

INVITED REVIEW

Acoustics of percussion instruments: Recent progress

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Abstract: Recent research on the acoustics of percussion instruments has focussed on observing their modes of vibration and understanding how they radiate sound. Holographic interferometry, on account of its high resolution, is an especially useful method for modal analysis on a wide variety of percussion instruments. Several new percussion instruments as well as studies on some very ancient ones are described. New instruments include tuned wind chimes, Caribbean steelpans, major-third bells, bass handbells, Choirchimes, and glass instruments.

Keywords: Percussion, Drums, Xylophones, Marimbas, Cymbals, Gongs, Bells, Steelpans

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1. INTRODUCTION

Percussion instruments may be the oldest musical instruments in the world. They are also the most universal. The *New Grove Dictionary of Musical Instruments* has over 1,500 entries for drums alone. Many novel percussion instruments have been developed recently and more are in the experimental stage. What is often termed “contemporary sound” makes extensive use of percussion instruments. In this review, a few members of the percussion family which have been the main subjects of recent acoustical research will be discussed.

There are many instruments in the percussion family and a number of different ways in which to classify them. Sometimes they are divided into four groups: idiophones (xylophone, marimba, chimes, cymbals, gongs, etc.); membranophones (drums); aerophones (whistles, sirens); and chordophones (piano, harpsichord). Another system divides them into two groups: those that have definite pitch and those that do not. This review will be confined to idiophones and membranophones of definite and indefinite pitch.

2. DRUMS WITH DEFINITE PITCH

Drums have played an important role in nearly all musical cultures. Although the earliest drums were probably chunks of wood or stone placed over holes in earth, the most familiar type of drum consists of a membrane of animal skin or synthetic material stretched over some type of air enclosure.

It is well known that a membrane can vibrate in many modes which can be characterized by the numbers of

nodal diameters and nodal circles, as shown in Fig. 1. In a membrane of uniform thickness vibrating in a vacuum, these modes frequencies are not harmonically related. However, drums such as the orchestral kettledrums (timpani) and the Indian tabla are known to convey a clear sense of pitch, which generally requires that several partials in the sound be harmonics of the fundamental. The way in which this comes about has fascinated great scientists of the past, including Rayleigh and Raman.

Rayleigh recognized that the fundamental note of a kettledrum comes from the (1,1) mode, and he identified overtones about a perfect fifth (3:2 frequency ratio), a major seventh (15:8 frequency ratio), and an octave (2:1 frequency ratio) above the principal tone. We now know that the shift from the inharmonic partials of a membrane in vacuum into a harmonic relationship in a kettledrum is mainly the result of mass loading by the air in which the membrane vibrates [1, 2]. The kettle has resonances of its own that interact with the modes of the membrane that have similar shapes, and selecting the right kettle size becomes an important consideration in kettledrum design [3].

A baffled membrane vibrating in its (0,1) mode acts as a monopole source. It radiates its energy and damps out very rapidly; hence this mode is not a factor in kettledrum sound. The (1,1) mode, which is essentially a dipole source, radiates the note heard when a kettledrum is played, and this is supported by the (2,1) mode tuned a fifth higher, which resembles a quadrupole source, and the (3,1) mode tuned an octave higher, which resembles a sextupole source. This has been confirmed by studies of a kettledrum in a large anechoic room [4].

In the north Indian *tabla* and the south Indian *mrdanga* (also known as mirdangam or mirdang) Raman recognized that the shift of the inharmonic membrane modes into a harmonic relationship is accomplished by loading the membrane with a paste of starch, gum, iron oxide, charcoal or other materials [5]. The small diameter of their drumheads make tuning by air loading alone impractical.

3. DRUMS WITH INDEFINITE PITCH

The modern orchestral snare drum is a two-headed instrument about 35 cm in diameter and 13–20 cm deep. When the upper or batter head is struck, the lower or snare head vibrates against strands or cables of wire or gut (the snares). There is appreciable coupling between the two heads of a snare drum, especially at the lower frequencies. This coupling can take place acoustically, through the enclosed air, or mechanically, by way of the drum shell, and it leads to pairs of modes, as shown in Fig. 2. In the (0,1) pair, the membranes move either in the same or opposite directions, with the latter member having a much higher frequency due to considerable compression of the enclosed air. A simple two-mass model describes this mode pair quite well [6].

Drums originated in Africa, where drumming is still an integral part of most religious and secular ceremonies. Hundreds of different drums are played in various countries. One of the most popular African goblet-shaped drums in Western countries is the *djembé*, most often associated with the Malinke people of Mali and Guinea but played in other African countries as well. The membrane is most often goatskin, stretched and fastened by complex lacework to a wooden body. Rattles, tin sheets (*sèssè*), and wire rings may be attached to the edge of the skin. The *djembé*, played with the hands, is capable of producing a wide variety of sounds, including a bass note around 70 to 80 Hz, which appears to be due to the Helmholtz resonance of the shell, and strong components in the vicinity of 400 to 800 Hz due to membrane vibrations. Partial in the sound extend out to 3,000 Hz or more [7].

Drums have been used for centuries in Japanese temples. In Buddhist temples, it has been said that the sound of the drum is the voice of Buddha. In Shinto temples it is said that drums have a spirit (*kami*) and that with a drum one can talk to the spirits of animals, water and fire. Drums were also used to motivate warriors into battle and to entertain at town festivals and weddings [8]. More recently, the Japanese *taiko* (drum) has come out of its traditional setting, and today's taiko bands have given new life to this old tradition. Japan's most famous taiko band, the Kodo Drummers, who represent the pinnacle of taiko drumming, have performed in many countries of the

world.

Japanese drums fall into two main classes: braced heads and nailed heads. In the nailed drums, the drumheads are fastened to convex barrel-shaped cylinders of wood. In braced drums, the drum heads are secured to iron rings, larger in diameter than the supporting cylinders. The two heads are connected by a cord that passes in "W" form through holes along the edges of the two heads. Nailed drums include the large o-daiko, the turi-daiko ("hanging drum"), and the ko-daiko. Braced drums include the da-daiko, the ni-daiko, the kakko, the uta-daiko and the tsuzumi.

The *o-daiko* is a large nailed drum consisting of two cowhide membranes stretched tightly across the ends of a wooden cylinder 50–100 cm in diameter and about 1 m in length. The drum, hanging freely in a wooden frame, is struck with large felt-padded beaters. It is often used in religious functions at shrines, where its deep rumbling sound adds solemnity to the occasion. Obata and Tesima found modes of vibration in the o-daiko to be somewhat similar to those in the bass drum [8]. Pairs of (0,1) modes were found to have frequencies that ranged from about 168 Hz and 193 Hz, under conditions of high humidity, to 202 Hz and 227 Hz at low humidity. In the higher mode of each pair, the two membranes move in opposite directions. The next mode at 333 Hz was identified as the (1,1) mode, and the (2,1) mode was found at 468 Hz.

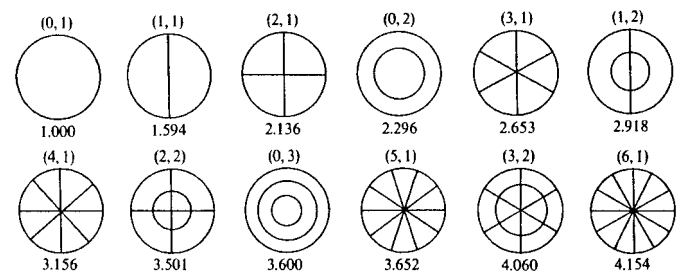


Fig. 1 Vibrational modes of a membrane, showing radial and circular nodes and the customary mode designation (the first number gives the number of radial nodes, and the second the number of circular nodes, including the one at the edge). The number below each mode diagram gives the frequency of the mode compare to the fundamental (0,1) mode.

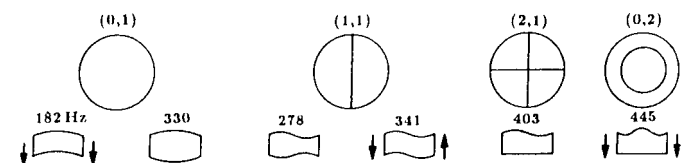


Fig. 2 The six lowest resonances observed in a snare drum include two mode pairs based on the (0,1) and (1,1) membrane modes [6].

The *turi-daiko* is a small hanging drum used in Japanese drama and in the classical orchestra. The cylindrical wooden bodies of these drums are usually hollowed out of a single log. Obata and Tesima [8] measured the modal frequencies of a shallow *turi-daiko* 29 cm in diameter with a length of 7 cm. A single (0,1) mode was observed to have a frequency of 195 Hz. Their experiments showed that the fundamental frequency is lowered by increasing the length (volume) of the drum.

The *tsuzumi* or *tudumi* is a braced drum consisting of a body with cup-shaped ends and leather heads on both ends. There are two types of *tsuzumis*: o-*tsuzumi* and ko-*tsuzumi*. The length of the o-*tsuzumi* (about 29 cm) is typically a little larger than the ko-*tsuzumi* (25 cm), but the main difference is the drumhead. Whereas the o-*tsuzumi* has heads of uniform density, the top head of the ko-*tsuzumi* has a circular groove called the *kannyu* which forms a sort of annular membrane having vibrational mode frequencies that are nearly harmonic [9]. A few sheets of Japanese paper wet with saliva (called *choshigami*) cover an area of about 1 cm² at the center of the bottom head, which tunes the modes of this head in a nearly harmonic relationship as well.

Professional players use a number of different playing styles in performing on the o-*tsuzumi* and ko-*tsuzumi*. *Kashira* is a style of forcefully striking the membrane, while *kan* is a style where the membrane is struck normally. In the *otsu* style of playing the ko-*tsuzumi*, the player loosens the *shirabeo* just after striking, causing a downward pitch glide; pitch changes of 16% have been noted.

Figure 3 shows spectra of an o-*tsuzumi* tone played in the *kashira* style and a ko-*tsuzumi* tone played in the *otsu* style. The o-*tsuzumi* tone shows a strong doublet at frequencies of 1,717 Hz and 1,834 Hz which originates from the (1,1) mode. The ko-*tsuzumi* tone, has a strong fundamental of 270 Hz and several other partials closely harmonic in frequency to the fundamental [9].

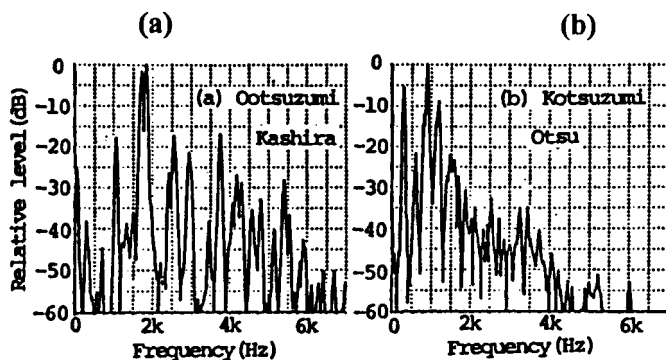


Fig. 3 (a) Spectrum of o-*tsuzumi* played in the *kashira* style; (b) spectrum of ko-*tsuzumi* played in the *otsu* style [9].

Spectra of the o-*tsuzumi* tones and ko-*tsuzumi* tones played in several styles are shown in Fig. 4. Mode designations and frequency ratios to the fundamental appear above each spectrum. Note the nearly harmonic relationship of partials in the ko-*tsuzumi* spectrum [9].

4. XYLOPHONES AND MARIMBAS

The modern xylophone has between 3 and 4 octaves of wood or synthetic bars laid out in piano-keyboard fashion, with the sharps and flats in a raised row behind the naturals. The bars are undercut at the center to tune the second vibrational mode to three times the frequency of the fundamental (as compared to 2.76 times the fundamental in a bar of rectangular cross section and uniform thickness). A closed-pipe resonator is generally placed under each bar to amplify both the fundamental and the first overtone.

Studies of decay times in wooden xylophone bars without resonators have shown that the decay process is mainly determined by internal losses; radiation losses and friction at the cord support appear to be insignificant. The frequency dependence of the damping constant α or the decay time t_d can be expressed by $\alpha(f) = 1/t_d = a_0 + a_1 f^2$, where a_0 and a_1 depend on the wood species [10].

Holz [11] compares the acoustically important properties of xylophone bar materials and concludes that the “ideal” wood is characterized by a density of 0.80 to 0.95 g/cm³ (800 to 950 kg/m³) and an elastic (Young’s) modulus of 15 to 20 GPa. These conditions are met by several Palissandre species, some other tropical woods, and also by cherry wood. In order to be suitable substitutes for wood, glass-fiber reinforced plastics should be pressed and molded, rather than hand lay-up laminates, Holz cautions.

The marimba typically includes 3 to 4½ octaves of tuned bars of rosewood or synthetic material, graduated in width from about 4.5 to 6.4 cm. A deep arch cut in the underside allows tuning of the overtones. The first overtone is normally tuned to 4 times the fundamental frequency. The second overtone (third mode of vibration) is often not deliberately tuned, but Bork and Meyer found that, given a choice, listeners preferred the sound of bars in which the third partial is tuned midway between a major and minor third above the triple octave (i.e., $f_3 = 9.88 f_1$) [12].

Numerical calculations by Orduña-Bustamante show contours to be cut for bars having harmonic ratios 1:3:6, 1:4:8, and 1:4:9 [13]. However, Summers, *et al.* have used Rayleigh theory to show that f_2/f_1 ratios of 3 or 4 can be obtained with a simple rectangular cut [14]. Bork has given a discussion of practical marimba tuning [15].

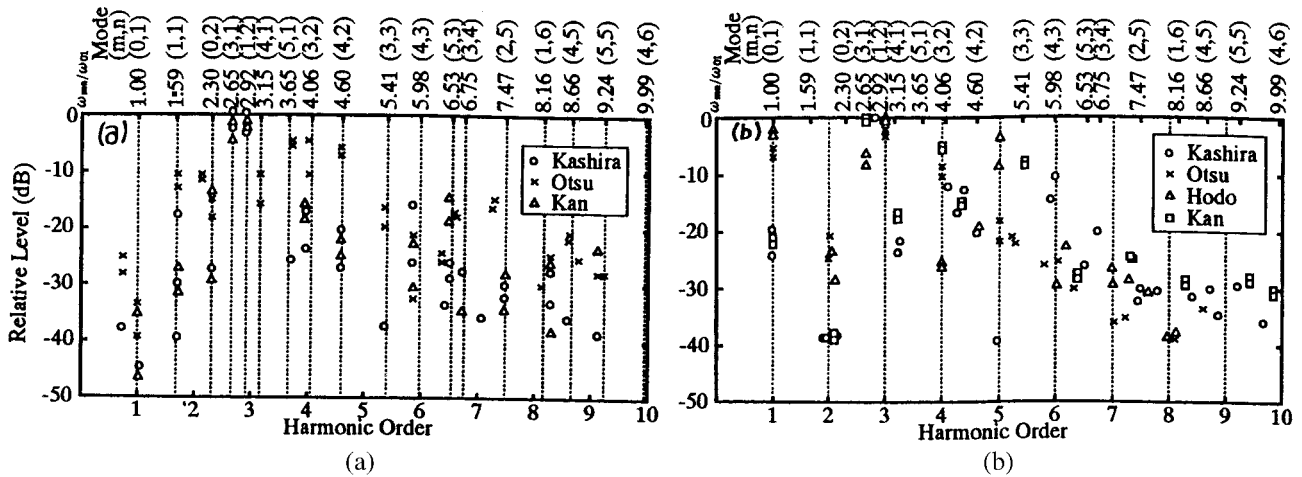


Fig. 4 (a) Spectra of o-tsumi played in three style; (b) spectra of ko-tsumi played in four styles [9].

5. METALLOPHONES

The term metallophone describes metal idiophones, usually with rectangular or hollow circular cross section. Metallophones commonly used in orchestras and bands include glockenspiel, bell lyra, celesta, vibraphones, and orchestra chimes (or tubular bells) [1]. A variety of metallophones are used in Indonesian gamelans.

Wind chimes generally consist of metal tubes or rods suspended so that the blowing wind activates a clapper that strikes all of the tubes or rods in turn. When these tubes are carefully tuned, wind chimes become sonorous musical instruments. Woodstock Percussion in Shokan, New York began making tuned wind chimes in 1979, and since that time more than 5 million sets of Woodstock Chimes have been sold. Percussionist Garry Kvistad, who founded Woodstock Percussion, selected 5 different pentatonic scales for his Chimes of Olympos, Chimes of Partch, Chimes of Lun, Chimes of Java, and Chimes of Bali.

Aluminum tubes, because of their long decay times and their ease of tuning, have been used by several contemporary instrument builders. Lydia Ayers uses more than 200 tubes in her Woodstock Gamelan. Her expandable instrument includes several racks of tubes with diameters of 25 to 30 mm (1 to 1.2 in) plus 26 larger hanging tubes similar to orchestra chimes. There are 75 tones in the middle octave, allowing for experimentation in custom tunings [16].

In his zoomoozophone, Dean Drummond uses 129 aluminum tubes tuned to a 31-note per octave scale. The instruments is divided into 5 sections, each on its own stand, except the top two sections share a stand. Played by one or more percussionists, the tubes are stuck with yarn-wrapped mallets or bowed with a bass bow. The tuning of the zoomoozophone follows the “tonality diamond” of Harry Partch centered on G₄ (392 Hz) [17].

6. CYMBALS, GONGS, AND PLATES

6.1. Cymbals

Many different types of cymbals are used in orchestras, marching bands, concert bands, and jazz bands. Orchestral cymbals are usually between 40 and 55 cm in diameter and are often designated as “French,” “Viennese,” and “Germanic” in order of increasing thickness. Jazz drummers use cymbals designated by such onomatopoeic terms as “crash,” “ride,” “swish,” “splash,” “ping,” and “pang.”

Using electronic TV holography, Wilbur recorded over 100 modes of vibration in a 46-cm diameter medium crash cymbal, 23 of which are shown in Fig. 5. The bright lines indicate the nodal lines and the fringes indicate isoamplitude contours. The edge, which lies just outside the largest nodal circle, is difficult to see. The modes are labeled (m,n), the first number m designating the number of nodal diameters and the second n the number of nodal circles. In the n = 0 modes (top row), the center of the cymbal vibrates very little, and this nodal region expands as m increases.

At least three prominent features have been observed in the sound of a cymbal: the strike sound that results from rapid wave propagation during the first millisecond, the buildup of strong peaks around 700–1,000 Hz in the sound spectrum during the next 10 or 20 ms, and the strong aftersound in the range of 3–5 kHz that dominates the sound a second or so after striking and gives the cymbal its “shimmer.” [17]

The propagation of bending waves on a cymbal immediately after momentary excitement with a laser pulse can be traced, as shown in Fig. 6, by using double-pulsed video holography [18]. The field of view is about 20 × 15 cm and the cymbal was pulsed at a point 10 cm (about half its radius) from the outer edge. Because of dispersion

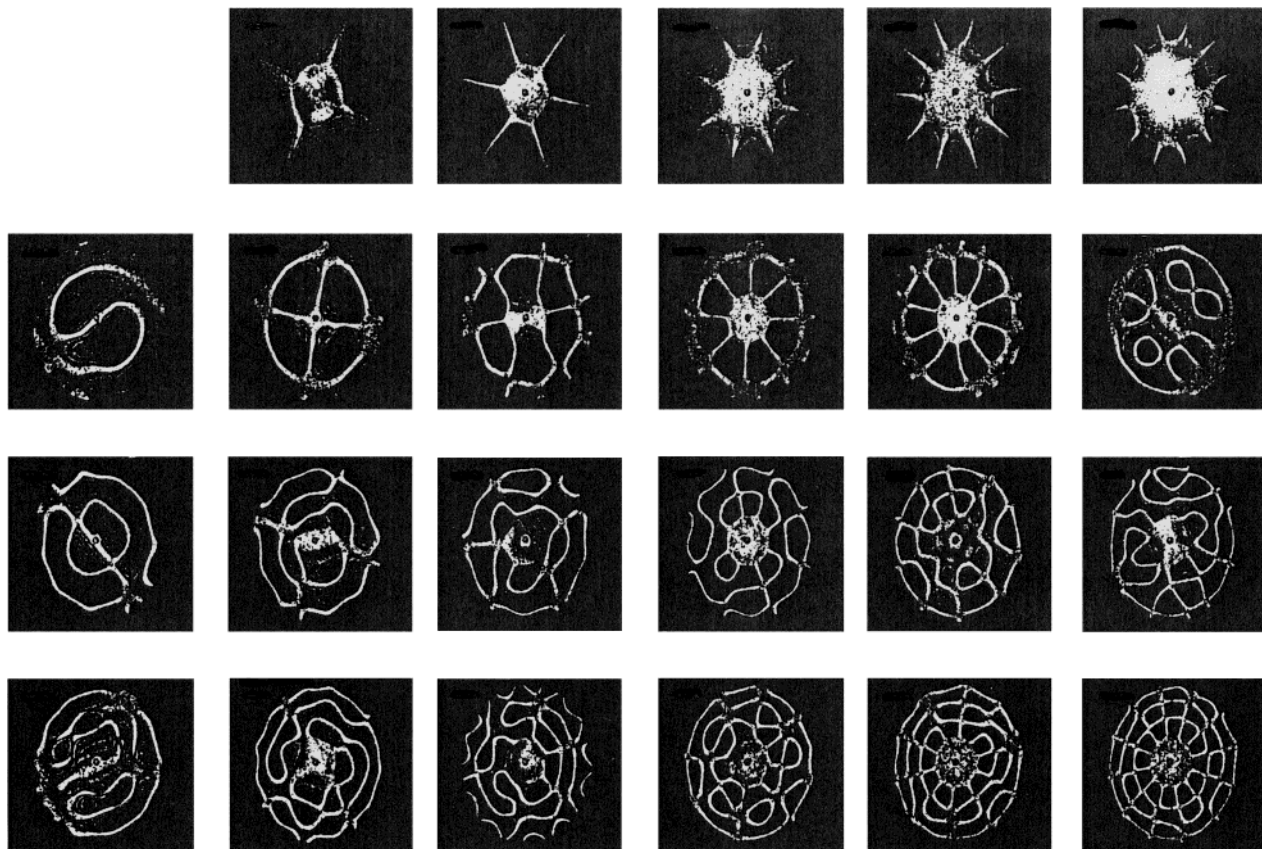


Fig. 5 Vibrational modes of a 46-cm diameter medium crash cymbal.

of bending waves, the first to be seen have short wavelengths, about 5 mm in this case, a frequency of about 340 kHz and a propagation speed of about 1,700 m/s. These are followed by waves of longer wavelength and greater amplitude, which are subsequently reflected from the outer edge of the cymbal (at the far right-hand side) and from the central dome (near the left-hand side) to interfere with the circular wave fronts. The normal modes do not, however, become distinguishable until a time Δt after the initial excitation that is determined by the separation Δf between the modes by the relation $\Delta f \Delta t \simeq 1$.

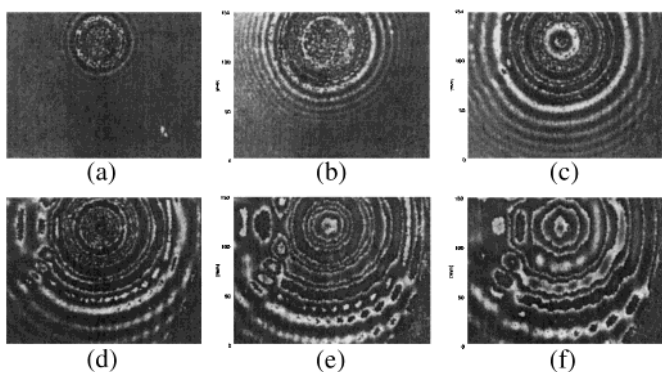


Fig. 6 Phase maps showing wave propagation outward from a point 10 cm from the edge of a cymbal. Time after impulse: (a) 30 μ s; (b) 60 μ s; (c) 120 μ s; (d) 180 μ s; (e) 240 μ s; (f) 300 μ s [18].

6.2. Nonlinear Effects in Cymbals

The conversion of energy from the low-frequency modes that are initially excited, when the cymbal is struck, into the high-frequency vibrations that are responsible for much of the characteristic cymbal sound embodies some interesting physics. There is considerable evidence that the vibrations exhibit chaotic behavior [19–22]. The road to chaos appears to follow the following stages: first the generation of harmonics, then the generation of subharmonics, and finally chaotic behavior.

Large-amplitude excitation of a flat circular plate at a frequency near one of its normal modes of vibration leads to “bifurcation” associated with doubling or tripling of the vibration period. The same behavior is observed for an orchestral cymbal excited sinusoidally at its center, one particular cymbal giving a five-fold increase in period and a subsequent major-chord-like sound based on the fifth subharmonic of the excitation frequency [20]. The fourth and seventh subharmonics have been observed in other cymbals [21], along with harmonics of these subharmonics (in other words, partials having frequencies $n/4$, $n/5$, or $n/7$ times the excitation frequency).

Figure 7 shows phase plots (velocity vs displacement near the edge) for a Zildjian thin crash cymbal 41 cm (16 inches) in diameter driven sinusoidally at the center with

a shaker. The driving frequency was 192 Hz and the drive amplitude started small and increased in 3 steps over a 20:1 range. Note the successive appearance of harmonics, subharmonics, and chaotic behavior.

Velocity spectra and phase plots are shown in Fig. 8 for the same cymbal center driven at 320 Hz. The first set shows harmonics of the driving frequency, while the second set at twice the driving current shows subharmonic generation, and the third shows chaotic behavior. In the spectrum of Fig. 8(b), we can see harmonics of $1/5$ the driving frequency, four of which appear between successive harmonics of the driving frequency (marked by small squares). When the drive frequency was raised to 450 Hz, the road to chaos was similar, but the subharmonics are now harmonics of $1/7$ the driving frequency [21].

Brass, bronze, and steel plates of the same size (and approximately the same thickness) as the cymbal also show nonlinear behavior leading to chaos. In general, subharmonic generation and chaotic behavior required slightly higher vibration amplitudes in the flat plates than in the cymbals. Subharmonic generation was more difficult to observe in the plates; in general, they tended to move directly to chaotic behavior as the vibration amplitude increased.

A mathematical analysis of cymbal vibrations using nonlinear signal processing methods reveals that there are between 3 and 7 active degrees of freedom and that physical modeling will require a like number of equations [22]. Because of its nonlinear behavior, the cymbal is a difficult, but not impossible, musical instrument to model for sound synthesis, for example. In fact, percussionists are sometimes asked to play live "cymbal sounds" for recordings using electronic drum machines.

6.3. Bell Plates

Large metal bell plates, like chimes or tubular bells, are used in orchestras and bands to produce sounds with bell-like quality, as in Wagner's "Parsifal," for example. Various shapes and materials have been used, but some of the best results have been obtained with rectangular steel plates having length-to-width ratios around $L/W = \sqrt{2}$ ($= 1.41$). Large steel bell plates are reported to have a more distinct strike note than tubular bells [23].

In constructing a set of tuned bell plates, it is convenient to make the thickness and the material of all the plates the same. Their lengths and widths will then be inversely proportional to the square root of the frequency. When a set of steel bell plates was fine-tuned by ear, the final length-to-width ratios that gave the best sound in the individual plates were found to range from 1.35 to 1.63, which includes the ratio $L/W = \sqrt{2}$ [23].

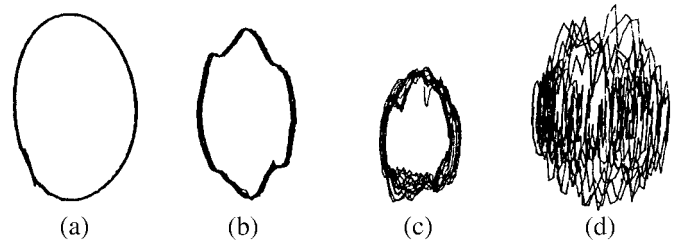


Fig. 7 Phase plots (velocity vs displacement) for a thin crash cymbal center-driven at 192 Hz; (a) linear behavior at 0.05 A; (b) harmonics present at 0.15 A; (c) subharmonics (including their harmonics) present at 0.5 A; (d) chaotic vibration at 1 A [21].

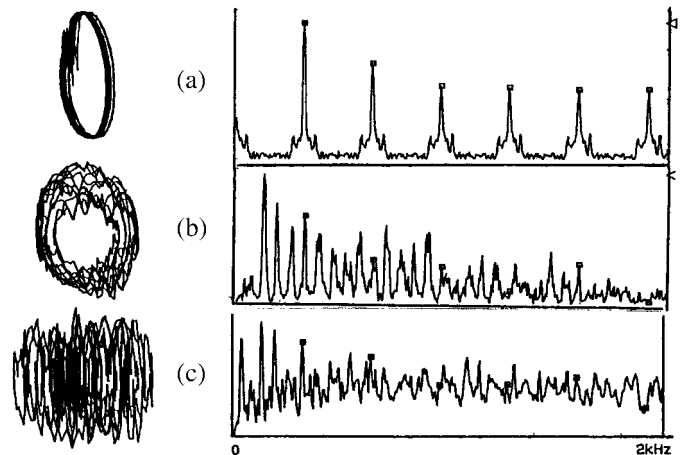


Fig. 8 Phase plots and velocity spectra for a cymbal center-driven at 320 Hz: (a) harmonic generation at 0.3 A drive current; (b) subharmonics at 0.6 A; (c) chaotic behavior at 1.4 A [21].

In a bell plate tuned to A440, with $L/W = 1.40$, the sound spectrum showed a hum note at 213 Hz, a fundamental at 438 Hz, and an octave partial at 875 Hz. These strong partials, due to the (2,0), (0,2), and (2,2) modes (See Section 8.4), are reasonably close to a harmonic series.

7. CARIBBEAN STEELPANS

The Caribbean steelpan is probably the most important new acoustical musical instrument to develop in the 20th century. In addition to being the foremost musical instrument in its home country, Trinidad and Tobago, steel bands are becoming increasingly popular in Europe, North America and some Asian countries as well. The modern family of steelpans now covers a 5-octave range, and steel bands of today use them to play calypso, popular, jazz, and Western classical music.

Modern steel pans are known by various names, such as tenor (or lead), double second, double tenor, guitar, cello, quadrophonic, and bass. The tenor pan has from 28 to 32 notes, but each bass pan has only 3 to 5, so the bass drummer plays on six or more pans in the manner of a

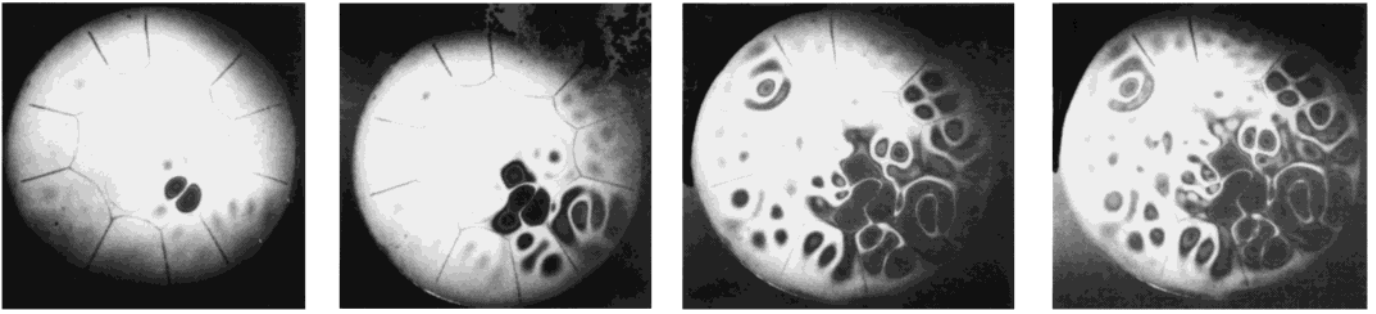


Fig. 9 Vibrations in a double second pan when the $G_5^\#$ note area is driven at various forces at the second harmonic of its fundamental frequency [24].

timpanist. Most steelpans are played with a pair of short wood or aluminum sticks wrapped with surgical rubber. The bass pans are played with a beater consisting of a sponge rubber ball on a stick.

Holographic interferometry is a convenient way to study the normal modes of vibration in steelpans, both the individual note areas and the global modes of the entire pan. Figure 9 shows holographic interferograms illustrating the motion of a double-second pan when the $G_5^\#$ note area is driven at various force amplitudes at the second harmonic of its fundamental frequency. At low amplitude, only the $G_5^\#$ note area vibrates, but as the amplitude increases, more and more other notes respond as well. As high amplitude, nearly the entire playing surface responds [24].

Holographic interferograms of the note areas in several different pans are shown in Reference [25], along with charts showing the relative frequencies of the lower modes. The second mode is nearly always tuned to twice the fundamental frequency, while the third mode is often tuned to three times the fundamental, at least in the lowest notes.

Vibrational modes of a steelpan skirt are shown in Fig. 10. These modes are formed by bending waves that propagate around the skirt. When a note area is struck, sympathetic vibrations are set up in the skirt which have been measured to be from 19 to 41 dB lower in amplitude at the note frequency [24]. Nevertheless, the skirt, because of its large surface area, radiates a substantial amount of sound.

Being a new instrument, steelpans are still evolving. The original steelpans were fabricated from empty 55-gallon oil drums, thousands of which were left on the beaches of Trinidad after World War II. Later, steelpan makers began to prefer new drums, and now many makers are using custom-made drums and materials. The Swiss firm Panart has pioneered the use of “nitrided” steel which has a pliable interior but a very high surface hardness to make a durable playing surface and stabilize the tuning of

the pan.

Recently, Panart has developed the new *pang* family of steelpans, each note of which has an appropriately sized elliptical dome, which forms a durable strike point and stabilizes the overtones. The lead pan, called the *ping*, is shown in Fig. 11, along with holographic interferograms of the first eight vibrational modes. The raised elliptical dome is sketched on the interferograms [26].

8. EASTERN AND WESTERN BELLS

Bells have been a part of almost every culture in human history. They are one of the most cherished musical instruments. Bells existed in China at least as early as 1600 BC. Bells developed as Western musical instruments in the seventeenth century when bell founders such as van Eyck and the Hemony brothers learned how to tune their partials harmonically. Van Eyck concluded that the best sounding bells had five partials tuned harmonically to form intervals of an octave (above and below), a minor third, and a fifth with the strike note. Today, many fine carillons in the Low Countries in Europe attest to their great tuning skills.

For years, some carillonneurs have felt that a composition in a major key, especially if it includes chords with many notes, might sound better if played on bells with a major character, which suggests replacing the strong minor-third partial with a major-third partial. Efforts to fabricate such bells were not successful, however, because raising the minor-third partial by changing the profile also changed other partials. Employing a technique for structural optimization using finite element methods, however, scientists at the Technical University in Eindhoven and the Eijsbouts Bellfoundry in the Netherlands were able to design bells with the minor-third partial replaced by a major-third [27].

The art of casting bells developed to a high level of sophistication in China during the Shang dynasty (1766–1123 BC). Most bells were cast using the “piece-mold” technique, which was particularly convenient for casting

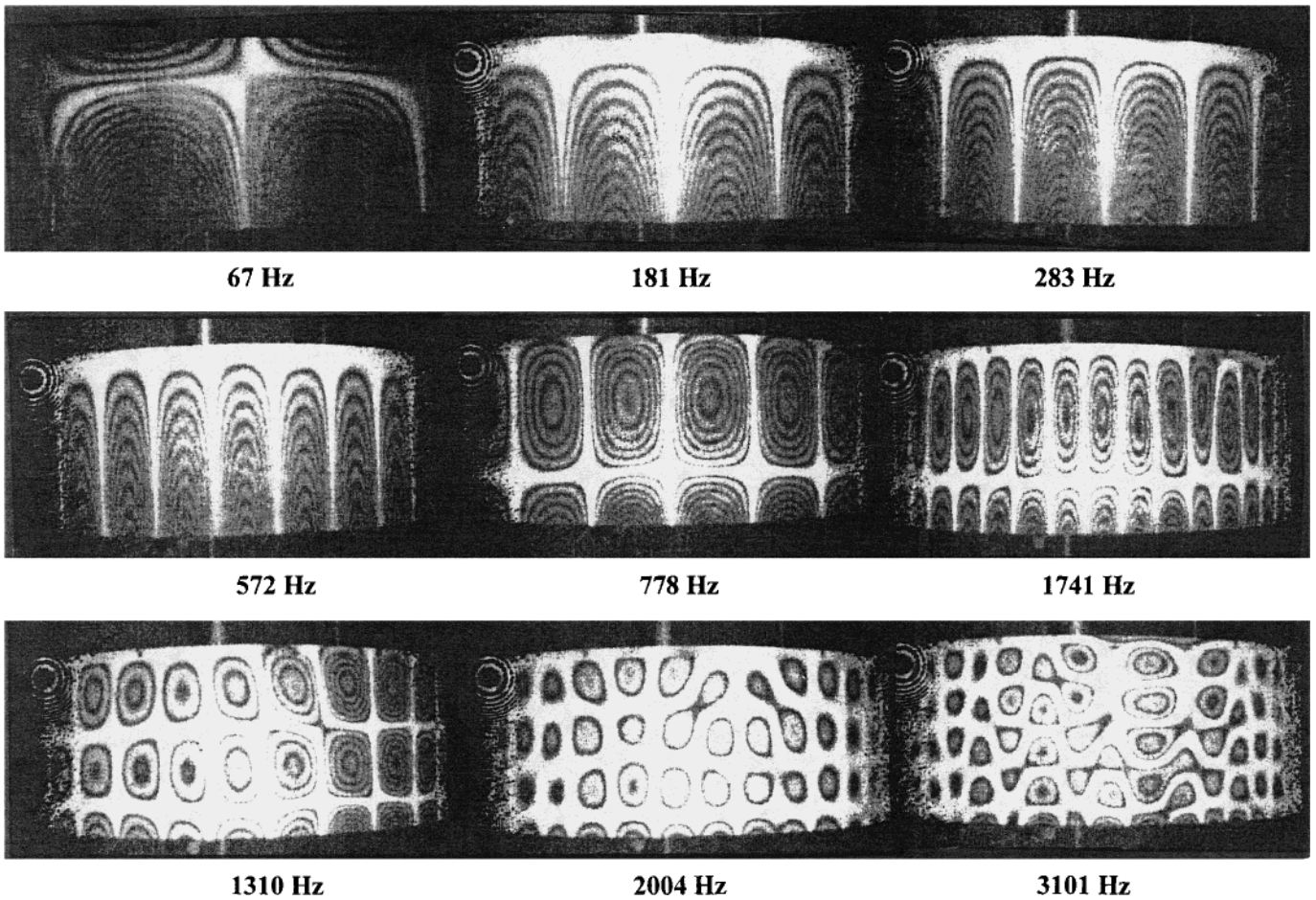


Fig. 10 Vibrational modes of the skirt of a steelpan.

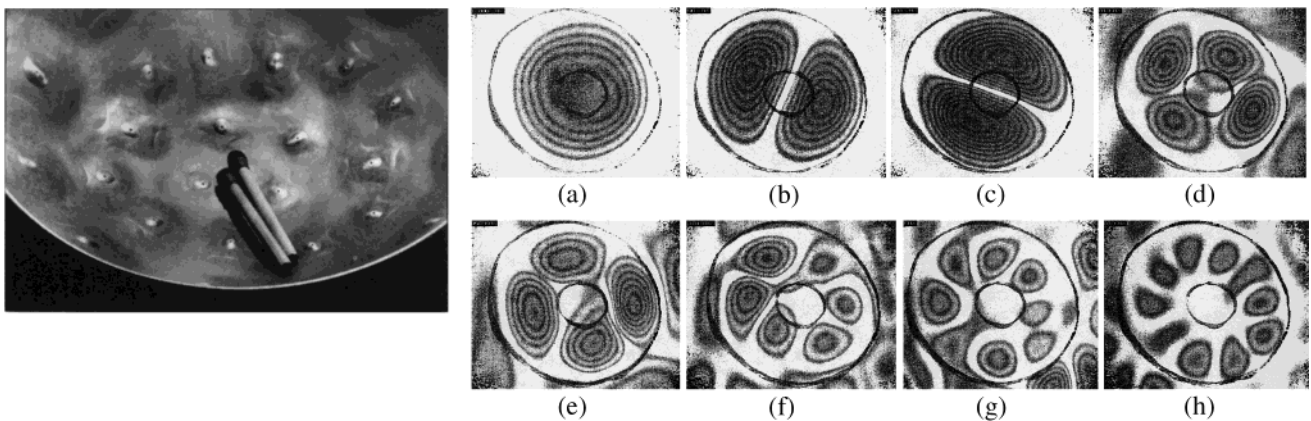
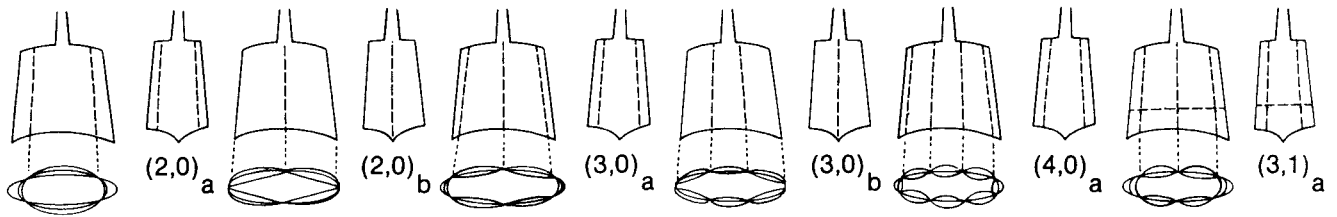


Fig. 11 Left: ping; right: first eight modes of the C_4 note area of a ping shown by means of electronic holography: (a) (0,1) mode at 261 Hz; (b) $(1,1)_a$ mode at 519 Hz; (c) $(1,1)_b$ mode at 773 Hz; (d) $(2,1)_a$ mode at 1,992 Hz; (e) $(2,1)_b$ mode at 2,052 Hz; (f) (3,1) mode at 3,097 Hz; (g) (4,1) mode at 3,904 Hz; (h) (5,1) at 4,919 Hz [26].

oval or almond-shaped bells that sounded two different tones. Bells became status-defining objects. It is hardly any wonder that persons of wealth and power coveted bell chimes for their burial tombs. The most remarkable set of bells discovered to date is the 65-bell set discovered in the tomb of Zeng Hou Yi (Marquis Yi of Zeng) in 1987.

Figure 12 compares the modes of vibration of almond-shaped Chinese two-tone bells with a Western church bell. Each mode is split into a doublet, which is designated by $(m, n)_a$ and $(m, n)_b$ in each case. The musical interval between the A and B fundamental notes in ancient bells ranges from 200 to 500 cents ($2/12$ to $5/12$

Chinese bell



Church bell

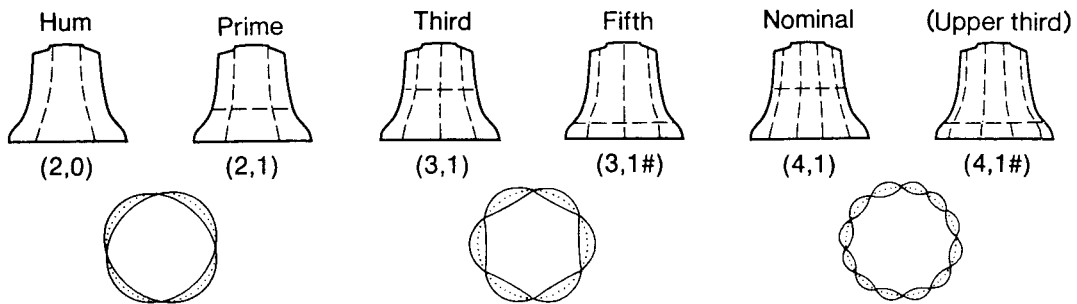


Fig. 12 First six modes of vibration in: (a) Chinese two-tone bell; (b) Western church bell.

of an octave), although in many bells the interval is close to a minor third (300 cents) [28]. Holographic interferograms of the mode doublets observed in a modern Chinese two-tone bell (based on the ancient bells) are shown in Fig. 13 [29].

9. HANDBELLS

Tuned handbells developed in England in the eighteenth century. One early use of handbells was to provide tower bellringers with a convenient means to practice change ringing. In more recent years, handbell choirs have become popular in schools and churches; some 40,000 choirs are reported in the United States alone. Handbells are now available over a range of 7 octaves.

Demand for handbells of lower and lower pitch has led to development of bass bells as low as G_0 (fundamental frequency of 24.5 Hz). Unfortunately, large bass bells radiate inefficiently, especially bells made of bronze, because the speed of bending waves is well below the speed of sound in air, and therefore they operate well below the coincidence frequency. In order to obtain a higher radiation efficiency and thereby enhance the sound of bass bells, the Malmark company makes bass handbells of aluminum. These aluminum bells are larger in diameter than the corresponding bronze bells, and they have lower coincidence frequencies, both of which lead to more efficient radiation of bass notes. In addition, they are considerably lighter in weight, and thus they are much more easily handled by bell ringers. Holographic interferograms of vibra-

tional modes in a G_1 aluminum bass handbell are shown in Fig. 14 [30].

The Choirchime, also developed by the Malmark company, is essentially a closed-end self-resonant tuning fork with a handbell clapper. Now available in chromatic sets up to 5 octaves, Choirchimes have become very popular in schools and churches, both for teaching and performing music. Choirchimes are presently available from G_2 (98 Hz) to C_8 (4,186 Hz). The closed-tube design used in Choirchimes keeps the lower-pitched chimes to a manageable length. The vibrational modes of Choirchimes include symmetrical and antisymmetrical bending modes both in the plane parallel to the slotted faces and perpendicular to this plane [17].

Cow bells have been used to track cattle in the Alps and other mountainous regions for centuries. The best made Swiss treichels or cow bells are musical instruments with a fine sound. Vibrational modes of a large 20-cm Swiss treichel are described in Reference [17].

10. GLASS MUSICAL INSTRUMENTS

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 France, an instrument known as the “verillons” consisted of 18 glasses mounted on a board. The player tapped the glasses with long sticks. At least as early as the 17th century it was discovered that

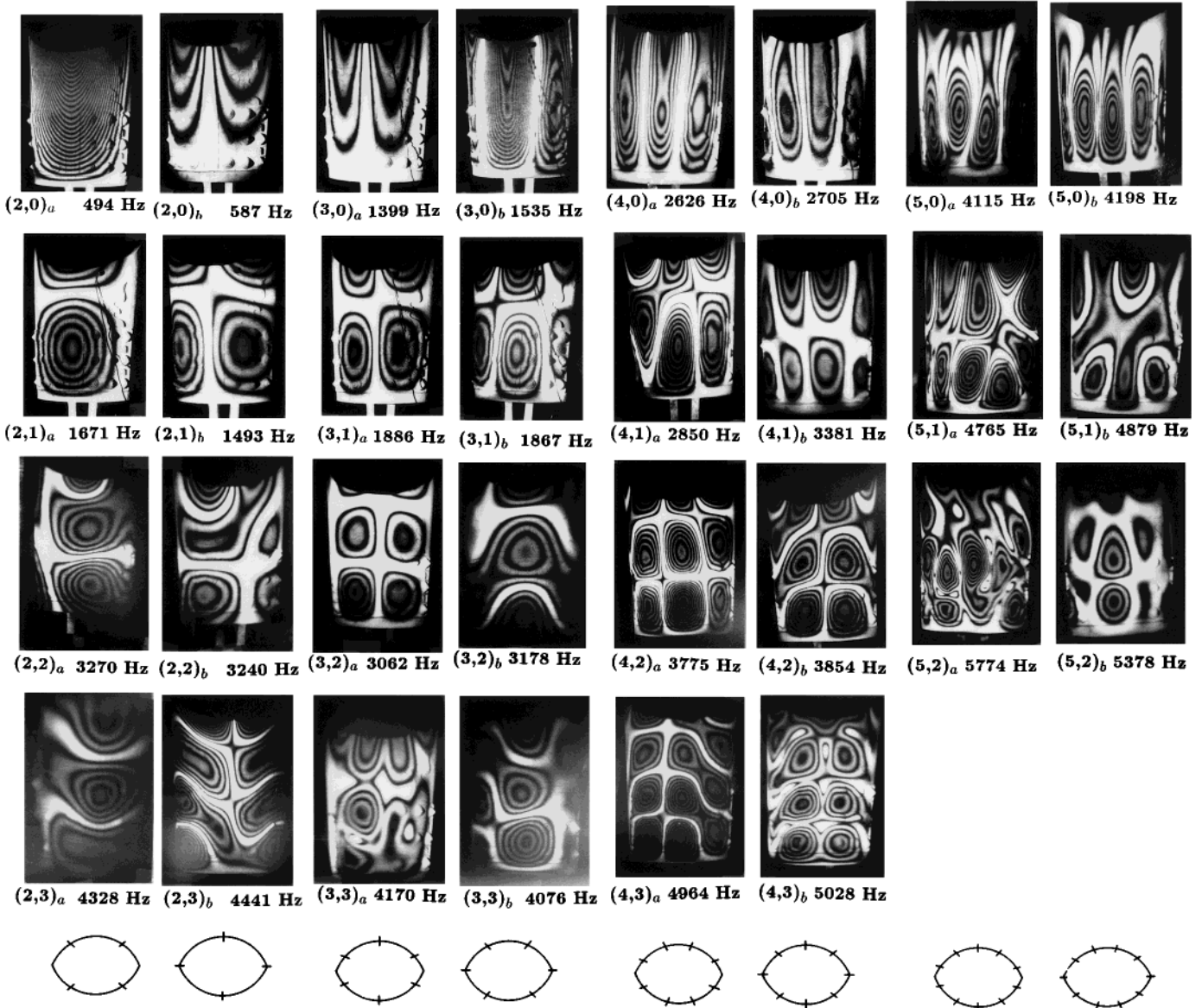


Fig. 13 Holographic interferograms showing mode doublets in a modern Chinese two-tone bell [29].

wine glasses, when rubbed with a wet finger, produced a musical tone. Harsdorfer's *Deliciae Physicomathematicae* (Nuremberg, 1677) has the following prescription: "To produce a merry wine-music, take eight glasses of equal form; put in the one a spoonful of wine, in the other two, in the third three, and so on. Then let eight persons, with fingers dipped in wine, at the same moment pass them over the brims of the glasses, and there will be heard a very merry wine-music, that the very ears will tingle." [31]

10.1. Glass Harmonica

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, called the *armonica* by its inventor 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).

The vibrational modes of a wineglass rather closely resemble the flexural modes of a large church bell. The principal modes of vibration result from the propagation of bending waves around the glass, resulting in $2m$ 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.

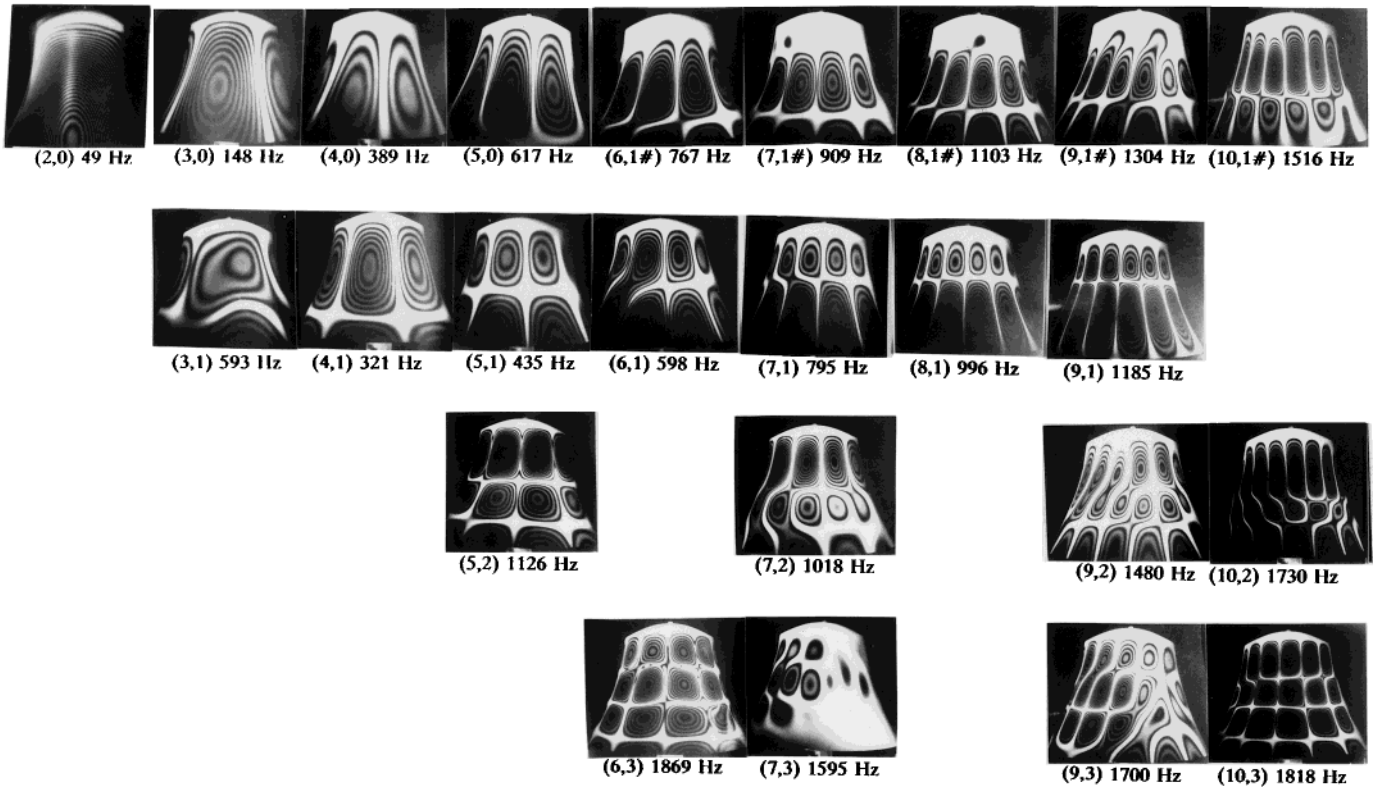


Fig. 14 Holographic interferograms of vibrational modes in a G_1 aluminum bass handbell [30].

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; 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 tangential force (rubbing with a finger) or a radial force (with a violin bow or a mallet).

Several normal modes in a wineglass are shown in Fig. 15. At higher frequencies, the motion is concentrated mainly near the rim of the glass. A moving finger excites vibrations in the glass through a “stick-slip” action, 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.

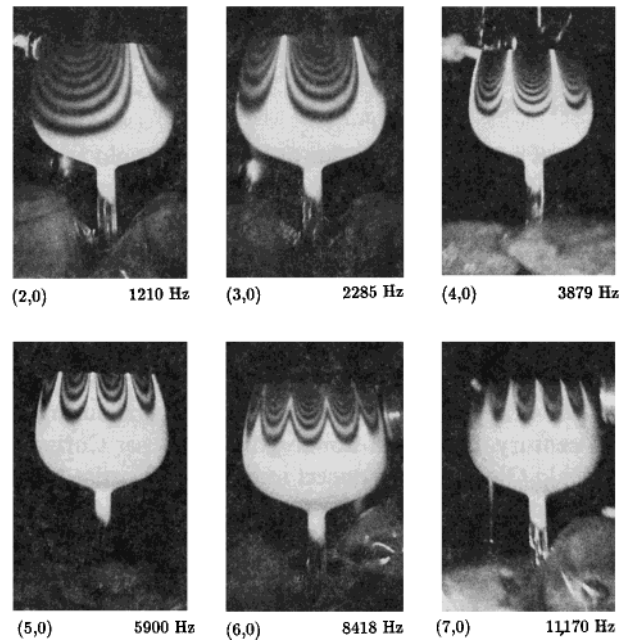


Fig. 15 Holographic interferograms of 6 vibrational modes in a wineglass [32].

10.2. Verrophone

The verrophone uses tuned glass tubes rather than bowls or glasses. The vertical tubes are played by rubbing in the same way as the wineglasses in a glass harp, but the larger radiating surface can produce a greater sound output.

10.3. Glass Orchestra

The Sasaki Crystal company has produced a wide variety of glass musical instruments, including glass marimbas, glass chimes, glass trumpets, glass horns, glass alpenhorns, and glass flutes. The Kassel Glass Orches-

tra in Germany, led by Walter Sons, plays on a variety of glass percussion and wind instruments, including vases, bowls, glass spheres, dishes, sheets of flat glass, glass flutes and glass tubes.

10.4. Other Glass Instruments

Composer-inventer Harry Partch constructed his own musical world of percussion instruments. Partch's rich heritage of instruments includes at least two glass instruments: "cloud chamber bowls" and "mazda marimba." His tuned cloud chamber bowls are actually cut from acid carboys, while the mazda marimba consists of light bulbs of various sizes [17].

French composer and instrument maker Jean-Claude Chapuis has developed a number of glass instruments. His glass balafon is a marimba-like instrument with a set of cylindrical glass rods set over a box-like resonating chamber and played with mallets. The crystallophone is another mallet instrument with flat bars of plate glass [17].

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