Acoustics of the glass harmonica

Thomas D. Rossing
Physics Department, Northern Illinois University, DeKalb, Illinois 60115

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Glass harmonicas or glass harps, consisting of sets of tuned glasses, were already popular in Europe when Benjamin Franklin designed an improved style of instrument that he called an armonica. The modes of a wineglass resemble the flexural modes of a bell. Striking the glass excites a number of these modes, but rubbing the rim with a finger or bowing it radially with a violin bow generally excites a single mode. As the player's finger moves around the rim of the glass, the nodes and antinodes move with it, resulting in a pulsating sound.

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INTRODUCTION

Wineglasses can be musical instruments. The dinner guest who playfully rubs a wetted finger around the rim of a wineglass to make it "sing" is joining Mozart, Gluck, Benjamin Franklin, and others who have constructed or performed on glass harmonicas.

Glass harmonicas are basically of two types. One type employs vertical wine glasses, arranged so that the performer can rub more than one glass at a time. A collection of glasses played in this manner is sometimes called a glass harp. The other type, invented by Benjamin Franklin, employs glass bowls or cups turned by a horizontal axle, so the performer need only touch the rims of the bowls as they rotate to set them into vibration (Franklin's instruments can be seen in several museums, including the Franklin Museum in Philadelphia.) Both types of instruments are shown in Fig. 1.

In this paper, we briefly discuss the rich history of these instruments and report some experiments to determine how various types of glasses vibrate and produce sound.

I. BRIEF HISTORY

Glass musical instruments are probably as old as glassmaking. The 14th century Chinese *shui chan* consisted of nine glass cups struck by a stick. There are also 15th century Arabic references to musical cups (*kizam*) and jars (*khaurabi*). In Gafori's *Theoria Musicae* (Milano, 1492) is a woodcut showing the musical use of glasses in a "pythagorean" experiment.[1]

The practice of rubbing the rims of glass vessels to produce steady tones became popular in Europe during the 18th century. In 1746 in London, the composer Christoph Willibald Gluck gave a concert in London advertised as "a concert on 26 drinking glasses tuned with spring water, accompanied with the whole band, being a new instrument of his own invention, upon which he performs whatever may be done on a violin or harpsichord." [1] (A bit of an exaggeration, no doubt.)

On a trip to England, Benjamin Franklin heard a set of glasses by E. H. Daval in Cambridge. In a letter to a friend in Italy in 1762. Franklin wrote, "Being charmed by the sweetness of its tones, and the music he produced from it, I wished only to see the glasses disposed in a more convenient form, and brought together in a narrower compass, so as to admit of a greater number of tunes, and all within reach of hand to a person sitting before the instrument." [2] Franklin called his instrument the armonica.

Famous Europeans who became armonica players included Marie Antoinette and Franz Mesmer, the hypnotist. Mozart learned to play the instrument and composed several pieces for it, as did Beethoven. Franklin himself composed several songs for the instrument, and Donizetti wrote a part for glass harmonica in the accompaniment to Lucia's mad scene in *Lucia di Lammermoor*, although the part is nowadays generally played on a flute.

Several attempts have been made to add a keyboard. Marianne Kirchgessner was reported to be a virtuoso on the keyboard version during the 19th century, and it may have been the keyboard version that Mozart first heard. Organist E. Power Biggs arranged to have the Schlicker organ company build a keyboard version, on which he played a concert in 1956 to commemorate the 250th anniversary of Franklin's birth (and the 200th anniversary of Mozart's birth), but apparently the instrument was not particularly successful.

In this century, interest in the glass harmonica has been kept alive by Bruno Hoffman and a few other dedicated performers. In 1988, a group of glass music enthusiasts banded together to form an organization called Glass Music International, which has held several glass music festivals and now publishes a quarterly called *Glass Music World*.

At the 121st meeting of the Acoustical Society of America in Baltimore (1991), attendees at a special session devoted to the acoustics of glass musical instruments heard performances on a glass harp by Jamey Turner and on a Franklin-type armonica by Alisa Nakashian.

II. MODES OF VIBRATION

The vibrational modes of a wineglass rather closely resemble the flexural modes of a large church bell[3] or a small handbell[4] and especially those observed in a Chinese *qing*.[5] The principal modes of vibration result from the propagation of bending waves around the glass, resulting in

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(a)

(b)

FIG. 1. (a) Glass harp played by Jamey Turner; (b) Franklin-type armonica shown with its builder Gerhard Finkenbeiner.

$2m$ nodes around the circumference. In the lowest mode with $m=2$ (corresponding to the (2,0) mode in a bell), the rim of the glass changes from circular to elliptical twice per cycle, as shown in Fig. 2. To a first approximation, at least, the radial and tangential components of the motion are proportional to $m \sin m\theta$ and $\cos m\theta$, respectively;[6] for the (2,0) mode the maximum tangential motion is half the maximum normal motion. This means the glass can be excited by applying either a normal or a tangential force. A paper by French[7] considers the theory of wineglass vibrations in some detail.

The modes of vibration of wineglasses or glass bowls can be conveniently studied in the laboratory by means of holographic interferometry.[8] This technique, widely used to study vibrating structures, results in interferograms that resemble contour maps and indicate the amount of motion at each point on the glass, as shown in Fig. 3.

Figure 4(a) shows the modal frequencies for several wineglasses and brandy snifters as functions of m. The

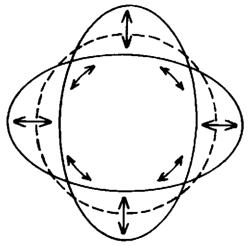

FIG. 2. Top view (exaggerated) of a wine glass vibrating in its fundamental mode (similar to the 2,0 mode in a bell). For $m=2$, the tangential amplitude is half the normal amplitude.

modal frequencies lie pretty well along straight lines with slopes of 2 on a logarithmic graph; that is, frequency is nearly proportional to m^2, as in a cylindrical shell. A similar plot in Fig. 4(b) shows modal frequencies for three armonica bowls blown by Gerhard Finkenbeiner, a scientific glassblower in Waltham, Massachusetts.

For any given mode, the modal frequency is roughly proportional to the thickness and inversely proportional to the square of the radius. Why the square of the radius? Because the speed of flexural waves is proportional to $\sqrt{f}$. Thus, if the time for a wave to travel the circumference is taken to be its period, we can say that

$$1/f = 2\pi r/k\sqrt{f}, \text{ from which } f \propto 1/r^2.$$

III. RUBBING, BOWING, STRIKING

Since the modes of vibration of glasses or bowls have both normal and tangential components, they can be excited by either a normal or a tangential force. Glass harmonicas are usually played by rubbing the rim of the glass

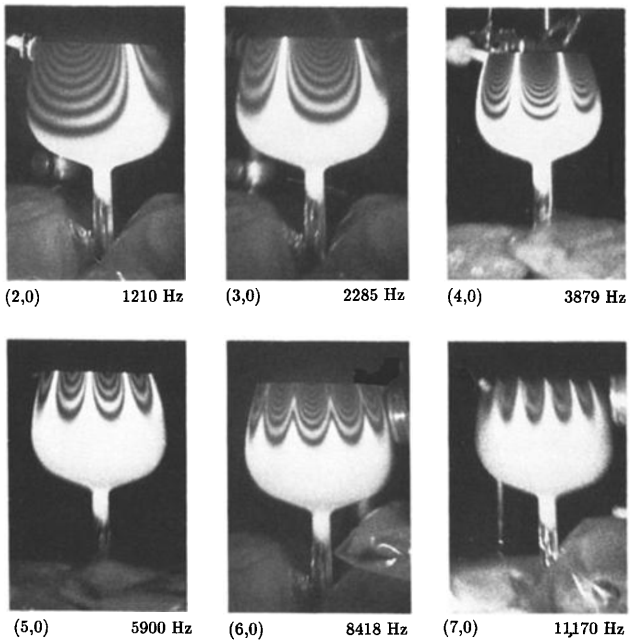

FIG. 3. Holographic interferograms of 6 modes in a wineglass. The amplitude changes by $\lambda/2$ in moving from one dark (or bright) fringe to the next one ($\lambda = 633$ nm is the wavelength of red light).

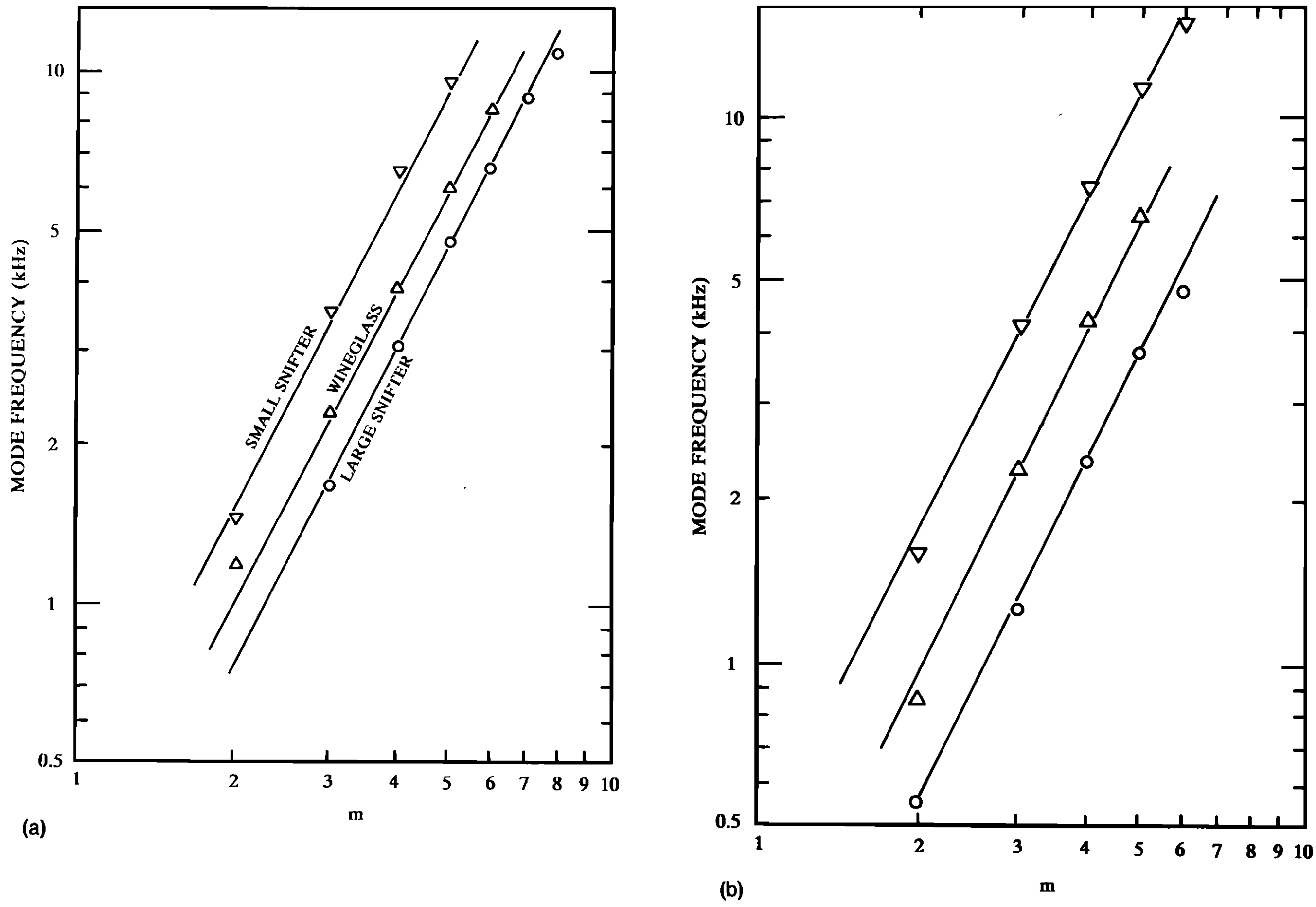

FIG. 4. Modal frequencies as a function of mode number *m*, where 2*m* is the number of nodal meridians: (a) a wineglass and two brandy snifters; (b) three armonica bowls.

or bowl tangentially with a wet finger, but striking the glass with a mallet or bowing it radially with a violin bow also sets it into vibration.

A moving finger appears to excite vibrations in the glass through a "stick-slip" process, much as a moving violin bow excites a violin string. During a part of a vibration cycle, the rim of the glass at the point of contact moves with the finger; during the balance of the cycle it loses contact and "slips" back toward its equilibrium position. This results in a sound that consists of a fundamental plus a number of harmonic overtones, although not nearly so many as the sound of a violin. The location of the maximum motion follows the moving finger around the glass.

Although rubbing a glass with a wet finger tends to excite only the (20) mode and its harmonics, tapping it excites the other modes as well. By bowing it radially with a violin bow, we have been able to excite either the (20) mode or the (30) mode (although not at the same time), and higher modes may be possible as well. Figure 5 shows sound spectra from a wineglass excited by rubbing with a wet finger, tapping with a yarn-wrapped vibraphone mallet, and bowing with a violin bow. In Fig. 5(d) the glass was touched with two fingers at locations that suppress the (20) mode and thus encourage the (30) mode. It should be noted that bowing is also a "stick-slip" process, and only one mode can couple in a stable way to the bow at the same time unless two mode frequencies are near enough to having a harmonic relationship that mode locking can occur.

In the wineglass spectra shown in Fig. 5, the fifth harmonic of the (20) mode and the fundamental of the (50) mode are close together in frequency (5990 and 5997 Hz, respectively), and because of resonance coupling they appear rather prominently in all four spectra. [Coupling also appears between the seventh harmonic of the (20) mode and the fundamental of the (60) mode (8380 and 8423 Hz, respectively).] In the spectra of a large brandy snifter in Fig. 6, no such modal coupling occurs, and the harmonics of the rubbed glass fall off in a more regular way.

Bowing with a violin bow [Figs. 5(c) and 6(c)] excites several modes, although the (20) mode is easily the strongest [even more than the sound spectra indicate, because the sound radiation efficiency increases rapidly with frequency near the coincidence frequency, and thus the higher-order modes radiate much more efficiently than the (20) mode[9]]. The spectrum in Fig. 6(c) was recorded just after attack, before the steady state was reached, and thus the higher modes appear in the spectrum. In Fig. 6(d), as in Fig. 5(d), an effort has been made to suppress the (20) mode and to enhance the higher modes by constraining the glass at appropriate points with the fingers.

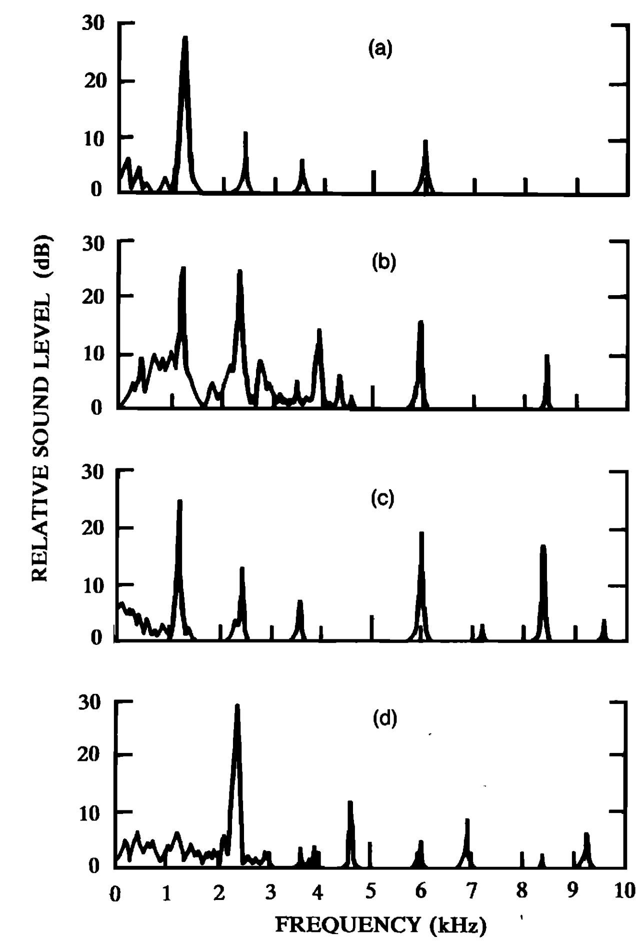

FIG. 5. Sound spectra of a wineglass: (a) rubbing with a wet finger; (b) tapping with a yarn-wrapped mallet; (c) bowing with a violin bow; (d) bowing so as to excite the (30) mode.

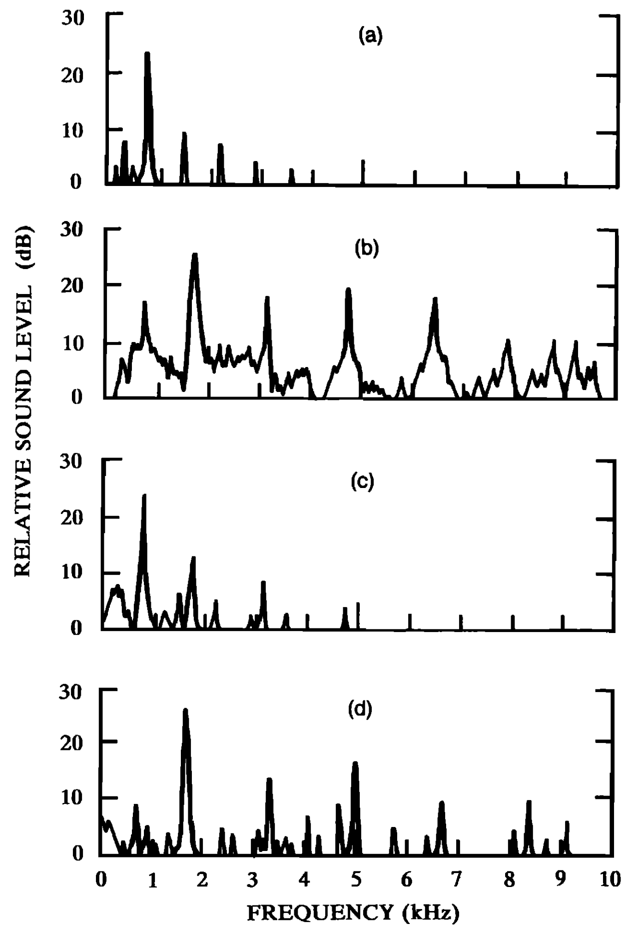

FIG. 6. Sound spectra of a large brandy snifter: (a) rubbing with a wet finger; (b) tapping with a yarn-wrapped mallet; (c) bowing with a violin bow; (d) bowing so as to excite the (30) mode.

As the finger moves around the rim of the glass, the region of maximum vibration follows the moving finger, resulting in a sound that pulsates with about 4 to 8 beats per second, depending upon the speed of the player's finger, as shown in Fig. 7.

Rayleigh[10] describes an interesting experiment that I have not yet tried to duplicate (but perhaps some reader has). A glass bell jar ("air-pump receiver," he calls it) is set into vibration by rubbing the edge with a moistened finger. "A small chip in the rim, reflecting the light of a candle, gave a bright spot whose motion could be observed with a Coddington lens suitably fixed. As the finger was carried round, the line of vibration was seen to revolve with an angular velocity double that of the finger; and the amount of excursion (indicated by the length of the line of light), though variable, was finite in every position." What Rayleigh is describing is a rather complicated stick-slip (tangential) motion, somewhat like the so-called Helmholtz motion of a bowed violin string.[11] Perhaps someone has investigated wineglass motion using modern stroboscopic and photographic equipment, but I am not aware of any report in the published literature.

Although an earlier investigation of the acoustics of the armonica reported more than 20 prominent harmonics in the sound spectrum,[12] we find the sound to be dominated by the fundamental as it is in the case of the glasses shown in Figs. 5 and 6. Spectra of the sound from striking and rubbing an armonica bowl are shown in Fig. 8. Note that striking it excites the (3,0), (4,0), (5,0), and (6,0) modes as well as the (2,0) mode, while the rubbing spectrum shows a fundamental and second harmonic, both emitted by the (2,0) mode.

Spectra of two armonica notes extracted from a compact disc recording are shown in Fig. 9. The note in Fig. 9(a) (G_5) shows a second harmonic 26 dB below the fundamental. The note in Fig. 9(b) has three overtones, 20 to 40 dB below the fundamental, that are slightly flat from the 2nd, 3rd, and 4th harmonics. Although the spectrum of the

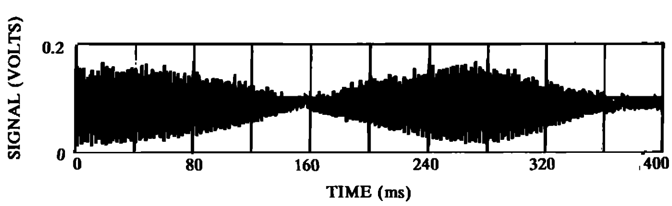

FIG. 7. Oscillograph of sound pressure from the large brandy snifter, showing a beat rate of 5 Hz (corresponding to $1\frac{1}{4}$ rotations of the finger per second).

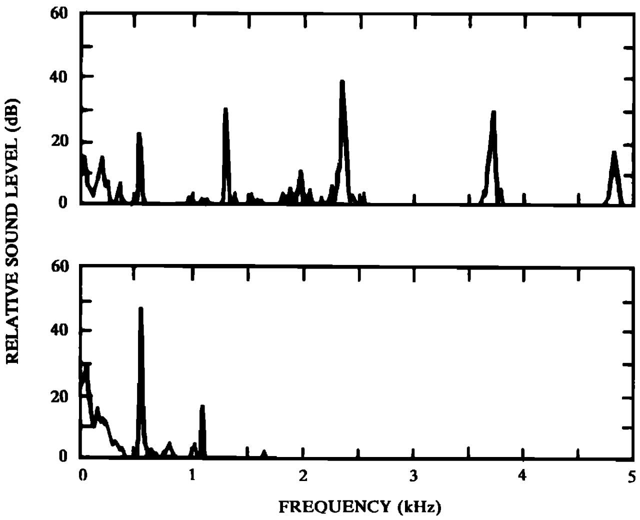

FIG. 8. Spectra of sound from striking (upper) and rubbing (lower) an armonica bowl.

force exerted by the player's finger is rich in harmonics, only the fundamental component matches the frequency of a vibrational mode (unlike the case of a violin string, also excited by a stick-slip mechanism, whose mode frequencies are harmonically related).

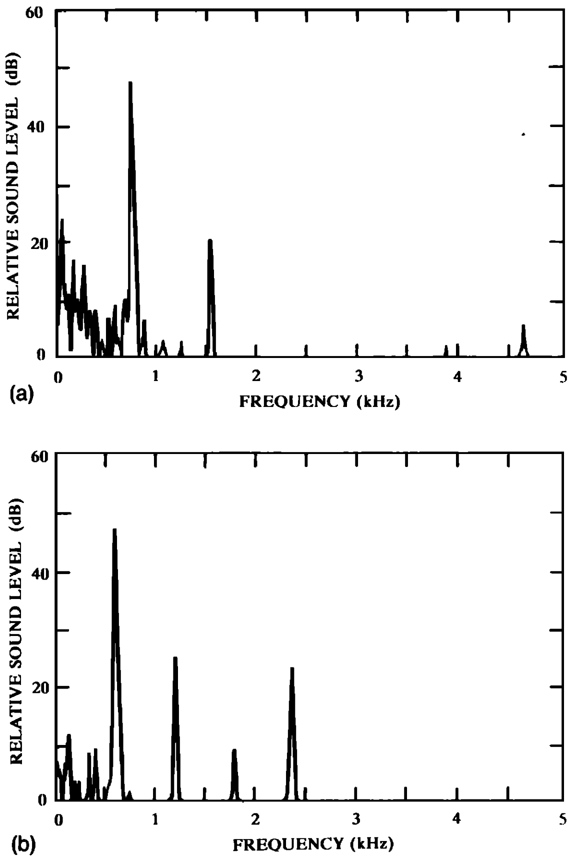

FIG. 9. Spectra of two armonica notes recorded on a compact disc; (a) G_5 with a second harmonic; (b) D_5 with three nearly harmonic overtones.[13]

IV. SELECTING AND TUNING THE GLASSES

A glance at available photographs of glass-harmonica performers suggests that a rather wide variety of glasses can be used. Brandy snifters appear to be quite widely used. Wineglasses with a large bowl diameter and a slightly narrower mouth appear to be popular as well. Makers of Franklin-type armonicas apparently prefer a harder quartz glass for durability. Glasses that have a clear and persistent ring when tapped will probably play well.

Finding glasses with similar qualities over a large range of sizes is a problem. One builder reported making over half the notes of a 3-octave instrument from 8-oz. glasses by slicing off layers of varying size from the rim using a carbide tool and a torch.[14] Fine tuning can be accomplished by grinding. Grinding down the rim raises the frequency, whereas thinning the glass bowl near the base lowers the frequency. Fire polishing the rim raises the frequency slightly.

Fine tuning can also be accomplished by adding water (or wine), but the range of tuning is small. We found that filling various glasses about 1/4 full lowered the playing frequencies from 0.3% to 0.9% (5 to 15 cents). Filling the same glasses half full lowered the frequencies up to 6% (one semitone or 100 cents). Water affects the playing quality, however, and during a long concert or rehearsal the liquid level can change because of evaporation. Thus it is better to fine-tune the glasses by careful grinding.

V. LOUDNESS AND TIMBRE

The player has relatively little control over the steady-state sound of a glass harmonica, as compared with other musical instruments. Moving the finger faster increases the level of the radiated sound, but only by 10 dB or less, unlike the violin where the player has considerable control over loudness by varying the bow speed. Furthermore, the player does not have the means to add higher harmonics, a feature that is associated with crescendos on most musical instruments.

VI. CONCLUDING REMARKS

The glass harmonica has an interesting history, and it is heartening to note the resurgence of interest in recent years. It also has some interesting acoustical features, unlike any other musical instrument I know.

ACKNOWLEDGMENTS

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