The Acoustics of the Modern Jazz Drum Kit

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Introduction

Other than the human voice, there is likely no musical technique older than using percussion to produce rhythmic beats (Morley, 2013). Anthropologists and historians have described possible scenarios where ancient people created rhythmic sounds by either striking their bodies, stamping their feet, or through the repeated striking of tools on stone or wood (Blades, 1992; Montagu, 2002). The earliest examples of percussion instruments crafted by people include rattles, rasps, and shakers that were used rhythmically.

The modern percussion family has grown well beyond simple rhythmic instruments. Some percussion instruments are tuned to musical pitches for melodic or harmonic purposes. However, many percussion instruments do not have a definite pitch. In general, the more harmonic the peaks in the spectrum are, the easier it is for us to hear the sound as having a definite pitch.

In this article, we first examine the differences between drums with and without definite pitch. We then trace the historical and technical development of the components of the modern jazz drum kit. For an example of a jazz drum kit, see youtu.be/sKbk1LcsuUM.

Frame Drums

The frame drum, one of the simplest drum types, does not have a definite musical pitch. It is constructed by stretching a thin, flexible membrane over a rigid hoop (see youtu.be/LF7ybVKX2p4). A frame drum's sound can be varied by changing the size of the drum, the mass and stiffness of the drumhead, how tightly the drumhead is stretched, and the technique used to play the drum (see **Multimedia File 1** at acousticstoday.org/scottmedia). Throughout history, frame drums have been used in musical traditions worldwide. Evidence of their use has been found in Mesopotamia dating as far back as ca. 3000–2700 BCE (Blades, 1992).

Striking the drumhead of a frame drum, whether by hand or with a beater, causes the drumhead to oscillate. Most frame drums are sufficiently small such that the effect of air loading on the drumhead is small. Therefore, the drumhead vibrates near frequencies corresponding to the ideal modes of vibration of a stretched membrane. Each mode vibrates not only at a particular frequency but with a unique pattern called a mode shape.

The mode shapes of a uniform membrane can be predicted by solving the wave equation in cylindrical coordinates, a mathematically complex process. What is important, however, is that the predicted modal frequencies are not integer multiples of the lowest mode. The solutions predict all the resonances of the drum. Depending on where the drummer hits the drumhead, the resulting motion of the drumhead is a combination of all the vibration modes, each with their own amplitude and phase.

The first 12 mode shapes for a stretched membrane are shown in **Figure 1**. The mode shapes are characterized by the location and number of lines or circles where minimum vibration occurs. Whereas a one-dimensional standing wave (such as a tautly stretched string) has points of minimum vibration called nodes, the two-dimensional standing waves refer to the lines or circles of minimum vibration as either nodal lines or nodal circles. For the circular membrane, the lines are often referred to as nodal diameters because the line bisects the circular membrane. The notation (m,n) labels the mode shapes according to the number of nodal diameters (m) and number of nodal circles (n). Regardless of how the drumhead is secured to the frame drum, the drumhead will be held in place at the rim. Therefore, each mode of

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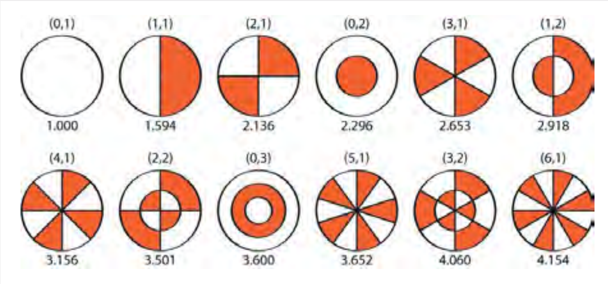


Figure 1. *First 12 modes of vibration of a circular membrane. The nomenclature [*(m,n)*; above each mode shape] is used where m denotes the number of nodal diameters and n denotes the number of nodal circles. The ratio of modal frequency to frequency of the lowest mode is below each mode shape.*

vibration has at least one nodal circle located at the rim. The ratio of the mode's frequency to the frequency of the lowest mode is shown below each mode shape. For example, a drum having a frequency of 100 Hz for the (0,1) mode would be expected to have a frequency of around 159 Hz for (1,1) mode because 100 Hz multiplied by 1.594 is close to 159 Hz. The (2,1) mode would be expected to be close to 214 Hz because 2.136 multiplied by 100 Hz is close to 214 Hz. The modes for this type of drum are not harmonically related so there is no definite pitch associated with the sound of the drum.

Drums with a Definite Pitch

On being struck, frame drums (and many other drums) do not have a specific pitch associated with their sound. Although such drums can be tuned to sound that is relatively higher or lower, a listener would not associate the sound of the drum with a specific musical note. At the same time, some exceptions exist of pitched drums that are tuned such that they are played with a definite pitch. A few examples that we discuss here are the mridangam, tabla, and timpani.

Mridangam and Tabla

The mridangam and tabla drums from India are some of the most studied pitched drums. The mridangam (see **Figure 2,** *left*) is a long barrel-shaped drum with drumheads of differing sizes on opposite ends. It is used in Carnatic music traditions common in South India (see youtu.be/AI9RJbljBLw). The tabla (**Figure 2,** *right*) is a single instrument that consists of two single-headed drums of different sizes. It is used in Hindustani classical music and originated in North India (see youtu.be/r31oe7Sm0vI?t=10).

What makes the Indian drums acoustically interesting is that the drum makers apply several layers of a paste to the center of the drumhead that brings the first five overtones into harmonic alignment. The dried paste is seen in **Figure 2** as the central dark circular patch on each drumhead. Because there is a strong harmonic series of the first five partials, the sound of these drums is recognizable as a definite pitch. The acoustics of these drums were studied in detail by the Nobel laureate C. V. Raman who was the first to write about them in a scientific journal (Raman and Kumar, 1920). Mode shapes from his later work (Raman, 1935) are shown in **Figure 3**.

Raman sprinkled fine-grained sand on the drumhead before the drum was struck. On hitting the drumhead,

Figure 2. *The mridangam (**left**) is an Indian drum held in the drummer's lap and played while the drummer is seated. The tabla (**right**) is an Indian two-drum instrument usually performed with the drummer sitting on the floor and the drums in front of the performer, who is also on the floor. The drumheads are layered with a paste designed to tune the drumhead modes harmonically. Tabla image reproduced from Wikimedia Commons (see w.wiki/5aPC), licensed under CC BY SA 4.0 (see creativecommons.org/licenses/by-sa/4.0). Author http://muzyczny.pl.*

Figure 3. *Mode shapes of the mridangam or tabla drumhead. Fine-grained sand was sprinkled on the drumheads. On striking, the grains moved to nodal lines where the motion of the drumhead was at a minimum. Reproduced from Raman (1935), with permission of Springer.*

sand grains gathered at the vibrational nodal lines. Raman found that he could excite different modes by changing where the drum was struck. For some of the shapes, holding his fingers at the location of a nodal line allowed that mode to be revealed.

Although much of the early studies of Indian drums focused on mass loading the membranes to form a harmonic spectrum, recent work on the tabla has shown that the air inside the drum also affects the harmonicity of the sound (Tiwari and Gupta, 2017). The air-loading effect is greater for the left-hand tabla drum, the larger of the pair.

Timpani

A pitched drum used both rhythmically and at least somewhat melodically is the timpani. The timpani is recognizable as the large drum used by orchestras having a kettle-shaped bowl over which the drumhead is stretched. A single timpanist in an orchestra may play from three to six timpani, each tuned to a particular pitch (see **Multimedia File 2** and **Multimedia File 3** at acousticstoday.org/scottmedia).

A pedal at the timpani's base allows for tuning the drum via an internal mechanism that uniformly adjusts the tension of the drumhead. The drums are tuned to specific notes for each musical piece performed, and it is not uncommon for the timpanist to retune one or more drums during the performance of a piece.

The acoustics of the timpani has been studied since Lord Rayleigh's time. The timpani has a definite pitch because the lowest several modes of vibration are in harmonic alignment. Looking at **Figure 1**, it is not apparent how this could be possible. However, several factors contribute to giving the timpani its pitch.

Foremost is that the air above the drumhead provides a significant load that lowers the frequencies of the vibration modes. Rayleigh first identified that the pitch of the timpani originates from the (1,1) mode and not the lower (0,1) mode. Because the two antinode regions of the (1,1) mode move with opposite phases, the movement of the drumhead causes the air above it to slosh back and forth.

Another factor affecting the sound of the timpani is that only the modes with the single nodal circle (located at the rim) contribute significantly to the sound spectrum. Modes with nodal circles in the middle of the drumhead tend to decay quickly. Also, the timpanist affects the deemphasis of these modes. By striking the timpani about a quarter into the center, the excitation point is close to the nodal circle of several modes, so these modes are not strongly excited.

Finally, as seen with the tabla, the air inside the kettle also influences the drumhead resonances. Internal air loading of the drumhead is responsible for fine tuning of the frequencies, but it is a measurable effect.

Measurements of a 26-inch timpani showed that the (1,1), (2,1), (3,1), (4,1), and (5,1) modes had frequency ratios of 1.00:1.50:1.98:2.44:2.91 (Christian et. al., 1984). This set of ratios is close to 1:1.5:2:2.5:3. By multiplying the ratios by a factor of two, they are seen to be the same ratios as 2:3:4:5:6. Because of the harmonic nature of these modes, we are able recognize the definite pitch of the timpani.

History and Acoustics of Drum Kit Instruments

One of America's first musical inventions was the drum kit. This hybrid instrument consolidated its pieces from around the world into a rhythmically mesmerizing voice. The pieces making up a drum kit include drums, cymbals, and a myriad array of auxiliary instruments. Drums used in a drum kit include snare drums, bass drums, and toms, all of which are cylindrical drums with a drumhead on each side.

We first explore the maturation of the drum kit due to social and cultural influences, percussionist ingenuity, and stylistic development. Then we examine the acoustics of the most common drum kit components.

Evolution of the Modern Jazz Drum Kit

Before discussing the evolution of the modern drum kit, we must examine the historical and cultural foundation leading to its creation. We explore how African and Middle Eastern diasporas, improvisation, and immigration all contributed to the development of the drums in Western European societies and, specifically, the drum kit in the United States.

The snare drum, bass drum, and cymbals are the foundational percussion instruments of the drum kit. Although the snare drum was derived from the tabor during the Renaissance, Europeans appropriated bass drums (davul), cymbals (zil), and other auxiliary percussion from the Ottoman Empire. In particular, Janissary music, a Turkish military style (see youtu.be/D0Fyf63qI_E), profoundly impacted the instrumentation of Western European military music. Use of these instruments spread to military bands and orchestras throughout Europe (Montagu, 2002).

Percussion instruments, specifically drums, played a critical role in many African cultures. Drums were used to communicate between villages, using different tones to broadcast a message to an individual or the entire community. Subsequently, during legalized slavery, drumming was prohibited in the United States. Slave holders could not permit this mode of communication because they did not want enslaved persons to have a form of communication unbeknownst to their enslavers (Dean, 2012). Additionally, stripping Africans of their cultural attachments was a form of psychological warfare to make them more compliant.

However, Congo Square in New Orleans, Louisiana, was one of the few locations where the enslaved could play their native instruments. On days off, enslaved people from the region gathered in Congo Square, now known as Louis Armstrong Park, to worship and celebrate. These practices gave them a meager sense of connection to their cultural heritage. West African rhythms blended with the diverse cultures of New Orleans, setting the stage for many musical genres to be born in the United States, including the blues, jazz, rhythm and blues, and rock and roll.

After the American Civil War, military musicians pawned their instruments and even left instruments on the battlefield, allowing affordable access to instruments to freed slaves and the lower class. The United States was also inundated with immigrants from all over Europe and Asia. Immigrants brought families, cherished items, and, most importantly, musical traditions and indigenous instruments. Consequently, melodies, harmonies, and instruments converged, providing a platform for the auxiliary percussion, toms, and Chinese cymbals (see **Figure 4** for examples of toms and cymbals).

The last salient element is improvisation. Ethnomusicologist Paul Berliner (1994, p. 221) defines improvisation best as the "real-time composing — instantaneous decision making in applying and altering musical materials and conceiving new ideas." The notion of instantaneous composing, individually or collectively, is intertwined in West African cultures. Drums would interact, or employ "call and response," with dancers in sacred ceremonies and secular celebrations (Dean, 2012). This spontaneous exchange of ideas prevailed as a prominent American popular music feature in the early twentieth century. The syncretism of African and Middle Eastern

Figure 4. *Examples of drum kit outfits from the early twentieth century drum kit (**left**) and modern drum kit (**right**). Parts of the drum kits are (1) sock cymbal; (2) snare drum; (3) Chinese tom-tom; (4) wood blocks; (5) bass drum pedal; (6) bass drum; (7) hi-hat; (8) toms; and (9) ride cymbal. Vintage outfit image courtesy of Olympics Drums & Percussion Museum, Portland, Oregon.*

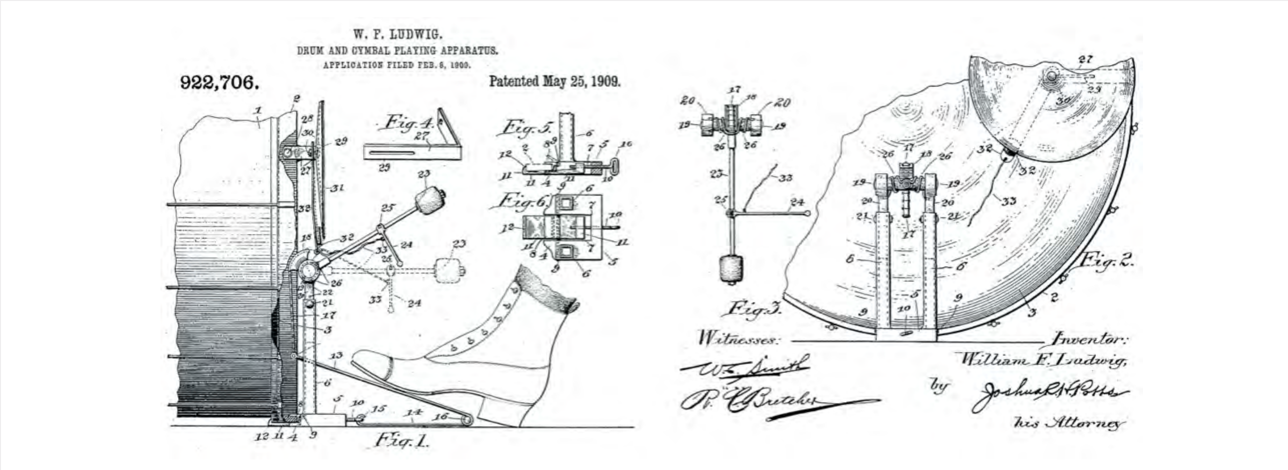


Figure 5. *Ludwig & Ludwig bass drum pedal with variable cymbal playing. From Ludwig (1909).*

Diasporas, elements of immigration in the United States, musical development in Congo Square, and improvisational language set the stage for the development of the modern drum kit.

Drummer Ingenuity

At the end of the nineteenth century, vaudeville and other theatrical variety shows were a significant source of entertainment, especially in the United States and Canada. Percussionists were in such high demand that an individual player needed to play multiple instruments simultaneously, including snare drum, bass drum, cymbal, and other auxiliary percussion. Drummers experimented with placing the snare drum on a chair to be able to also strike the bass drum and cymbals. This new technique was known as double drumming (see youtu.be/qM869WYpp-0?t=131). Drummers also performed as Foley artists by providing an extensive library of sounds and effects for silent films. Contraptions, such as the Chinese tom (tánggu) and woodblock, were attached and surrounded the percussionists to construct sound effects (see **Figure 4**). Drummers enveloping themselves with contraptions eventually led to the hybrid drum set being named a “trap” kit.

As improvisational use of the snare drum increased, companies noticed a need for drummers to be able to play the bass drum without using their hands. To solve this problem, entrepreneurs designed bass drum pedals that were initially cumbersome to use. Initial designs used a pendulum motion to control the pedal with the foot. This was unwieldy, especially for fast tempos. A major innovation was introduced by the Ludwig & Ludwig Drum Company, resulting in the modern bass drum pedal (Ludwig, 1909). Their design utilized a spring to retract the pedal to its original position for additional strikes (see **Figure 5**). The bass drum pedal additionally had a variable arm to strike a cymbal that was also attached to the bass drum.

Drummers gained more arm independence when cymbal strikes could be made by the left foot using a lowboy cymbal or a sock cymbal. The sock cymbal pedal is similar to the bass drum pedal, except that it allows the percussionist to strike two cymbals together using one foot. This contraption would soon evolve into the hi-hat, as seen in **Figure 4.**

The mythology of the transformation of the sock cymbal to the hi-hat is vague and ambiguous. Nonetheless, one drummer, Papa Jo Jones of the Count Basie Orchestra, realized that he wanted to continuously play the sock cymbal, but it was located at the same level as his feet. Eventually, the sock cymbals were raised to the same height as the snare drum and other contraptions, allowing for the drummer to easily reach the colliding cymbals with drumsticks. More importantly, Jones’ innovation completely altered the musical expression of the hi-hat. Jones redirected timekeeping from the bass drum to the hi-hat, emphasizing a swing beat, and resulting in the birth of the drummer’s modern jazz vocabulary.

A partnership between big band drummer Gene Krupa (see youtu.be/fyAUKU_ImNg) and the drum company

Slingerland established the movement from the early "contraption" set to the modern drum kit, with a new design for the toms. Initially, the calfskin drumhead was simply tacked onto the drum shell, similar to its Chinese counterpart, the tánggu (see **Figure 4**). By placing lugs on the side of the drum, tension in the drumhead could be adjusted, and tunable toms became a standard for future drum outfits.

Krupa also partnered with cymbal maker Avedis Zildjian to construct a more suitable cymbals, including the crash and splash cymbals. Krupa's simple suggestion of making a thinner cymbal was so profound that it produced the standard for all jazz cymbals. Reducing the thickness of the cymbal lowers the resonance frequencies and gives a more subtle attack, augmenting the articulation and allowing more musical expression.

Gretsch Drums was at the forefront of designing the drum kit and the cymbals in the bebop era, starting in the early 1940s. But one innovation stood above the rest. Drums shells were usually made from solid wood. As a result, environmental effects were always an issue when playing. Gretsch invented a manufacturing style that enabled the drum to be crafted, utilizing plywood; this approach mitigated humidity and temperature effects. Although this construction was developed in the late 1920s, its usage did not gain traction until the growing popularity of Gretsch Drums during the bebop era of the 1940s (Brennan, 2020).

In the 1950s, Marion "Chick" Evans and Remo Belli designed new drumheads from mylar, a plastic material used for aircraft in World War II (Brennan, 2020). Originally, animal hide was used for the membrane, but this would succumb to environmental elements such as humidity and temperature. Consistency between multiple hides was also minimal at best. In contrast, the plastic mylar drumheads minimized the environmental and geometric irregularities. Growth in popularity of the mylar heads led to the standardization of drum shell sizes and the modern jazz drum kit as we know it.

Musical Transformation

By the 1940s, a dichotomy between popular and high art music formed two types of influential styles: rhythm and blues and bebop. Rhythm and blues serviced dancers and continued using the identical drum sizes from the early onset of the drum kit. However, bebop's progressive interactive language required subtle modifications to the kit.

Drummer Kenny Clark (see youtu.be/COxQsRokpqQ) revolutionized how the swing feel was driven within the band by moving the swing beat from the hi-hat, as Papa Jo Jones did, to the top cymbal, which eventually was named the ride cymbal (see **Figure 4**). Clark's innovation also led to stylistic adjustments with the snare and bass drums. Rhythmic interjection between the snare drum and bass drum complimented the melody, leading to the term "comping." The new vocabulary required a smaller bass drum. Up to this point, drum kits in the swing era still used bass drums associated with marching bands (24-26 inches in diameter). Many bebop drummers, including Max Roach and Roy Haynes, downsized to a 20-inch bass drum to accommodate the expanding musicality of the drum kit. Cymbals also grew, up to 24 inches. The increased diameters created a darker tone, departing from the higher pitched auxiliary effects cymbal sound.

By this point in history, the drum kit was fully recognizable in its modern form. Drummers have continued to experiment with drum kit construction, but we now turn our attention to exploring the acoustics of the major drum kit components.

Figure 6. *A snare drum as seen from the bottom or the snare head side. The coiled wires running across the snare head are the snares that give the snare drum its characteristic crisp staccato sound. Also shown on the interior of this drum is a dampener pressed against the batter head of the drum. The dampener reduces an unwanted sound that drummers call an "edge ring" by suppressing the third resonance of the batter head.*

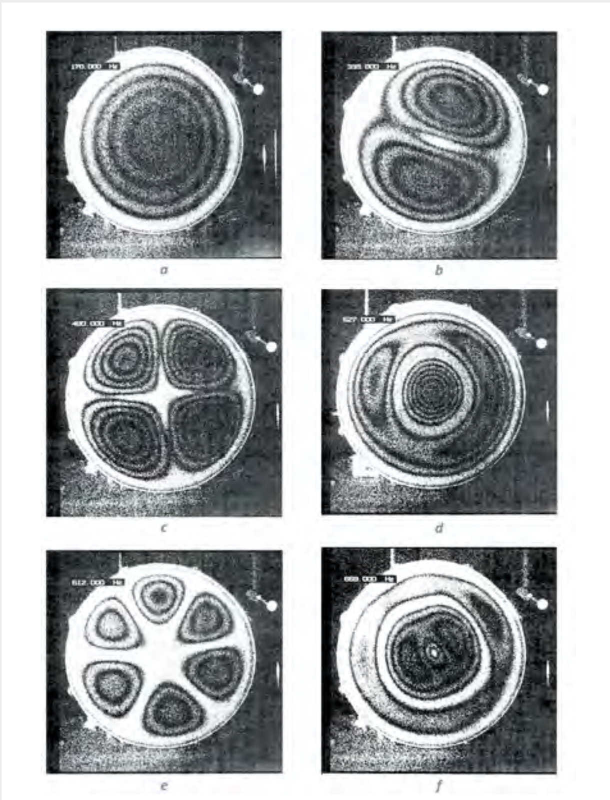


Figure 7. *Holographic interferograms of the first six modes of the batter head of a snare drum (Larkin and Morrison, 2010).* ***a:*** *(0,1) Mode;* ***b:*** *(1,1) mode;* ***c:*** *(2,1) mode;* ***d:*** *(0,2) mode;* ***e:*** *(3,1) mode;* ***f:*** *(1,2) mode. Figures first appeared in Percussive Notes. Reprinted with permission of the Percussive Arts Society, Inc. (see www.pas.org).*

Acoustics of the Snare Drum

The first component of the drum kit we discuss is the acoustics of the snare drum. The snare drum is a cylindrical drum with a drumhead on each side. The top drumhead, or batter head, is the side struck by the drummer. The bottom drumhead, or snare head, has a series of coiled wires, called the snares, stretched across it (see **Figure 6**), which are usually in contact with the snare head. The snares can be placed on or off the drumhead by a lever on the side of the drum (see **Multimedia File 4** at acousticstoday.org/scottmedia) so that when the snares are in contact with the snare head, the drum has the characteristic crisp sound associated with the snare drum (see **Multimedia File 5** at acousticstoday.org/scottmedia).

The modes of vibration of a snare drum as observed through electronic speckle-pattern interferometry are shown in **Figure 7**. In **Figure 6**, an internal dampener that is in contact with the batter head is shown. The dampener suppresses unwanted parts of the snare drum sound. Drummers call the unwanted sound an "edge ring" that does not have the short, staccato-like sound associated with the snare drum (Larkin, 2010). The mode primarily responsible for the edge ring is the (2,1) mode (see **Figure 7c**) The dampener is placed close to an antinode of this mode to reduce the edge ring.

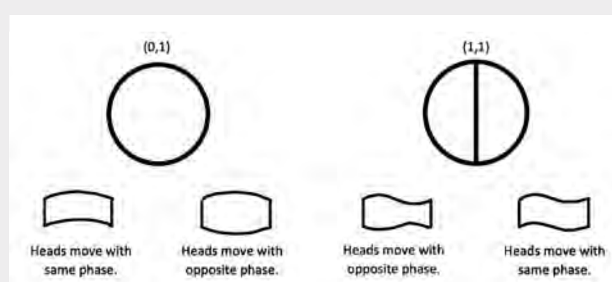
Acoustically, the snare drum differs from the frame drums, timpani, and tabla because the snare drum has two heads that act as a system of coupled oscillators (Rossing et al., 1992). Each drumhead is modeled as a spring-mass system, with the air in-between acting as a coupling spring. Because of the coupling between the heads, there is a mode where the two heads move in phase and a mode where the two heads move in opposite phases (see **Figure 8**). The coupling is particularly strong for the (0,1) and (1,1) membrane modes, but there is also a weak coupling between the two heads for the (0,2) membrane mode.

Tom Drums

The tom drum is a cylindrical drum with a drumhead on top and bottom and is similar in design to the snare drum. The major difference between the tom drum and the snare drum is that the tom drum does not have metal snares on the bottom head.

Drum kits may be equipped with toms of different sizes. Although it is quite clear that the pitch of a tom drum decreases as the size increases, generally we would not expect to be able to associate a particular musical

Figure 8. *Coupled modes of vibration for the batter and snare heads on a snare drum. The strongest coupling is between the (0,1) and (1,1) modes. Figure adapted from Rossing et al. (1992).*



pitch with the sound of the tom drum because the resonances of the drum are not expected to have a harmonic relationship.

Surprisingly, through careful tuning of the batter and resonant (bottom) heads, the frequency ratios of the first three modes of the tom can be aligned to a nearly 1:1.5:2 relationship (Richardson et al., 2012), the same ratio as what gave the timpani its definite pitch! Achieving this tuning relies on the strong coupling between the (0,1) modes of the two heads. No matter how each head is tuned, the (0,1) frequency of each head matches the other head's (0,1) frequency. This allows tuning of other resonances to find a harmonic relationship.

Bass Drum

The kick drum, or bass drum, is the largest cylindrical drum with two heads used in the drum kit. The term "kick" comes from the pedal mechanism. Research done on the bass drum has been mainly focused on the concert or orchestral bass drum (Fletcher and Bassett, 1978). The size of the kick drum is, on average, smaller than a concert bass drum (16-28 inches in diameter for kick drums versus 28-40 inches in diameter for concert bass drums). We can assume that in general the acoustics of the concert bass drum will be largely the same as for a kick drum.

Unlike the timpani, the kick drum is typically struck closer to the center of the drumhead. Playing the timpani in the center of the drumhead results in a dull, thumping sound that is considered undesirable for that instrument, whereas the kick drum is intended to have such a tone.

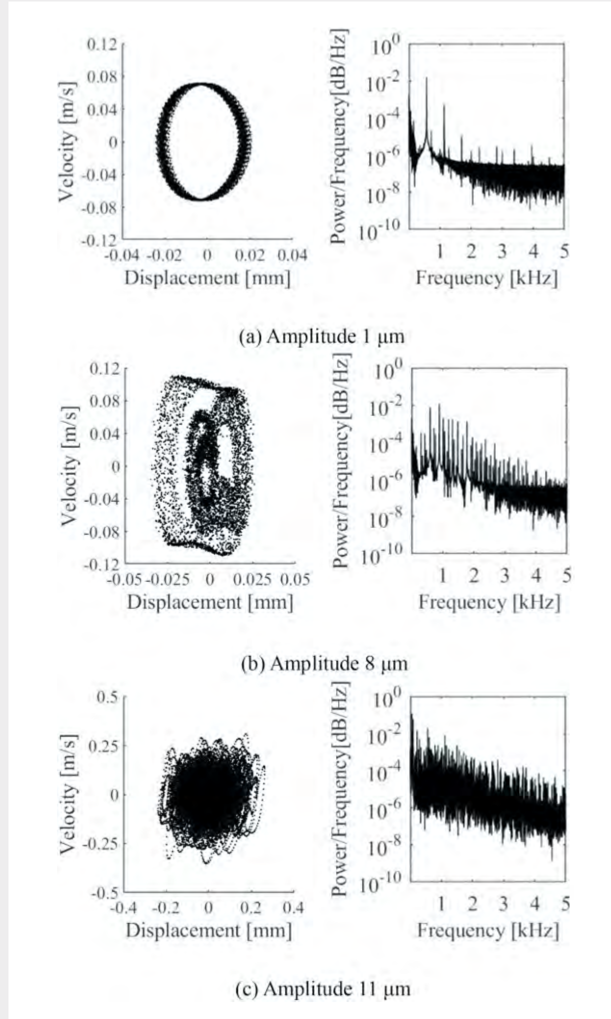


Figure 9. *Phase space plots and sound spectra for cymbal driven sinusoidally with increasing drive amplitudes.* ***a:*** *1 μm;* ***b:*** *8 μm;* ***c:*** *11 μm. Reproduced from Aihara and Ito (2022), with permission of Elsevier.*

Cymbals

Of all the instruments in the drum kit, the cymbals are by far the most acoustically complex. The cymbal is a metallic disc having a slight taper from the edge toward the middle, with a raised dome in the center of the cymbal. The cymbal is mounted on a stand through a hole in the center.

Comparing the normal modes of a cymbal with a flat plate fixed in its center, it is somewhat surprising to find that the mode shapes are similar (Rossing, 2000). That is, the features of the cymbal's profile do not significantly change the shapes of the resonances. Looking at the normal modes of the cymbal does not completely explain its sound because the vibration of the cymbal is highly nonlinear.

Due to their nonlinear behavior, driving a cymbal sinusoidally produces undertones and overtones at extremely low amplitudes (Chaigne et al., 2005), and at high-driving amplitudes, the cymbal vibrations are chaotic. A common way to represent the vibration transitions from quasi-linear to chaotic is by showing a phase space plot in combination with a spectrum. See **Figure 9** for an example from Aihara and Ito (2022).

As a result of the nonlinear nature of its vibration, the spectrum of a crash cymbal changes dramatically after the initial strike. Rossing (2000) described the change in the sound spectrum after the strike on a medium crash cymbal. The sound energy immediately after the strike is dominated by low frequencies, under 700 Hz. The energy shifts to midfrequencies (700-1,000 Hz) and then to the 3- to 5-kHz range within 100 milliseconds after the strike (Rossing, 2000). The high frequencies give the crash cymbal its characteristic "shimmering" sound.

Conclusion

The modern drum kit is composed of instruments with a rich history accessible for acoustical study. We have only touched on a few of the most prominent percussion instruments. Other percussion instruments such as the xylophone, the marimba, chimes, bells, the steelpan family, and auxiliary percussion instruments (such as triangles, tambourines, blocks, and gongs) are all acoustically unique.

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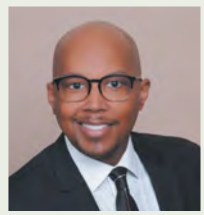

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