Acoustics of percussion instruments—Part II

Thomas D. Rossing

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Acoustics of percussion instruments – Part II

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The purpose of this article is to describe the basic acoustical principles of percussion instruments for teachers and serious students of physics and music. In Part I we discussed the vibrations of bars, tubes, and rods and the way they are used in glockenspiels, marimbas, xylophones, vibes, chimes, and triangles.[1] In this article, we extend the discussion to percussion instruments whose vibrating members are multidimensional.

Vibrations of membranes

The theoretical membrane, as described by Rayleigh,[2] "is a perfectly flexible and infinitely thin lamina of solid matter, of uniform material and thickness, which is stretched in all directions by a tension so great as to remain sensibly unaltered during the vibrations and displacements contemplated." The ideal membrane is assumed to have a uniform density of σ kg/m^2 and to be pulled evenly by a tension T newtons/m around its edge; like the ideal string, it is assumed to be infinitely flexible. Under these conditions, waves in the membrane travel with a velocity $c = \sqrt{T/\sigma}$. The wave equation describing the displacement w of a point on the surface is:

$$\nabla^2 w = \frac{1}{c^2}\frac{\partial^2 w}{\partial t^2}$$

(See box page 279)

Note that the wave velocity increases with the square root of tension, as in the case of a flexible string. One interesting difference between the ideal string and the ideal membrane is that a small point force applied to the membrane would produce an infinite deflection at that point,[3] although any small amount of stiffness limits the deflection in a real membrane.

Solutions to the wave equation for circular membranes involve the well-known Bessel functions. The modes are not harmonic (i.e., their frequencies are not multiples of a fundamental frequency) as in the case of a vibrating string. The modes are usually described by two integers m and n, where m denotes the number of nodal diameters and n the numbers of nodal circles. Figure 1 shows the shapes of a few membrane

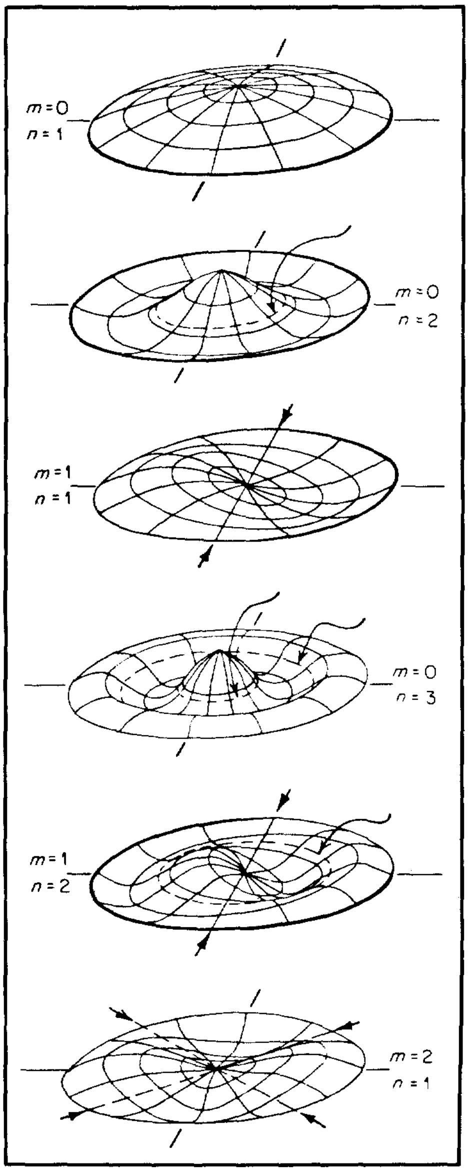


Fig. 1. Shapes of some normal modes of vibration of the circular membrane. Arrows point to nodal lines. [From P.M. Morse and K.U. Ingard, *Theoretical Acoustics* (McGraw-Hill, New York, 1968)], p. 212, by permission.

Professor Rossing's picture and biography appeared with Part I of this article in our December 1976 issue.

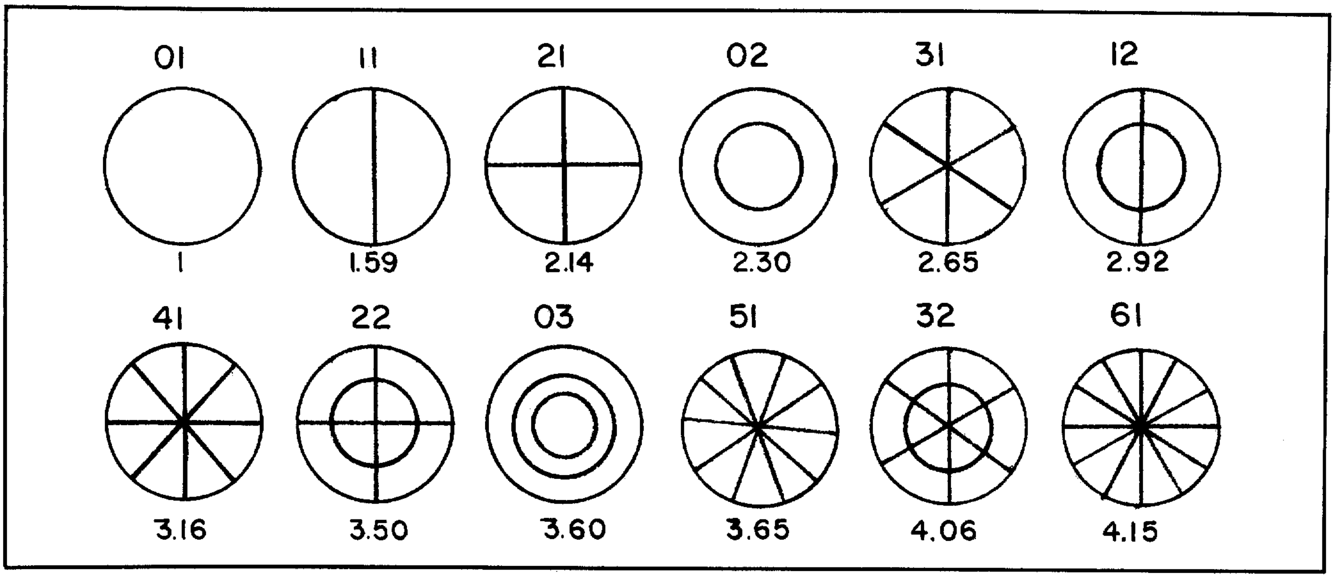


Fig. 2. Modes of an ideal membrane, showing radial and circular nodes, and the customary mode designation (the first number gives the number of radial modes, and the second number the circular nodes including the one at the edge). The number below each mode diagram gives the frequency of that mode compared to the fundamental (01) mode.

Solutions to the Membrane Equation

The Laplacian operator ∇^2 may be written in rectangular or polar co-ordinates depending upon the shape of the membrane (see Ref. 3).

A. Unlimited membrane:

$w(x, y\ t) = F_\theta\ (x \cos\theta + y \sin\theta - ct)$ is a solution which represents a wave traveling in a direction which makes an angle θ with the x-axis.

B. Rectangular membrane (rigid frame with sides a and b in length):

Wave equation

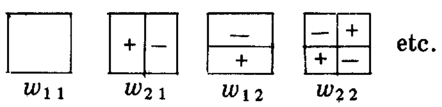
$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} = \frac{1}{c^2}\frac{\partial^2 w}{\partial t^2} \text{ has solutions:}$$

$$w_{mn} = A \sin\frac{\pi m x}{a} \sin\frac{\pi n y}{b} \cos 2\pi f_{mn} t$$

The modal frequencies are:

$$f_{mn} = \frac{1}{2c}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

These modes have shapes as follows:



C. Circular membrane (rigid frame of radius a):

Wave equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 w}{\partial \phi^2} = \frac{1}{c^2}\frac{\partial^2 w}{\partial t^2} \text{ has solutions:}$$

$$w_{mn} = A \cos m\phi\ J_m\left(\frac{2\pi f_{mn} r}{c}\right) \cos 2\pi f_{mn} t$$

[$J_m\ (z)$ is a Bessel function of order m].

The modal frequencies are:

$$f_{mn} = \frac{c}{2a}\beta_{mn} \quad \left(\beta_{mn} \simeq n + \frac{m}{2} - ¼ \text{ for large } n\right)$$

Modal shapes and frequencies are illustrated in Figs. 1 and 2.

modes. Figure 2 illustrates the first 12 modes along with the frequencies compared to the fundamental (01) mode.

Timpani

Drums consist of membranes of animal skin or synthetic material stretched over some type of air enclosure. Some drums (e.g., timpani, tabla, boobams) sound a definite pitch; others convey almost no sense of pitch at all. Drums are important in nearly all musical cultures, and constitute one of the most universally used type of musical instrument throughout history.

The timpani or kettledrum is perhaps the most important drum in the orchestra, one member of the percussion section usually devoting his attention exclusively to this instrument. During the last century, various mechanisms were developed for changing the tension and tuning the heads rapidly. Most modern timpani have a pedal-operated tensioning mechanism in addition to six or eight tensioning screws around the rim of the kettle. The pedal typically allows the player to vary the tension over a range of 2 to 1, which corresponds to a tuning range of about a musical fourth. A modern pedal-equipped kettledrum is shown in Fig. 3.

At one time timpani heads were calfskin, but this material has gradually given way to Mylar (polyethylene terephthalate). Calfskin heads require a great deal of hand labor to prepare, and great skill to tune properly. Many orchestral timpanists prefer them for concert work under controlled humidity, but use Mylar under other conditions such as touring. Mylar is insensitive to humidity and easier to tune, due to its homogeneity. A thickness of 0.0075 in. is considered standard for Mylar timpani heads. Timpani kettles are roughly hemispherical; copper is the preferred

Fig. 3. A modern kettledrum with suspended bowl and pedal-operated mechanism for tuning.

TABLE I
Vibration frequencies of a kettledrum, a drumhead without the kettle, and an ideal membrane

Mode	Kettledrum		Drumhead Alone		Ideal Membrane
	f	f/f_{11}	f	f/f_{11}	f/f_{11}
01	127 Hz	.85	82 Hz	.53	.63
11	150	1.00	155	1.00	1.00
21	127	1.51	229	1.48	1.34
02	252	1.68	241	1.55	1.44
31	298	1.99	297	1.92	1.66
12	314	2.09	323	2.08	1.83
41	366	2.44	366	2.36	1.98
22	401	2.67	402	2.59	2.20
03	418	2.79	407	2.63	2.26
51	434	2.89	431	2.78	2.29
32	448	2.99	479	3.09	2.55
61	462	3.08	484	3.12	2.61
13	478	3.19	497	3.21	2.66
42			515	3.32	2.89

material, although Fiberglas and other materials are frequently used.

Although the modes of vibration of an ideal membrane are not harmonic, a carefully tuned timpani is known to sound a strong principal note plus two or more harmonic overtones. Rayleigh[2] recognized the principal note as coming from the 11 mode and recognized overtones about a perfect fifth ($f{:}f_1 = 3{:}2$), a major seventh (16:9) and a near octave (2:1) above the principal tone. Taylor[4] identified a tenth (octave plus a third or $f{:}f_1 = 5{:}2$) by humming near the drumhead, which is a technique timpanists sometimes use to fine-tune the instrument.

How are the inharmonic modes of the ideal membrane coaxed into a harmonic relationship? We have not seen a detailed theory, but a qualitative explanation is not too difficult to construct. A real timpani drumhead has some stiffness of its own, and it is strongly coupled to the air enclosed by the kettle on one side and free air on the other side. The stiffness of the membrane, like the stiffness of piano strings, raises the frequencies of the higher overtones, while the motion of the air lowers the frequency of certain modes (such as the 11 and 21) in a rather complicated way. Our experimental studies thus far[5] indicate that air-loading is the more important effect, and this is in agreement with the experiments of Manzer and Smith using a wire-mesh membrane.[6]

We should point out that the frequencies of the fundamental (01) and other symmetrical modes (02, 03, etc.) will be raised by the "stiffness" of the enclosed air in the kettle. Morse[7] has calculated this frequency rise to be approximately 5-6% for the 01 mode, 0.2% for the 02 mode, etc. (This is not unlike the increase in the resonance frequency of a loudspeaker when it is mounted in an air-tight enclosure.) However, the assumption is made incorrectly that the frequencies of the musically-important unsymmetric modes will be unaffected by the air in the kettle.

Table I shows data taken by Craig Anderson in our laboratory with a 26 in. Ludwig kettledrum and an identical drum without the kettle. In both cases the ratios of the frequencies to the principal (11) mode are given. The drumhead can be driven rather easily with a crude driver consisting of a loudspeaker, a soda straw and a wad of chewing gum.[5] However, to identify as many individual modes as Craig did, great care must be taken to achieve uniform tension. Even then, modes 22, 03 and 51, which are nearly degenerate (i.e., have nearly the same frequency), tend to mix together to form three new modes.

An interesting way to study the effect of air loading on the various membrane modes is to calculate the velocity of the waves as they propagate across the membrane. Waves corresponding to the lower modes are slowed down more than those of the higher modes, as shown in Fig. 4. Note that the 01 mode is raised substantially (and the 02 mode a lesser amount) by the stiffness of the air in the kettle. The wave velocity appears to be about 90 m/sec (about 1/4 the speed of sound in air) for the higher modes, suggesting that the spreading of the frequencies due to membrane stiffness is small.

The sound spectra obtained by striking the drum in its "normal" place (about 1/4 of the way from edge to center) and at the center are shown in Fig. 5. Note that the fundamental mode (01) appears much stronger when the drum is struck at the center, as do the other symmetrical modes (02, 03). They damp out rather quickly (~ 0.6 sec), however, so they do not produce much of a drum sound. In fact, striking the drum at the center produces quite a dull, unmusical sound.

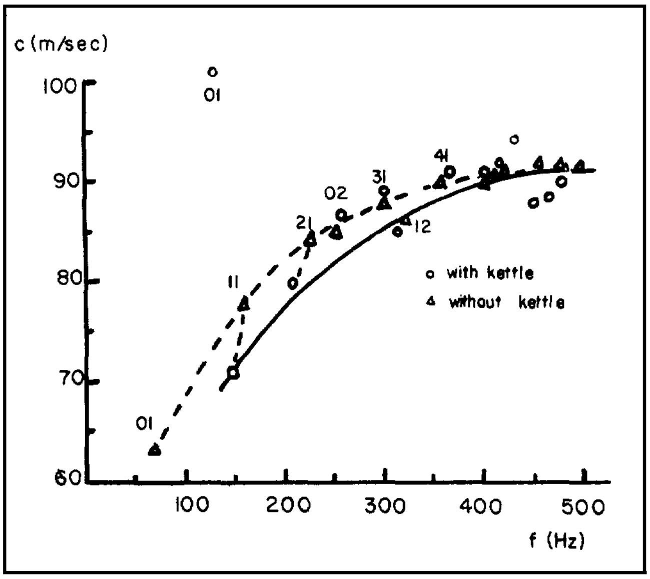


Fig. 4. Velocity of waves in a drumhead at four different modes with and without the kettle.

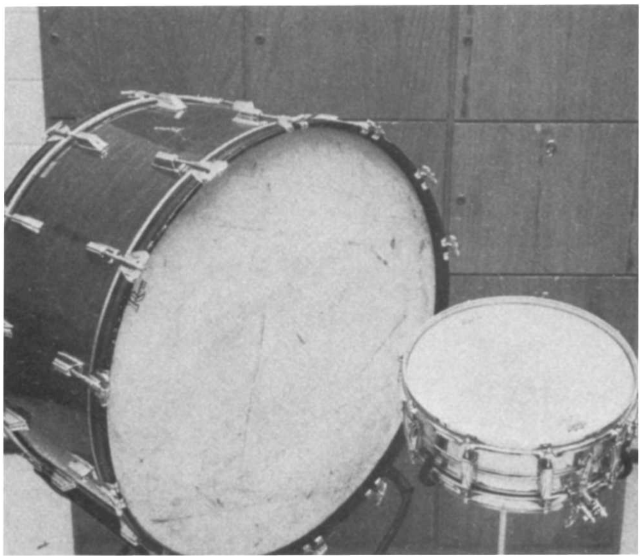


Fig. 6. Bass drum and snare drum.

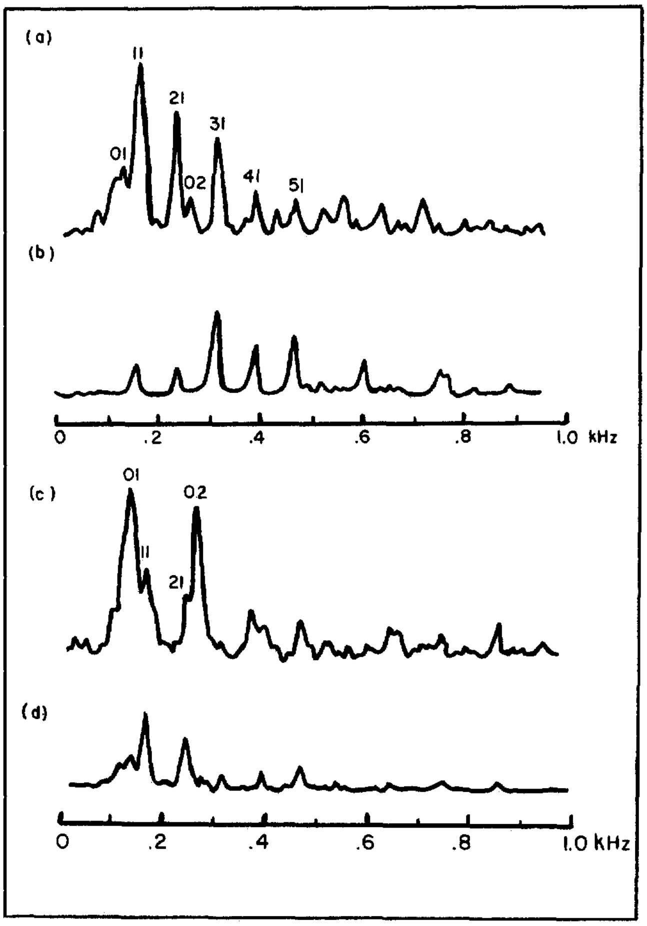


Fig. 5. Sound spectra from a 26 in. timpani tuned to E_3. (a) Approx. 0.03 sec after striking at the normal point; (b) Approx. 1 sec later; (c) Approx. 0.03 sec after striking at the center; (d) Approx. 1 sec later. These were recorded on a Honeywell SAI-51B real-time spectrum analyzer.

Normal striking technique produces prominent partials with frequencies in the ratios 0.85: 1 : 1.51 : 1.99 : 2.44 : 2.89. If we ignore the heavily-damped fundamental, the others are nearly in the ratios 1 : 1.5 : 2 : 2.5, a harmonic series built on a nonexistent fundamental an octave below the principal tone. Measurements on timpani of other sizes give similar results.[5] It is a little surprising that the pitch of timpani corresponds to the pitch of the principal tone rather than the missing fundamental of the harmonic series, which would be an octave lower. Apparently the strengths and durations of the overtones are insufficient, compared to the principal tone, to establish the harmonic series of the missing fundamental. Brindle,[8] however, observed that a gentle stroke at the proper spot with a soft beater can produce a rather indistinct sound an octave lower.

Other drums

Among drums which convey an indefinite pitch or none at all are the bass drum, snare drum, tenor drum, tomtom, conga, bongo, etc. Many drums of this type have two heads, and each head is given a slightly different tension. Thus the many inharmonic partials of the two heads produce the indefinite pitch which will blend with music in any key.

Bass drums are typically 28-40 in. in diameter. Single-headed or "gong" drums produce a "mellow" sound, although two-headed drums with their more indefinite pitch are usually preferred in bands and orchestras. Fletcher and Bassett[9] identified well over 100 partials in the sound of a bass drum.

Snare drums are double-headed drums about 14 in. in diameter and 5 to 8 in. deep. Strands of gut or wire, called snares, are stretched across the lower (snare) head, which vibrates against the snares when the upper (batter) head is struck. A mechanism is included for lowering the snares away from the head so that the drum produces a sound similar to a tomtom of equivalent size. Snare drums are

Fig. 7. Typical jazz or trap drum set including snare drum, pedal-operated bass drum, three tomtoms, and three cymbals.

played with wooden sticks having tapered ends and a small knob. Parade drums and field drums are names given to large-size snare drums for outdoor use.

Perhaps this is an appropriate time to say a few words about calfskin drumheads. Calfskin heads, even when prepared by an expert craftsman, are not uniform in density and strength. However, by studying Mylar and calfskin heads on bass and field drums, Hardy and Ancell[10] confirmed in the laboratory what many experienced drummers know: calfskin is capable of a larger range of tension and under some conditions has more damping. The peak sound spectra were found to be quite similar, although Mylar had a slightly louder sound during a drum roll due to lower damping. The principal advantage of Mylar, however, is its insensitivity to humidity and moisture.

Fig. 8. Conga drum.

Tomtoms are unsnared drums which are made in a number of sizes from 8 to 18 in. in diameter. Tomtoms may have either one or two heads, the more indefinite pitch of the two-headed type usually being preferred for orchestral work.

Heads with a center patch of greater thickness are achieving some popularity. These are said to give a "centered," slightly "tubby" sound with a more distinct pitch. In our laboratory, we compared the sound spectra and the frequencies with and without dots for tomtoms of a number of sizes. In the 12-in. tomtom, for example, we found the first three modal frequencies nearly in the ratio 1:2:3. This ratio was altered in a somewhat unpredictable fashion by the addition of dots of various sizes to the heads as shown in Table II. In this experiment the heads were of 7.5-mil (0.0075 in.) thick Mylar, and the dots were of the same material 10-mil thick. Addition of the dots was found to increase the decay time of nearly all modes.

Bongos and congas are two popular types of drums played with the hands and used extensively in Latin American music. Bongos are typically 6 to 8 in. in diameter and about 5 in. deep. Factory-made bongos usually include a tensioning mechanism, although in hand-made drums, the skin is often nailed directly to the wooden shell. Conga drums are larger than bongos, having diameters of 10 to 12 in. and thick, tapered shells 25-30 in. long.

TABLE II

Modal frequencies of a 12 in. diameter tomtom with and without center dots

Mode	No Dot		3½ in. Dot		4½ in. Dot		5½ in. Dot	
	f	f/f_{01}	f	f/f_{01}	f	f/f_{01}	f	f/f_{01}
01	147 Hz	1	144 Hz	1	142 Hz	1	140 Hz	1
11	318	2.16	307	2.13	305	2.15	289	2.06
21	461	3.14	455	3.16	450	3.17	434	3.10
02	526	3.58	522	3.63	485	3.42	474	3.39
31	591	4.02	583	4.05	581	4.09	566	4.04
12	684	4.65			681	4.80		
41	703	4.78	693	4.81	701	4.94	693	4.95

Many types of drums from Africa and Asia and other parts of the world are becoming popular in American music. One drum which is particularly interesting acoustically is the tabla from India. The tabla is a single-headed drum with a closed resonating chamber. The head is tensioned by straps which stretch vertically from top to bottom as shown in Fig. 9. Cylindrical pieces of wood are inserted between the straps, and by moving these up and down the drum can be finely tuned.

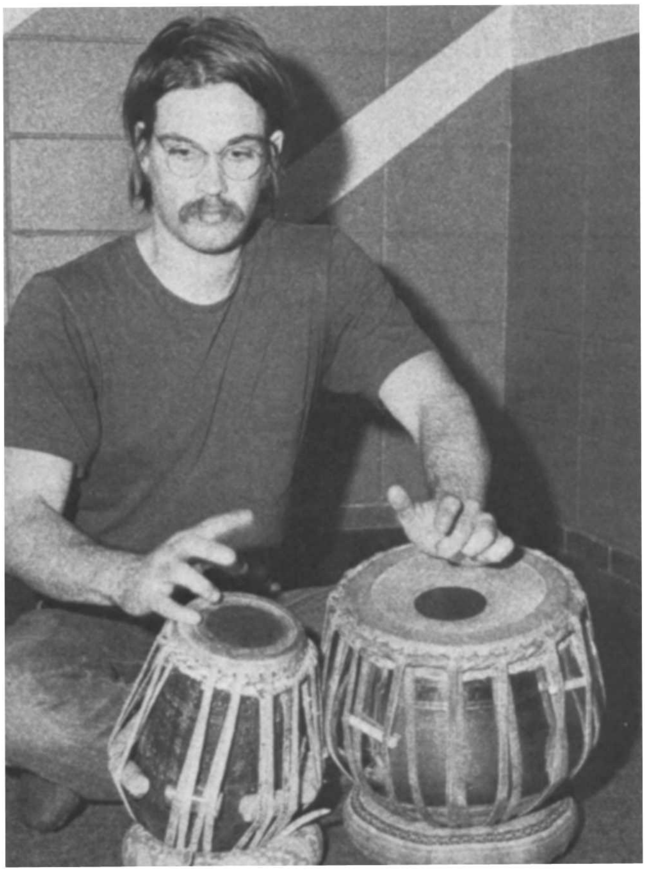


Fig. 9. Indian drums of the tabla family: *tabla* on the left and *banya* on the right. Note the tensioning straps and the drumhead loaded with paste in the center.

The tabla is loaded at the center by a paste of iron-oxide, charcoal, starch, and gum which hardens but remains flexible.[11] C. V. Raman[12] (who won a Nobel prize for his work in spectroscopy but also wrote several articles on the acoustics of violins) observed that the first four overtones of the tabla are harmonics of the fundamental by virtue of the extra load. Later, he discovered that these five harmonics really result from nine modes of vibration, several of which have the same frequencies; the 11 mode is the 2nd harmonic, the 21 and 02 both vibrate at the 3rd harmonic, the 12 and 31 modes at the 4th harmonic, and the 03, 22 and 41 at the 5th harmonic. (One can see a tendency toward such a mode grouping in the frequencies of the tomtom with the 5 ½ in. dot in Table II.)

Vibrations of plates

Vibrating plates bear the same relationship to membranes that vibrating bars do to strings. Whereas in strings and membranes the restoring force results from the tension, in bars and plates it results from the stiffness of the solid material. In plates and bars, the overtones tend to be substantially higher than the fundamental. They can vibrate with a variety of boundary conditions, including clamped and free edges.

One of the interesting ways to study the modes of vibration of plates is by the use of Chladni patterns,[13] first described by E. F. F. Chladni in 1787. Coarse particles (such as salt or sand) sprinkled on a vibrating membrane or plate, collect along the nodal lines, whereas very fine particles (such as cork dust or lycopodium powder) behave oppositely, being carried by air currents to areas of maximum vibration.

Circular plates can vibrate in many normal modes, which have n nodal diameters and m nodal circles. In a real plate, complex modes may occur which are actually combinations of the normal modes. Chladni observed that for $m = 0$, the frequencies of the normal modes are proportional to the number of nodal diameters n. Glenn Green, a high school physics teacher who recently spent a day in our laboratory, found that the frequencies of the first dozen modes of a circular aluminum plate were approximately proportional to $(n + 3m)^2$ rather than the $(n + 2m)^2$ suggested by Rayleigh (this also appears to be true for the many modal frequencies reported by Ravenhall

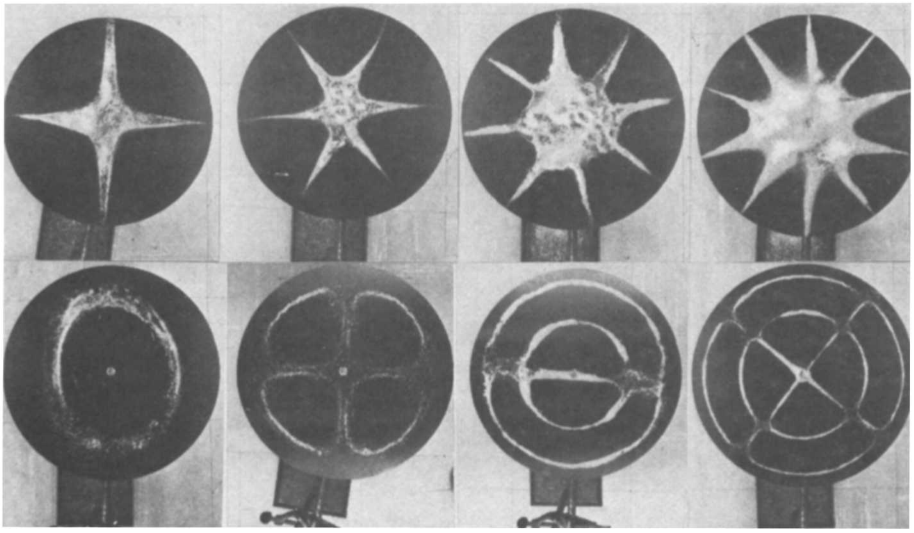


Fig. 10. Chladni patterns of a circular plate. The first four have 2, 3, 4, and 5 nodal lines, no nodal circles; the second four have 1 or 2 nodal circles.

and Som[14]). Chladni patterns for several modes are shown in Fig. 10.

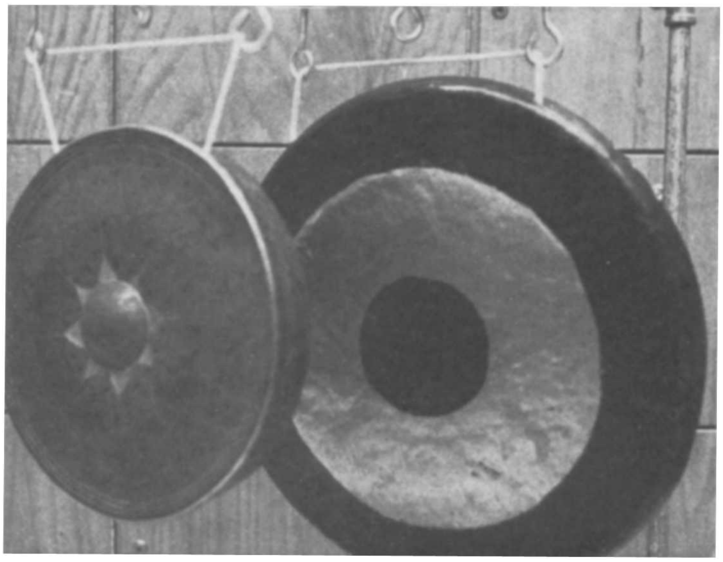
Before leaving the fascinating subject of Chladni patterns let me mention that there are a number of convenient ways to excite Chladni patterns: by bowing the edge, by touching the plate with dry ice, with sound waves from a loudspeaker, with a fluctuating magnetic field, and with a mechanical vibrator. Using a steel plate, a magnetic drive field can be applied with a small ferrite rod of the type used in AM radios or an rf choke with a magnetic core (the frequency of the magnetic field will be twice that of the driving current, of course). The dry ice method was used by Mary Waller in her extensive studies,[13] although she cautions that a very dense type of dry ice must be used. The bowing method is used by performing musicians to excite vibrations in cymbals and gongs; a variation of this, demonstrated to me by percussionist Garry Kvistad, is to attach a bow hair tautly to the plate and slide a finger along it slowly. Finally it should be pointed out that Chladni patterns are used by the makers of violins, guitars, and other string instruments to "tune" their plates,[15] and they make fascinating demonstrations and experiments for physics classes. Additional references appear in a recent resource letter.[16]

Gongs and tamtams

Gongs play a very important role in music of the Orient. They are usually made from bronze alloy discs with a deep rim and a protruding dome. Gongs used in orchestras usually range from 20 to 38 in. in diameter, and are often referred to as "Chinese gongs" or "Thailand gongs." Gongs are tuned to a definite pitch, and are usually struck near the

Fig. 11. (a) Gong (l) and tamtam (r); (b) Typical shapes of gongs and tamtams. Note the deeper rims and tuning domes of the gongs.

a.



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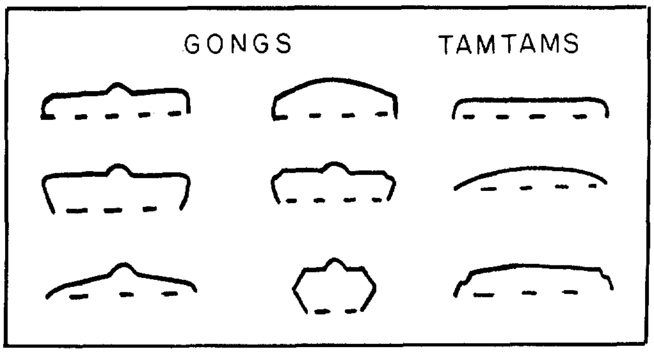


Fig. 12. Orchestral cymbals.

center with a massive soft mallet. The sound builds up relatively slowly and continues for a long time if the gong is not damped. Gongs form the basis of sophisticated ensembles throughout Indonesia known as Gamelan.

Tamtams are similar to gongs in appearance, and are often confused with them. The main differences between the two are that tamtams do not have the dome of the gong, their rim is not as deep, and the metal is thinner. Tamtams sound a much less definite pitch than gongs. In fact the sound of a tamtam may be described as between that of a gong and cymbal. Figure 11 shows the shapes of a number of different gongs and tamtams.

Cymbals

Cymbals are among the oldest of musical instruments and have had both religious and military usage in a number of cultures. Turkish-type cymbals generally used in orchestras and bands are saucer-shaped with a small dome in the center, as contrasted with Chinese-type cymbals which have a turned-up edge more like a tamtam. Orchestral cymbals are usually between 17 and 22 in. in diameter, and made of bronze. The leading manufacturer of cymbals, the Avedis Zildjean Co., claims that its secret process for treating cymbal alloys was discovered in 1623.[17]

Sound spectra of five orchestral cymbals from 16 in. to 20 in. in diameter have been recorded by John Baldwin.[18] His spectra are reproduced in Fig. 13. Unlike the gong and tamtam, the higher overtones of a cymbal appear more prominently when it is struck near the edge. An even brighter sound is obtained by striking two cymbals together.

Bells

Although bronze bells were known to have been cast in China at least a thousand years B.C., the art of tuning the overtones of bells probably began in Europe during the 14th century. The technique of tuning was perfected during the 17th century by Dutch bell founders, especially the Hemony brothers. The Hemonys are said to have done for bell-making what the Cremona violin makers did for their art. Unfortunately, the "secrets" of their tuning techniques were lost until rediscovered centuries later.

Perhaps it is stretching the imagination a bit to think of a bell as being a plate, but the general principles of its vibrational behavior are similar. Although the mathematical description of the vibrations of a bell are understandably complex, the principal modes, at least, can be described by specifying the number of circular nodes and meridian nodes. The lowest mode of vibration, called the hum tone, is generally agreed to have four meridian nodes, so that alternate quarters of the bell move inward and outward.

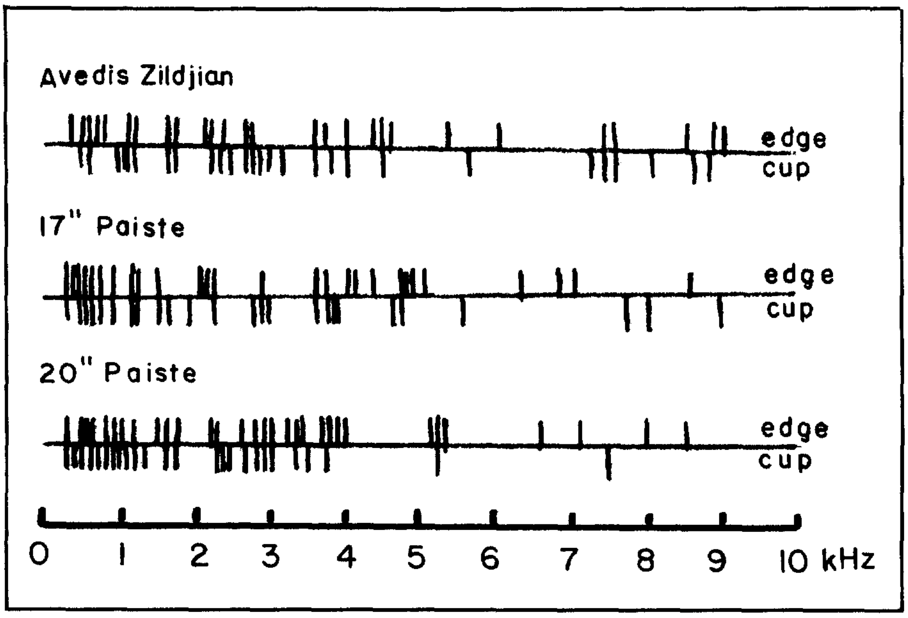


Fig. 13. Overtones of various cymbals struck near the central cup and near the edge (from Ref. 18).

TABLE III

Principal modes of tuned bells

Mode name	Frequency relative to strike tone	Meridian nodes Jo	Ty	GKN	Circular nodes Jo	Ty	GKN
hum	0.5	4	4	4	0	0	0
prime or fundamental	1.0	4	4	4	1	1	1
third	1.2	6	6	6	1	1	1
fifth	1.5	8	8	6	0	1	0
octave or nominal	2.0	8	8	8	1	1	1
upper third	2.5	8	0	8	2	1	0
upper fifth (twelfth)	3.0	10	10	10	0	1	1
upper octave	4.0	10	12	12	0	1	1

References

Jo: A. T. Jones, J. Acous. Soc. Am. 16, 253 (1920).
Ty: F. G. Tyzzer, J. Franklin Inst. 210, 61 (1930).
GKN: M. Grützmacher, W. Kallenbach, E. Nellessen, *Acustica* 16, 34 (1965/66).

Table III describes the principal bell modes of a carillon bell with so-called Flemish tuning. The mode called the third is tuned a minor third above the strike tone, whereas the upper third is a major third above the octave. The strike tone is determined by the octave, the twelfth and the upper octave, whose frequencies have the ratios 2 : 3 : 4, just as in chimes described in an earlier section. Unlike chimes, however, carillon bells have a mode called the prime or fundamental with a frequency at or near the strike tone. Careful studies have shown, however, that the pitch of the strike tone is determined by the three modes mentioned above rather than by the prime.[19] The character of the vibrations in the principal bell modes are shown in Fig. 14, which is adapted from a paper by Grützmacher *et al.*[20]

The so-called English tuning of bells is quite similar to the Flemish tuning, except that the hum note is tuned a sixth below the strike tone rather than an octave. English bells, usually designed for sequential "change" ringing rather than playing in harmony, are not nearly as carefully tuned as Flemish bells.

One of the most complete discussions of bell acoustics and also an account of tuning technique is given in a dissertation by E. W. Van Heuven.[21] Bells are usually cast thicker than required to allow for tuning, and then tuned by removing metal from the inside of the bell. In order to tune the different overtones, the vibration pattern must be known exactly, for thinning the bell at any particular place will have varying effect on the different overtones. Detailed tuning curves appear in Van Heuven's dissertation as well as elsewhere.

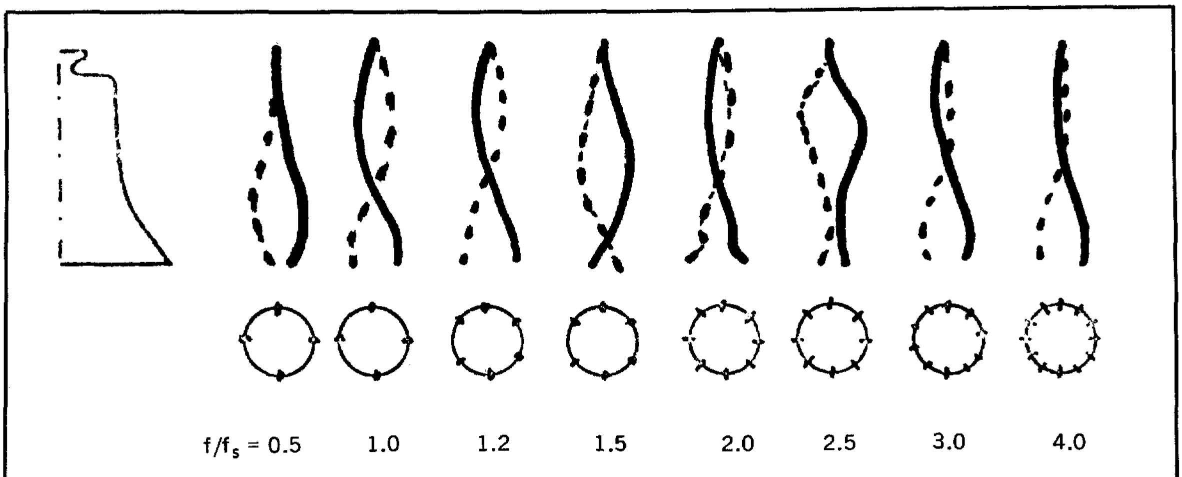
Many tuned carillons are in existence, although a number of fine bells were destroyed during World War II. The world's largest carillon is the 72-bell Rockefeller Memorial Carillon in New York cast by the English firm of Gillett and Johnston, with the largest bell weighing over 18 tons. The spectra of a number of bells were measured by Slaymaker and Meeker.[22]

Because of the high cost of casting and tuning bronze bells, most carillons in recent years have employed electromechanical bells, with tuned metal bars or rods, carefully shaped to vibrate with bell-like overtones. A suitable pickup device converts these vibrations to electrical signals which can be amplified and used to drive large loudspeakers, perhaps filtering out a few undesired overtones along the way.

Other percussion instruments

There are many other percussion instruments with interesting acoustical properties. Brindle[8] for example, describes 46 instruments of the idiophone type with at least

Fig. 14. First eight modes of vibration of a tuned bell (after Grützmacher, *et al.*[20]). These modes have 4 to 12 nodal meridians running the length of the bell; some have nodal circles around the bell, some do not. The frequencies are compared to that of the strike tone f_s.



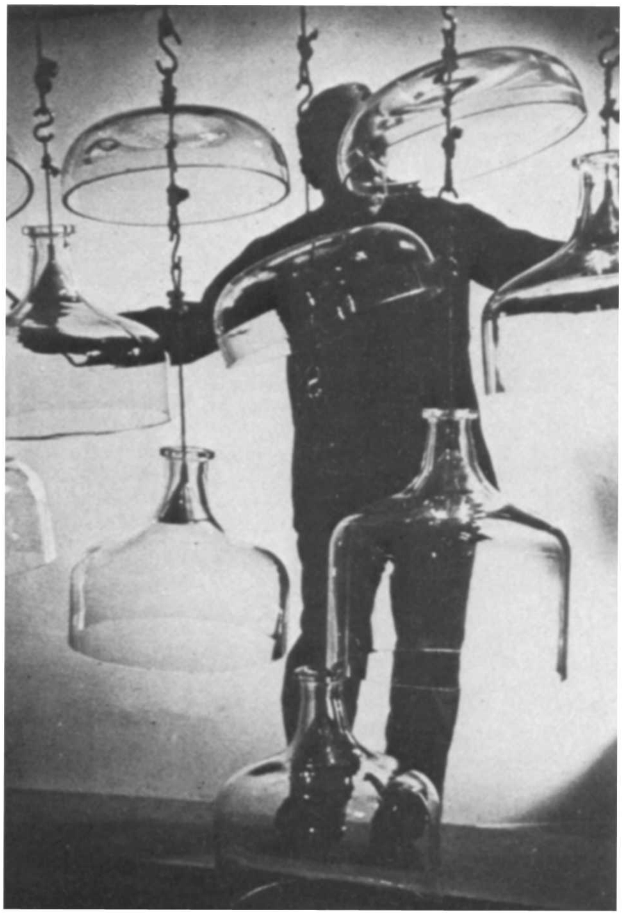


Fig. 15. Harry Partch playing his cloud chamber bowls. From H. Partch, *Genesis of a Music* (Da Capa Press, New York, 1974), by permission.

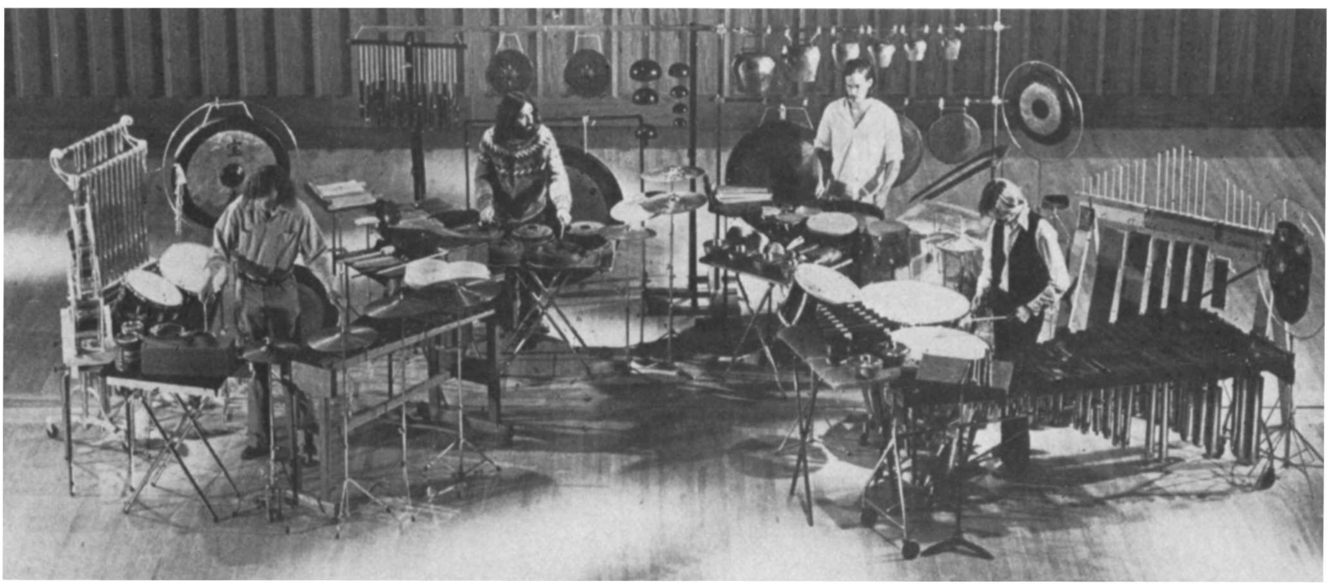
a paragraph or two about each. Figure 16 shows the variety of percussion instruments used in performance by a percussion ensemble. The piano and harpsichord are generally considered to be percussion instruments, belonging to a classification called *chordophones*. These instruments have been described in a number of articles and textbooks,[23] although further investigation of some of their acoustical properties would be an important contribution to musical acoustics.

An interesting group of percussion instruments which are becoming popular in this country are steel drums from Trinidad, the Virgin Islands, etc. These drums are made from large oil drums, heated and hammered into convex shapes. Certain sections of the drums are mechanically isolated by cutting grooves, and then tuned to different pitches by further hammering. Pallett[24] measured the mechanical impedance of a "ping-pong" drum (the drum of highest pitch in a steel drum band). For information about steel drums, including instructions for fabrication and tuning, an inexpensive paperback by folk-artist Pete Seeger is recommended.[25]

An instrument of historical interest, reviving in popularity, is the *glass harmonica*, the prototype of which is a wine glass stroked with a wet finger. One type of glass harmonica consists of goblets of various size attached to revolving spindles, although the ubiquitous Benjamin Franklin developed a type which consisted of glass bowls rotating on a treadle-driven shaft and wetted automatically by dipping into a pan. Mozart, Beethoven, and Gluck are among composers who have written for glass harmonica, and Bruno Hoffman has made several recordings.

Mention must be made of composer-inventor Harry Partch, who constructed his own musical world of microtones, elastic octaves, and percussion instruments made of cloud chamber bowls, hubcaps, bamboo, and light bulbs ("mazda marimba"). "I have often dreamed of a private home with a stairway which is in reality a Marimba Eroica," he writes, "with the longest block at the bottom and the shortest at the top. The owner could stipulate his favorite scale, then bounce up to bed at night hearing it."[26]

Fig. 16. The Blackearth Percussion Group in performance. Note the many standard and not-so-standard instruments (e.g., brake drums) used in modern percussion performance.



Conclusion

These two articles have attempted to describe the basic acoustical principles of percussion instruments for teachers and students of physics and music. It is hoped that they will stimulate some lively discussions, and perhaps some physics experiments in the band room (or percussion instruments in the physics laboratory).

I wish to thank Calvin Rose, Craig Anderson, and Garry Kvistad for their contributions, as well as to acknowledge valuable discussions with Professors Arthur Benade (Case-Western Reserve), Uno Ingard (M.I.T.), Thomas Hendrickson (Gettysburg), William Hartmann (Michigan State); also Tim Martin (Argonne National Lab.) and several others. Hera Leighton and R. Selman assisted in the translation of several papers on bell acoustics, and the Ludwig Drum Co. loaned us several drums. Some of the experimental studies were supported by a grant from the Research Corporation, and the manuscript for Part II was written while the author was visiting at the Massachusetts Institute of Technology.

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ERRATA for Part I which appeared in the December 1976 issue of *The Physics Teacher*:

P. 548 (Table I) l. 12 should read: ρ = density of string;
l. 22 should read: t = thickness.

P. 549, Fig. 3 should read: Orchestra bells (glockenspiel) and bell lyra.

P. 551, l. 155, change 5½ to 4½.

AN ANECDOTE

The Royal Institution in London has for more than a century sponsored a lecture series known as "Friday Discourses." According to tradition the lecturer and the Director enter the lecture hall at precisely 9:00 pm. The lecture is begun with no preliminary remarks (e.g., there is no "Good evening, ladies and gentlemen."). Each lecture is to last one hour; if the final word is uttered at the stroke of 10:00 the applause is thunderous.

The following anecdote concerning the Friday Discourses was related by Professor Ronald King of the Royal Institution during a recent visit I made.

One Friday evening Wheatstone was scheduled to deliver the discourse. Now Wheatstone was very shy in public; while waiting in the anteroom for nine o'clock to arrive he apparently panicked and bolted out of the building. He was last seen running down Albemarle Street. It would have been unheard of to cancel the lecture, so Faraday, using Wheatstone's notes, delivered the discourse. It lasted a mere forty minutes; he then spoke extemporaneously for a further twenty minutes about some of his ideas on the electromagnetic theory of light. Since Faraday did not like to discuss his theories in public until he had them worked through to his satisfaction, it is probable that he would not have made public his thinking on the subject at this point had he not felt the pressure of tradition to give a one-hour lecture.

R. WESLEY AMAN
Department of Physics
North Central College
Naperville, Illinois 60540