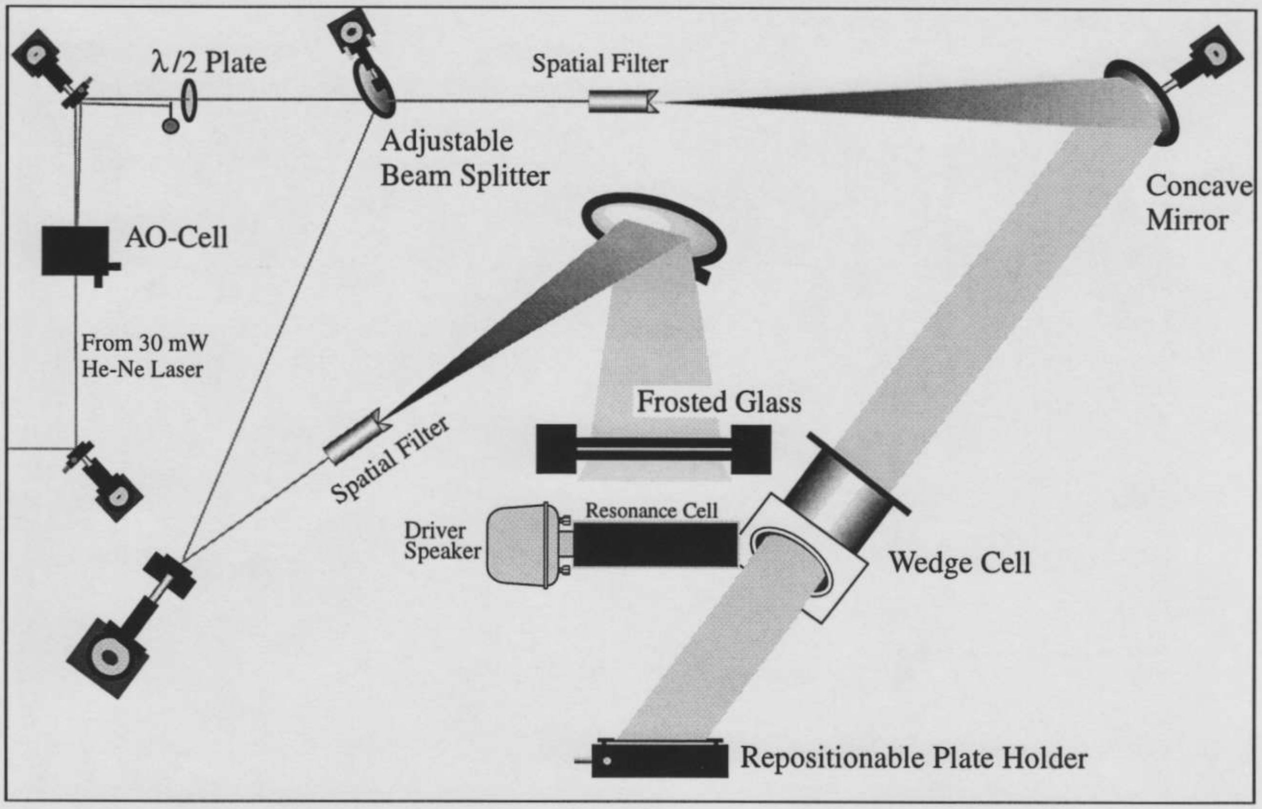

Figure 5: Real-time stroboscopic holography system for imaging standing sound waves.

blocked, and the amplitude modulated first order beam next passes through a $\lambda/2$ retardation plate which allows adjustment of the direction of linear polarization so as to minimize reflections off holographic plates. The remainder of the system is similiar to any transmission holographic layout, except in this case the "object" is a back-illuminated frosted glass plate which may be viewed through the sound resonance cell. In real-time holographic interferometry, one complex wavefront from the object is stored with a transmission hologram, and the developed holographic plate is precisely repositioned in its original location so that the holographic image of the object can directly interfere with the actual object. Any deformation of the object can then be observed in real-time in terms of observed fringes.

An aluminum resonance chamber was constructed for the system as shown in Fig. 4. The sound is coupled in from the speaker driver through a hole at one end. An O-ring seal allows the speaker to be tightly coupled to the chamber, and because driver speakers are enclosed in a sealed metal box, the entire speaker/sound chamber can be evacuated and filled with gas. Since the chamber is pressure driven from one end, all three modes of Figure 3 are driven efficiently. An external microphone monitors sound intensity through a membrane of transparent tape that covers a small hole at one end. It was found that the membrane causes a 40-45 dB attenuation in the sound level, and thus internal pressure levels up to 165 dB can be measured.

Fig. 5 shows a wedge shaped cell in the reference beam. It consists of a 6 inch diameter acrylic tube, with glass windows sealing each end, which may be evacuated and filled with gases. One end of the tube is sawed at a 30° angle to produce a linear change in cell path length from top to bottom. The wedge thus allows one to produce horizontal or vertical reference fringes which are localized on the sound resonance chamber. These reference fringes may be produced or adjusted by changing the gas or its pressure in the wedge after the hologram has been constructed and repositioned in its holder. Any change occuring in the optical path through the resonance chamber will move the reference fringes, and can be spatially quantified by recognizing that each reference fringe corresponds to a one wavelength change in optical path.

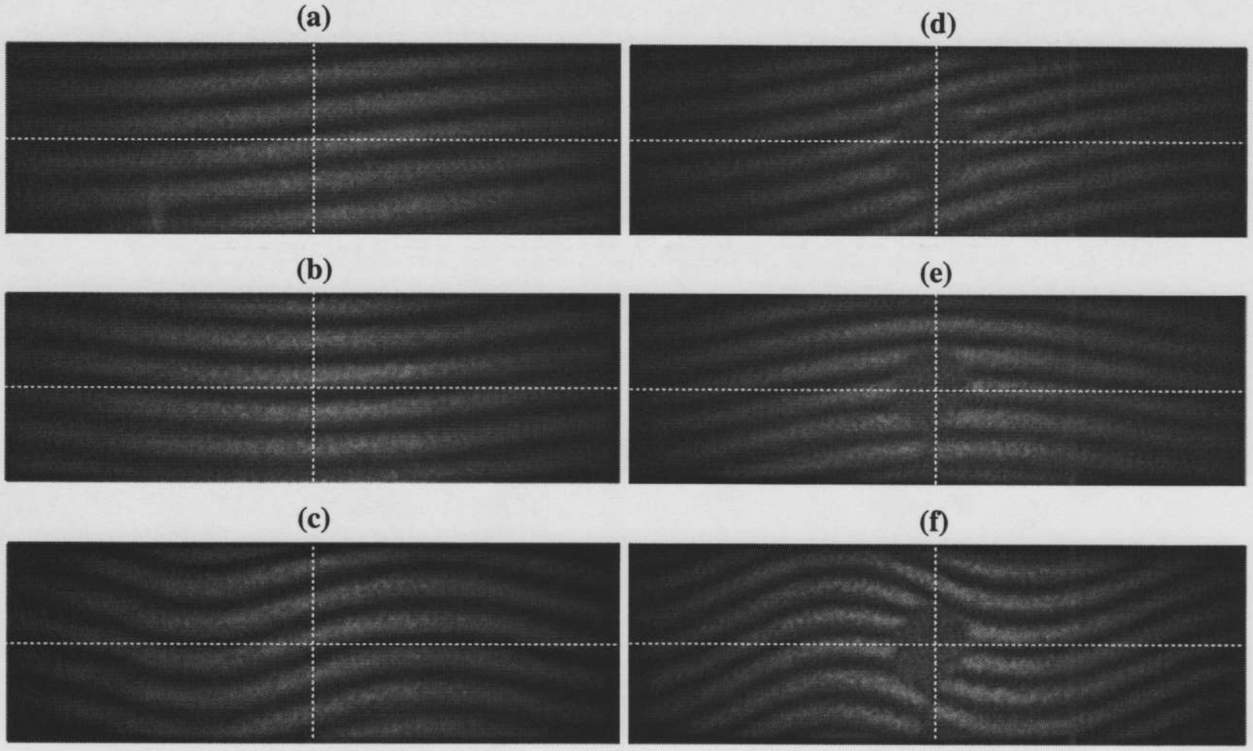

Figure 6: (a), (b), (c). Frame grabber images from videotape of f_1, f_2 and f_3 modes. (d), (e), (f). Images for higher mode amplitudes achieved with cylinder at cell center.

A hologram is first made showing the illuminated frosted glass surface as viewed through the undriven resonance chamber. This hologram is precisely repositioned so that the holographic image is observed to interfere with the actual scene. During this playback phase, air is allowed to enter the previously evacuated wedge, producing stable horizontal fringes of good contrast which are localized on the resonance chamber. Under these conditions a standing sound wave in the chamber would merely blur out the fringes as they oscillate at acoustic frequencies. Thus the AO modulation is now implemented, which allows the laser to be chopped at nearly the same frequency as the sound in the chamber. Effectively, then, the laser comes on only for a small fraction of the period of the sound, and may "freeze" the fringes in extreme positions as caused by the sound field. Two separate frequency generators are used for the sound and AO signals. This allows the two frequencies to be slightly different (by about 0.5 Hz) and produces an image in which one can observe the fringes to slowly oscillate in a vertical direction as a consequence of the sound field. The moving fringes may be easily recorded with a video camera for subsequent analysis.

The first trials were done with air in the resonance chamber and produced fringe motions of up to $\pm 1/2$ fringe at high intensities. With freon gas in the chamber, having an index of refraction almost four times that of air, large multiple fringe oscillations are observed. Fig. 6 displays the first three modes for the freon-filled cell. These extreme positions of the pressure fluctuations are chosen by a frame grabber[4] from videotapes of the each of the first three modes. As the speaker power is increased, the classic single frequency modal pattern yields to the presence of higher harmonics generated by the speaker/cell coupled system. Since the closed tube resonator has "good" harmonics, one begins to observe a progressing square wave that propagates back and forth across the cell. These harmonics act as a sink for the power from the speaker, and one in unable to further increase the amplitude of the fundamental. Fig. 6 shows the effect of a small cylinder placed at the center of the resonator which destroys the harmonic structure of the resonances, and thus allows much more power to be implemented in the fundamental. A real-time FFT

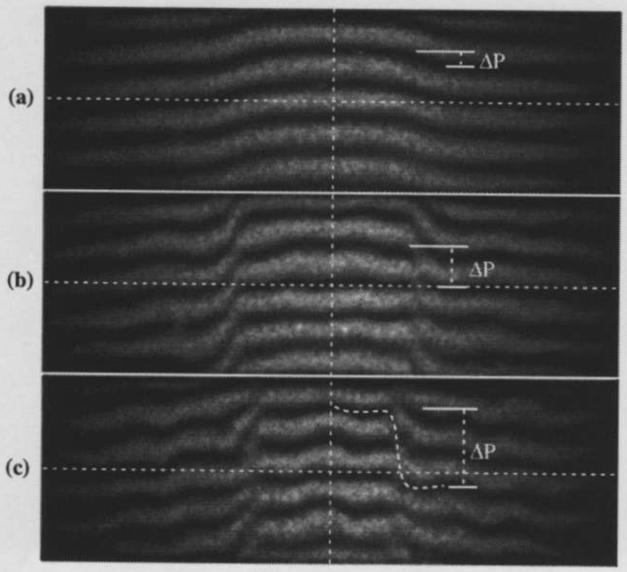

Figure 7: Frame grabber images of pressure variations resulting at three different intensity levels with high harmonic content at (a) 150 dB, (b) 160 dB, and (c) 165 dB.

system monitored the power spectrum of the radiated sound concurrent with the recording of the images.

Fig. 7 displays the high harmonic content image for varying sound intensity levels as approximated by the microphone. In this case the speaker and strobe frequency are tuned to identical values, and one can observe the change in the pressure amplitude of the stationary pattern as the sound intensity is adjusted. An increase in intensity level of 10 dB is seen to correspond to a pressure amplitude change of approximately a factor of three as expected.

Acknowledgements

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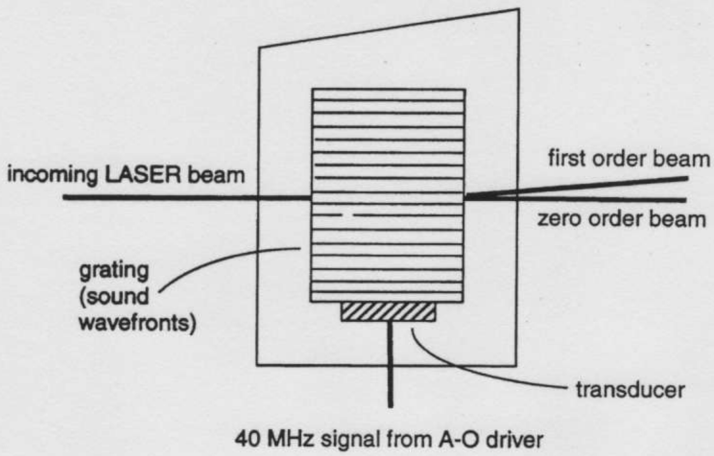
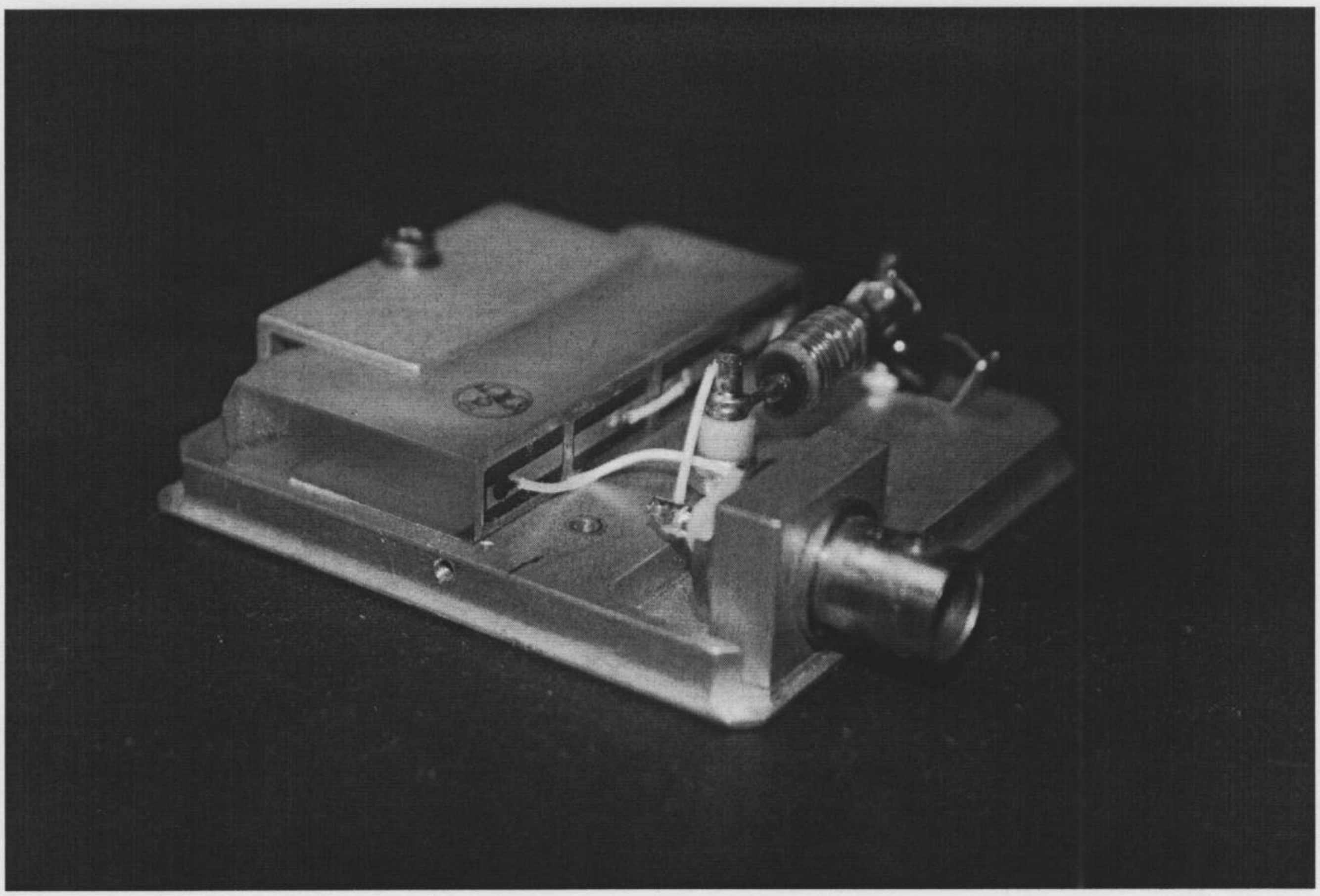
[2] T.D. Rossing and H.J. Sathoff, "Modes of vibration and Sound Radiation from Tuned Handbells," *J. Acoust. Soc. Am.,* **68**:1600-1605 (1980).

[3] T.D. Rossing, *The Science of Sound,* (Addison-Wesley, Reading, MA, 1982).

[4] Scion LG-3, Scion Corporation, 152 W. Patrick St., Frederick, MD 21701.

AO Driver for strobing the hologram during playback





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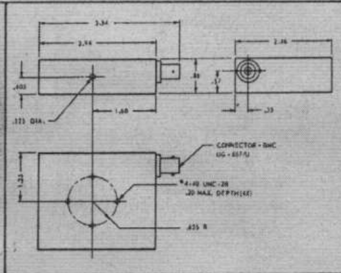

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