Volume 13 | Issue 4 Winter 2017

Acoustics Today

A Publication of the Acoustical Society of America

Acoustics and Vibration of Baseball and Softball Bats

Also In This Issue

- Isadore Rudnick (1917-1997): Acoustics in the Service of Physics
- Trespassing the Barrier of the Brain with Ultrasound
- Acoustics and Astronomy
- Theories About Target Range in Bat Sonar
- Some Work on the Diagnosis and Management of Kidney Stones with Ultrasound

Volume 13 | Issue 4 | Winter 2017

Acoustics Today

A Publication of the Acoustical Society of America

TABLE OF CONTENTS

8 From the Editor

10 From the President

Featured Articles

12 **Isadore Rudnick (1917-1997): Acoustics in the Service of Physics** - *Steven L. Garrett, Julian D. Maynard, and Seth J. Putterman*

"I don't consider myself an acoustician. I am a physicist who uses acoustical techniques and tools to understand physical systems."

21 **Trespassing the Barrier of the Brain with Ultrasound** – *Elisa E. Konofagou*

Focused ultrasound is a powerful tool for overcoming the immense hurdles in drug delivery that are posed in brain therapeutics.

27 **Acoustics and Astronomy** – *James F. Lynch*

The universe has a sound foundation!

35 **Acoustics and Vibration of Baseball and Softball Bats** – *Daniel A. Russell*

Vibrational modes of a bat explain the sweet spot, sting for mishits, a metal bat's "ping," and the trampoline effect.

43 **Theories about Target Ranging in Bat Sonar** – *James A. Simmons*

The frequency-modulated biosonar sounds transmitted by bats are well-suited to the accurate determination of target range and target.

52 **Some Work on the Diagnosis and Management of Kidney Stones with Ultrasound** - *Julianna C. Simon, Adam D. Maxwell, and Michael R. Bailey*

Ultrasound is currently the only noninvasive technology able to completely diagnose and manage kidney stones.

Sound Perspectives

60 **Ask an Acoustician** – *Micheal L. Dent*

63 **Technical Committee Report: Underwater Acoustics** – *Megan S. Ballard*

66 **Twenty-Five Years of the ASA Women in Acoustics Committee** – *Lauren M. Ronsse and Tracianne B. Neilsen*

69 **ASA Education and Outreach Program** – *L. Keeta Jones*

72 **ASA Sounds Out on Social Media** – *Dan Farrell and L. Keeta Jones*

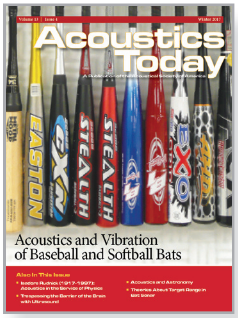
Departments

71 **Foundation Report** – *by Carl Rosenberg*

74 **Obituary**
Konstantin A. Naugolnykh | 1932-2017

76 **Classifieds, Business Directory, Advertisers Index**

About The Cover



Examples of the variety in baseball and softball bat construction. The cylindrical barrel vibrations in metal or composite bats affect their acoustic properties. Trademarks appearing in the cover photo are the property of their respective owners and used with permission. Picture copyright © 2017 Daniel A. Russell, University Park, PA. All rights reserved.

Acoustics and Vibration of Baseball and Softball Bats

Daniel A. Russell

Postal:
201 Applied Science Building
Pennsylvania State University
University Park
Pennsylvania 16802
USA

Email:
dar119@psu.edu

Vibrational modes of a bat explain the sweet spot, sting for mishits, a metal bat's "ping," and the trampoline effect.

Introduction

Baseball and softball are sports, similar to cricket, golf, tennis, hockey, and hurling, that involve a player swinging a handheld bat to hit a ball. In all of these sports, the impact between the ball and the bat, racket, stick, or club produces a sound heard by both players and fans. It also results in a postimpact vibration felt by the player holding the implement. A surprising fact is the extent to which the sound and vibration feedback matter to the player and especially how that feedback influences the perception of performance. The sensation of "feel" perceived by a player depends on the tactile sensation in the hands during and after the contact with the ball, as one would expect, but it is also strongly influenced by the sound of the impact. This has been studied extensively in the game of golf (Roberts et al., 2001, 2006) but also applies to baseball and any other game where a player holds an implement used to strike the ball. The perception of feel is composed of (1) vibration sensations in the hands, (2) sound of the impact, and (3) the perceived trajectory of the ball in flight (Hocknell et al., 1996). Popular Bat Wars (http://www.batwars.com) events held across the United States allow players at all levels to try out new bat models from manufacturers, and the ranking of player preference of softball bats is based on performance (distance), feel, balance, sound, and logo design and color. Four of those rankings are personal preferences, whereas two depend on acoustics and vibration.

This article describes the flexural bending and cylindrical barrel vibrations of baseball and softball bats. The flexural bending modes are used to identify the so-called "sweet spot" where impacts do not sting the hands. The source of a metal bat's "ping" is related to cylindrical modes in the barrel of an aluminum or composite bat, which give rise to a "trampoline effect." The vibration and acoustic properties of bats are discussed in relation to the development of performance standards. Finally, the myth of the corked wood bat is addressed.

Flexural Bending Vibrations in a Bat

Figure 1 shows a sampling of the variation available in baseball (**left**) and softball (**right**) bats from the author's laboratory collection of over 120 bats. Professional Major (and Minor) League Baseball (MLB) players exclusively use bats made from a single piece of solid wood, with maple and ash being the two most popular woods. College and high-school players primarily use aluminum and/or composite bats with a hollow barrel, although these bats must conform to a performance standard that regulates their performance to be essentially the same as a wood bat. Softball bats, used both for men's slow pitch and women's fast pitch, are almost all aluminum or composite hollow-barrel bats. Youth bats used by Little League Baseball are also aluminum or composite but with a much greater variation in length and weight than their adult counterparts. **Table 1** summarizes the variation

Figure 1. *Examples of the variety in baseball and softball bat construction.* ***Left****: Baseball bats.* ***Left to right:*** *pro-stock wood, replica of Heinie Groh's wood bottle bat, large knob wood bat for swing training, wood with composite coating, two piece with aluminum handle and laminated bamboo barrel, single-piece aluminum, two-piece aluminum, two-piece stiff composite handle with aluminum barrel, two-piece flexible composite handle with aluminum barrel, single-piece composite, composite with double-walled barrel, composite with very stiff handle, aluminum with vibration absorber in knob, aluminum with electronic vibration dissipation circuit on handle, and aluminum with aerodynamic holes in taper.* ***Right:*** *Softball bats.* ***Left to right:*** *wood, 1972 single-walled aluminum, 1993 graphite, 1993 titanium, single-walled aluminum, double-walled aluminum, triple-walled aluminum, two-piece composite handle with aluminum barrel, composite, composite high performance, multiwall (aluminum exterior with composite inner shell), high-performance aluminum double-walled barrel, two-piece antivibration joint with aluminum handle and triple-walled aluminum barrel, two-piece composite handle with aluminum double-walled barrel, two-piece composite handle joined to composite barrel, two-piece stiff handle with composite barrel, and two-piece composite handle with steel single-walled barrel.*

of bat dimensions and construction. For all bats, the handle end of the bat is much thinner than the barrel end. **Figure 2a** compares the diameter profiles of a baseball bat and softball bat of the same length.

Vibrational Mode Shapes and Frequencies

The violent collision between a baseball and bat can cause postimpact flexing and vibration of the bat. The frequency of the vibration and the corresponding standing wave patterns (mode shapes) depend on the materials and dimensions of the bat. **Figure 2, b** and **c,** shows the first two bending mode shapes for a baseball and softball bat compared with the mode shapes for a uniform beam with free ends. The mode shapes for the bats are similar to those of the free-free beam, except that the nodal points (where the displacement is zero) for the bats are shifted toward the thinner handle end and the vibration amplitude is not symmetric but is larger in the handle (Video 1 at http://acousticstoday.org/russell-media).

Vibrational mode shapes and frequencies for a baseball or softball bat are obtained by experimental modal analysis, in which a hammer instrumented with a force gauge is used to tap the bat at one location while the resulting acceleration is measured with an accelerometer at another location, producing a frequency-response function for that pair of input/output locations. If the accelerometer is held at a fixed location while the hammer impacts are moved along the length of the bat, the total set of frequency-response functions may be curve fit to extract vibrational mode shapes (representing the normalized displacement of each point relative to all of the other points), the resonance frequencies for those mode shapes, and the damping decay rates for the modes. For such an experiment, the bat is suspended on rubber bands in a free-free condition.

One might question whether a baseball bat, gripped in the hands, is best compared with a free-free beam instead of being clamped at the handle end. To answer, the frequencies for a handheld baseball bat are much closer to those of a free-free bat than they are for a bat clamped at the handle (Brody, 1990). Free-free boundary conditions provide a good approximation for the measurement and modeling of other handheld sports implements as well, including cricket bats (Brooks et al., 2006), golf clubs (Wang and Wu, 2005), and tennis rackets (Banwell et al., 2014).

Table 1. Dimensions and barrel constructions for baseball bats for various groups.

	Bat Length	Barrel Diameter	Barrel Length	Material	Barrel Type
Baseball, professional	31-34 in. (79-86 cm)	2.625 in. (6.7 cm)	3-5 in. (8-13 cm)	Wood	Solid
Baseball, college and high school	31-34 in. (79-86 cm)	2.625 in. (6.7 cm)	3-5 in. (8-13 cm)	Aluminum or composite	Hollow
Softball	33-34 in. (84-86 cm)	2.25 in. (5.7 cm)	10-14 in. (25-36 cm)	Aluminum or composite	Hollow
Youth baseball	18-30 in. (46-76 cm)	2.25 in. (5.7 cm)	8-10 in. (20-25 cm)	Aluminum or composite	Hollow

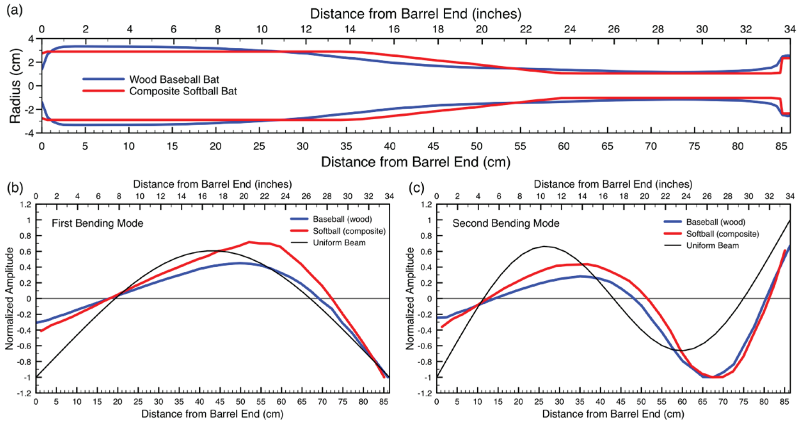


Figure 2. a: *Radius profiles for a baseball bat (wood and aluminum) and slow-pitch softball bat (composite). Measured mode shapes for a wood baseball and composite softball bat compared with a uniform beam: first bending mode (**b**); second bending mode (**c**). In both plots, the handle is at **right** and the barrel is at **left**.*

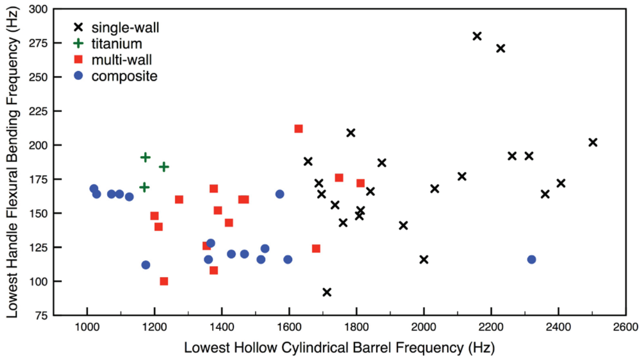


Figure 3. *The range of frequencies for the lowest flexural bending mode and lowest cylindrical barrel mode for slow-pitch softball bats of a variety of constructions. Single-walled aluminum bats entered the market in the early 1970s and older bats have higher frequencies, although the barrel frequencies moved to lower values as improvements in aluminum alloys allowed for thinner barrel walls without sacrificing durability. Double-walled aluminum bats entered the market in the mid-1990s and introduced a significant improvement in performance. In 1993, Easton, Louisville Slugger, and Worth introduced single-walled titanium alloy bats that hit balls so much faster that they were immediately banned. Composite graphite bats were introduced as early as 1993, but only after 2000 did carbon fiber composite bats begin to dominate the market. Modified from Russell (2004).*

A surprising validation of the free-free condition is the fact that a player's hands do not affect the bat-ball collision. The duration of the bat-ball collision, approximately 0.0007 s for baseball and 0.001 s for softball, is shorter than the time for bending vibrations to travel from the impact point on the barrel down to the handle and back. This means that the ball does not know that the handle of the bat exists because the ball has already broken contact with the bat before any vibration returns from the handle. The batted ball speed is the same if the bat handle is clamped in a rotating pivot, gripped by a player, or freely supported (Koenig et al., 2004). Brody (1990) even predicted that a batter could completely release the bat just before impact and the resulting ball trajectory would be the same as if the batter was firmly gripping the bat during the entire swing. This actually happened on May 12, 2012, when high-speed video captured Major League Baseball (MLB) player Todd Frazier hitting a home run even though the bat was slipping out of his hands and was completely free at the instant of impact with the ball (https://goo.gl/hQsB1Z).

The frequencies of the first two bending modes are important to the perception of feel because the human hand is most sensitive to vibrations with frequencies between 150 Hz and 550 Hz, with a peak sensitivity around 250 Hz (Reynolds et al., 1977). Variations in shape profiles, differences in material properties between wood and aluminum, and the fact that composite materials may be manipulated to design bat handles with varying degrees of flexibility allow a bat's bending frequencies to cover a fairly wide range. For softball and baseball bats, the frequency of the first bending mode typically falls between 80 Hz and 215 Hz and the second bending mode between 350 Hz and 750 Hz. **Figure 3** shows the range of vibrational frequencies for a collection of approximately 60 softball bats of various constructions. The *y*-axis of the plot shows the spread of frequencies for the lowest flexural bending mode in the handle; the *x*-axis of the plot shows the variation in frequency for the cylindrical shell vibrations in the hollow barrels of aluminum and composite bats (these are discussed in the **Hoop Modes, Ping, and the Trampoline Effect** section).

Bat Vibration: Sting and Sweet Spots

The definition of the sweet spot of a baseball bat is problematic because, as is the case for tennis rackets, the term sweet spot could refer to the location that minimizes the vibration and impulse felt by the hands, the location where the maximum amount of energy is transferred from bat to ball, or the location where the ball leaves the bat with maximum velocity, and these three locations do not coincide (Brody, 1986). Furthermore, even if the definition of the sweet spot is limited only to the location where the sensation of vibration and impulse in the hands is minimized, one still finds a fair amount of disagreement in the literature. The sweet spot for feel has been defined as the center of percussion, the node for the first bending mode, a location between the center of percussion and the node of the first bending mode, or the node of the second bending mode.

Vibrational Modes and the Sweet Zone

Cross (1998) identifies the sweet zone on a baseball bat as the impact location that minimizes the vibration felt by the hands. This is a narrow zone in the barrel of the bat, approximately 5-7 inches (12.7-17.8 cm) from the barrel end. As seen in **Figure 4**, this definition of the sweet zone falls between the nodes of the first and second bending modes. There is some disagreement in the literature as to whether the sting in the hands is due to the vibration of the first bending mode or a combination of the second bending mode and the initial impulse, having a time duration nearly the same as the period of the second bending mode, traveling along the bat immediately after the collision (Adair, 2001a; Cross, 2001). The first bending mode, with a frequency around 150 Hz, is easily felt by holding the bat lightly at the handle and tapping the barrel end of the bat on the ground. It is easy to locate the node for the first bending mode by lightly holding the bat at the handle and tapping the barrel to find the location where no vibration is felt. However, what a player feels during the violent collision between bat and ball is not the same as this simple test. High-speed video shows that the vibration in the handle can be large enough to cause the player's top hand to completely lose contact with the bat as the flexural impulse travels down the bat after impact (Video 2 at http://acousticstoday.org/russell-media), and the vibration can even be large enough for a wood bat to splinter or break (https://goo.gl/BZZrA3).

The painful sting resulting from an impact away from the sweet zone is most frequently felt in the fleshy region between thumb and forefinger in the top hand, the hand farthest from the knob of the handle. **Figure 4** shows that this sting location on the handle of a bat corresponds to an antinode for the second bending mode and a node for the first bending mode, suggesting that the second bending mode is more important to feel. Players tend to show a strong preference for bats in which the second bending mode has been heavily damped through the use of a vibration absorber tuned to the frequency of the second bending mode (Russell, 2006).

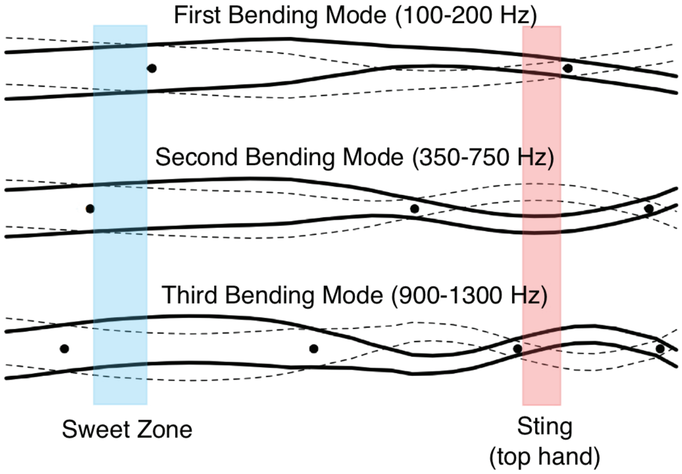


Figure 4. *Mode shapes for the first three bending modes of a slow-pitch softball bat, with relative displacements mapped to the physical dimensions of the bat.* ***Solid lines,*** *displacement of the bat at one extreme of the vibration;* ***dashed lines,*** *displacement half a period later, at the other extreme of the vibration cycle;* ***black dots,*** *nodes, locations where the vibrational amplitude is zero. The sweet zone is a region approximately 5-7 inches from the barrel end of the bat; impacts in this zone will minimally excite the bending modes into vibration. Impacts away from the sweet zone will cause the bat to vibrate, and the location where pain is most often felt in the top hand aligns with an antinode (maximum displacement and acceleration) of the second bending mode.*

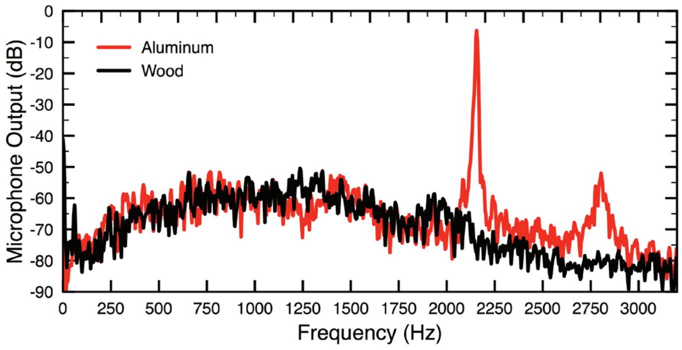


Figure 5. *Microphone responses for the impact of a baseball with a wood bat (Sound File 1 at http://acousticstoday.org/russell-media) and an aluminum bat (Sound File 2 at http://acousticstoday.org/russell-media). The high peak at approximately 2,200 Hz represents the characteristic "ping" produced by the aluminum bat and is due to the (n = 2, m = 1) cylindrical hoop mode in the hollow barrel. The smaller peak near 2,800 Hz is due to the (n = 2, m = 2) cylinder mode.*

Hoop Modes, Ping, and the Trampoline Effect

The Ping of an Aluminum Bat

The sound of the impact between a baseball and a wood bat at the sweet spot produces a "crack" (Sound File 1 at http://acousticstoday.org/russell-media), and experienced professional players use the impact sound as a clue to decide which way to begin running to catch the ball before it has traveled far enough for eye tracking to determine its trajectory (Adair, 2001b). An aluminum bat produces a distinct ping (Sound File 2 at http://acousticstoday.org/russell-media), a sound that many baseball purists decry. **Figure 5** shows the strong tonal component of the aluminum bat ping (the peak at 2,200 Hz) completely dominates the sound spectrum. The sound of an aluminum bat is distinctive enough that a forensic acoustic analysis of a recorded police emergency 911 call was able to identify a baseball bat found at a homicide crime scene as the probable murder weapon (Marr and Koenig, 2007).

The impact from the bat-ball collision can be loud enough to raise concerns about hearing health for softball players who are subjected to repeated loud impacts (Okuma and Takinami, 1994; Cook and Atcherson, 2014). Although individual ball impacts with an aluminum bat can produce levels as high as 124.6 dB at the approximate location of a batter's left ear, the normalized 8-hour equivalent A-weighted level is low enough to be pose little risk during a typical game. However, repeated exposure for a catcher during a game or a batter during batting practice could warrant the use of hearing protection.

Hoop Modes in Hollow Cylindrical Barrels

The barrel of a wood baseball bat is solid, but the barrels of aluminum and composite baseball and softball bats are hollow cylindrical shells. A hollow cylindrical shell exhibits several families of mode shapes expressed in terms of the angular position θ around the circumference of the barrel and the distance x along the length of the barrel according to

$$\varphi(x, \theta) = \cos(n\theta)\,\sin(mx/L) \qquad (1)$$

where φ represents the normalized radial displacement and L is the barrel length. The mode shape designations (n and m) indicate the number ($2n$) of axial nodal lines encountered as one traverses the circumference of the barrel and the number (m) of circumferential nodal circles encountered as one traverses the length of the barrel**.** The n nodes are actually diameters for the circular barrel cross section, and as one traverses the circumference, each diameter is encountered twice, so if $n = 2$, a total of 4 axial node lines are encountered around the circumference. **Figure 6a** illustrates the circumferential variation of the cylinder radius corresponding to different values of n. All of the mode shapes in the same family (same n value but different m values) have the same circumferential displacement but differ in radial displacement along the axial length of the barrel. The ($n = 0$) modes involve a uniform expansion of the barrel and are not observed in a bat. The ($n = 1$) modes are the flexural bending modes. The families of cylinder modes with $n > 2$ are all involved in the deformation and effective elastic property of the bat barrel during the collision with the ball. A spatial Fourier synthesis (**Figure 6b**) of the ($n = 2, 3, 4, 5$) modes closely resembles the initial deformation of the bat barrel during impact with the ball. This Fourier reconstruction agrees well with a finite element analysis model of the bat-ball collision (**Figure 6c**). The higher order cylinder modes are not easily observed for most bats and tend to have resonance frequencies high enough, with periods short enough, that the time duration of the impact between bat and ball prevent these modes from adding significantly to the acoustic or vibrational signature of the bat. Furthermore, because

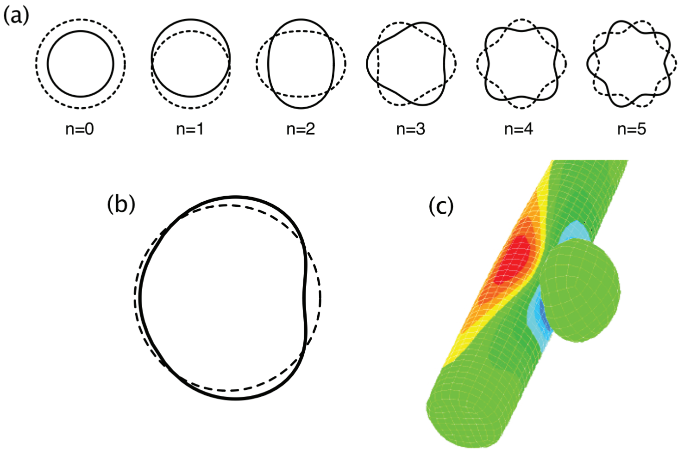


Figure 6. a: *Circumferential modes in the hollow cylindrical barrel of an aluminum or composite bat (Video 5 at http://acousticstoday.org/russell-media).* ***Solid*** *and* ***dashed lines,*** *extremes of the vibrational displacement, separated by half a cycle. The (n = 0) modes are breathing modes and are not observed. The (n = 1) modes are the flexural bending modes. The lowest frequency (n = 2) mode is called the "hoop mode" of the bat and is used to model the essential physics of the bat-ball collision.* ***b:*** *A spatial Fourier synthesis of the (n = 2, 3, 4, 5) modes produces the "kidney bean" shape that corresponds to the initial deformation of the barrel cross section on impact with a ball.* ***c:*** *A finite element model of the ball-bat collision shows the same initial bat deformation with a slight outward bulge (**red**) at the top and bottom of the bat cross section and a concave inward compression (**blue**).* ***c*** *modified from Mustone (2003).*

Figure 7. *A selection of softball bats with hollow metal or composite cylindrical barrels having hoop frequencies that form a good approximation of a musical scale. This "bat piano" can be used to play tunes (Video 4 at http://acousticstoday.org/russell-media).*

these cylinder modes only involve vibration in the hollow barrel, they have no influence on the perception of feel in the handle.

The Hoop Mode and the Trampoline Effect

The lowest frequency ($n = 2$, $m = 1$) cylinder mode of a bat barrel is called the "hoop mode" (Video 3 at http://acousticstoday.org/russell-media) and is responsible for the ping sound of the aluminum bat in **Figure 5**. This mode is also responsible for the potentially performance-enhancing trampoline effect in a hollow bat, similar to the trampoline effect provided by the titanium faceplate of a hollow golf club driver. The trampoline effect is so named because the elastic barrel of the bat does most of the work during the collision, elastically deforming and returning stored potential energy to the ball, much like when a person jumps on a trampoline. The frequency of the hoop mode depends on the material, thickness, and length of the barrel walls, and there is considerable variation in the hoop frequency. The frequency of the hoop mode for a softball bat, shown on the x-axis in **Figure 3**, ranges from 1,000 Hz to 2,500 Hz, which is more than a musical octave. **Figure 7** illustrates that it is possible to find softball bats with hoop frequencies roughly corresponding to the notes of a musical scale. With the right bats, one can even make a bat piano to play "Take Me Out to the Ball Game" (Video 4 at http://acousticstoday.org/russell-media; for a longer explanation of this video, see http://y2u.be/r4KTGj-2trQ).

The location of maximum amplitude for the ($n = 2$, $m = 1$) hoop mode, as measured from the barrel end of the bat, nearly coincides with the sweet zone. Not only will ball impacts in this region not sting the hands, but the ball could come off the bat faster if the trampoline effect has the right frequency. The effective elastic property of the barrel, due to the trampoline effect of the hoop mode, is measured in terms of the bat-ball coefficient of restitution (BBCOR), from which a number of other performance metrics, including batted-ball speed, may be calculated (Smith, 2001, 2008; Nathan, 2003; ASTM, 2014). The frequency of the ($n = 2$, $m = 1$) hoop mode correlates rather well with measured BBCOR values and batted-ball speeds for both softball bats (Russell, 2004) and baseball bats (Sutton and Sherwood, 2010; Nathan et al., 2011a). All other properties being equal, a bat with a lower hoop frequency will hit the ball faster and farther than a bat with a higher hoop frequency. The highest performing slow-pitch softball bat manufactured to date is the original composite Miken Velocit-E Ultra introduced in 2002, with a very low hoop frequency around 1,000 Hz (this bat was quickly banned and is not currently legal for play).

Aluminum and composite baseball bats currently used for college and high-school play are regulated by a performance standard that limits the BBCOR value to 0.5, which is essentially the maximum value for a wood bat. Aluminum and composite BBCOR 0.5 baseball bats have hoop frequencies above 1,800 Hz; at a frequency this high, the trampoline effect is too small to improve the batted-ball speed. There are still advantages to using a nonwood bat, such as increased durability, increased swing speed, and better bat control. However, since 2011, when the BBCOR standard was adopted, college baseball performance metrics (home runs per game, runs per game, batting average) have dropped to 1972 levels when only wood bats were used (https://goo.gl/YafZhz).

A relatively simple model of the bat-ball collision, adapted from a model of the golf ball-club impact, treats the hoop mode of the hollow bat as a linear mass-spring and the ball as a nonlinear mass-spring (to account for hysteresis and energy lost to friction during the collision). Analysis of collisions between these two mass-spring systems captures the essential physics of the collision between a ball and a hollow bat (Nathan et al., 2004), explains the correlation between low hoop frequency and high batted-ball speed, and predicts observed trends for bat performance (Russell, 2004).

Do Corked Wood Bats Have a Trampoline Effect?

Every once in a while, MLB players are caught trying to cheat by using illegally altered bats or substances. On June 3, 2003, Chicago Cubs outfielder Sammy Sosa was caught using an illegal corked bat. A few years earlier, in 1998, Sosa had captivated fans in an exciting race with St. Louis Cardinals' first baseman Mark McGuire in an attempt to break Roger Maris' long-standing record of 61 home runs in a single season. Sosa's illegal bat had a long hole (filled with cork) drilled down the center of the wood barrel (Russell, 2012). A question frequently posed about such illegally altered wood bats is, "Does a corked bat has a trampoline effect?" It turns out that a corked bat does indeed have hoop modes, but the frequency of the ($n = 2$, $m = 1$) hoop mode is well above 5,500 Hz, so high that it provides absolutely no improvement in performance over a solid bat. In fact, experimental measurements of bat performance reveal that a corked bat actually has a lower BBCOR than a solid bat and thus provides no physical performance advantage to a hitter (Nathan et al., 2011b).

Conclusions

The acoustic and vibrational characteristics of baseball bats described in this article are easily applicable to any other sport involving hand-held sticks, rackets, or clubs. The flexural bending vibrations of cricket bats and field hockey sticks play a similar role in the problem of sting and the identification of the sweet zone. Tennis rackets have flexural bending mode shapes as well as torsional modes that influence the vibration felt in the handle. The strings of a tennis racket vibrate like a membrane (drumhead) and the face of a golf club driver has mode shapes like a plate clamped at the edges. Both of these produce a trampoline effect that affects both the efficiency of the impact with the ball and the perception of quality for the player hearing the impact sound.

There is a wealth of opportunities for research on the acoustics and vibration of sports equipment. Understanding how an implement vibrates is the first step toward finding ways to minimize the vibration causing sting or injuries in the hands and arms. Understanding the trampoline effect in bats, rackets, and clubs is necessary for developing scientific tests to measure and regulate performance. Acoustics tools could be used to detect equipment that has been illegally altered. Composite materials and new innovations in equipment design can lead to implements that perform better and/or that provide a more desirable feel of the hands and ears of the player. And an awareness of acoustics could even enhance the enjoyment of watching a favorite player hit a home run to win a game.

Biosketch

Dan Russell is a professor of acoustics and distance education coordinator for the Graduate Program in Acoustics at Penn State. He has been studying the acoustics and vibration of sports equipment (baseball and softball bats, ice and field hockey sticks, tennis rackets, cricket bats, hurling sticks, golf drivers, putters and balls, ping-pong paddles, and basketballs) for 20 years. He has provided consulting and testing services for several manufacturers including Easton, Louisville Slugger, DeMarini, Marucci, Combat Baseball, Donnay Tennis, and Nike Golf and serves as a scientific advisor for USA Baseball. His animations website (http://acousticstoday.org/drussell) is well-known in the acoustics education community.

References

Adair, R. K., (2001a). Comment on "The sweet spot of a baseball bat." *American Journal of Physics* 69(2), 229-230. doi:10.1119/1.1286856.

Adair, R. K., (2001b). The crack-of-the-bat: The acoustics of the bat hitting the ball. *The Journal of the Acoustical Society of America* 109, 2497 (Abstract). Lay language version is available at http://acousticstoday.org/adair.

ASTM. (2014). *ASTM F2219-14, Standard Test Methods for Measuring High-Speed Bat Performance*. ASTM International, West Conshohocken, PA. Available for purchase from http://acousticstoday.org/standards.

Banwell, G. H., Roberts, J. R., Halkon, B. J., Rothberg, S. J., and Mohr, S. (2014). Understanding the dynamic behavior of a tennis racket under playing conditions. *Experimental Mechanics* 54, 527-537. doi:10.1007/s11340-013-9809-9.

Brody, H. (1986). The sweet spot of a baseball bat. *American Journal of Physics* 54(7), 640-643.

Brody, H. (1990). Models of baseball bats. *American Journal of Physics* 58(8), 756-758.

Brooks R., Mather, J. S. B., and Knowles, S. (2006). The influence of impact vibration modes and frequencies on cricket bat performance. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 220(4), 237-248. doi:10.1243/14644207JMDA107.

Cook, K., and Atcherson, S. R. (2014). Impulse noise: Can hitting a softball harm your hearing? *The Scientific World Journal*. doi:10.1155/2015/702723.

Cross, R. (1998). The sweet spot of a baseball bat. *American Journal of Physics* 66(9), 772-779.

Cross, R. (2001). Response to "Comment on 'The sweet spot of a baseball bat." *American Journal of Physics* 69(2), 231-232. doi:10.1119/1.1286857.

Hocknell, A., Jones, R., and Rothberg, S. J. (1996). Engineering 'feel' in the design of golf clubs. In Haake, S. J. (Ed.), *The Engineering of Sport: Proceedings of the First International Conference on the Engineering of Sport.* A. A. Balkema, Rotterdam, The Netherlands, pp. 333-337.

Koenig, K., Dillard, J. S., Nance, D. K., and Shafer, D. B. (2004). The effects of support conditions on baseball bat testing. In Hubbard, M., Mehta, R. D., and Pallis, J. D. (Eds.), *Engineering of Sport 5, Vol. 2.* International Sports Engineering Association, Sheffield, UK, pp. 87-93.

Marr, K. W., and Koenig, B. E. (2007). Fundamental frequency analysis of a metal baseball bat. *Forensic Science Communications* 9(1). Available at https://goo.gl/QpGN4W. Accessed September 17, 2017.

Mustone, T. J. (2003). *A Method to Evaluate and Predict the Performance of Baseball Bats Using Finite Elements*. MS Dissertation, University of Massachusetts, Lowell.

Nathan, A. M. (2003). Characterizing the performance of baseball bats. *American Journal of Physics* 71(2), 134-143. doi:10.1119/1.1522699.

Nathan, A. M., Russell, D. A., and Smith, L. V. (2004). The physics of the trampoline effect in baseball and softball bats. In Hubbard, M., Mehta, R. D., and Pallis, J. D. (Eds.), *Engineering of Sport 5*, *Vol. 2*. International Sports Engineering Association, Sheffield, UK, pp. 38-44.

Nathan, A. M., Crisco, J. J., Greenwald, R. M, Russell, D. A., and Smith, L.V. (2011a). A comparative study of baseball bat performance. *Sports Engineering* 13, 153-162. doi:10.1007/s12283-011-0065-4.

Nathan, A. M., Smith, L. V., Faber, W. L., and Russell, D. A. (2011b). Corked bats, juiced balls, and humidors: The physics of cheating in baseball. *American Journal of Physics* 79(6), 575-580. doi:10.1119/1.3554642.

Okuma, T., and Takinami, H. (1994). Sound produced by metal baseball bats. *Proceedings of Inter-Noise 94: Noise Quantity and Quality,* 1994 International Conference on Noise Control Engineering, vol. 3. Yokohama, Japan, August 29-31, 1994, pp. 1065-1068.

Reynolds, D. D., Standlee, K. G., and Angevine, E. N. (1977). Hand-arm vibration, part III: Subjective response characteristics of individuals to hand-induced vibration. *Journal of Sound and Vibration* 51(2), 267-282.

Roberts, J., Jones, R., Harwood, C., Mitchell, S., and Rothberg, S. (2001). Human perceptions of sports equipment under playing conditions. *Journal of Sports Sciences* 19, 485-497. doi:10.1080/026404101750238944.

Roberts, J. R., Jones, R., Rothberg, S. J., Mansfield, N. J., and Meyer, C. (2006). Influence of sound and vibration from sports impacts on players' perceptions of equipment quality. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 220(4), 215-227. doi:10.1243/14644207JMDA86.

Russell, D. A. (2004). Hoop frequency as a predictor of performance for softball bats. In Hubbard, M., Mehta, R. D., and Pallis, J. M. (Eds.), *Engineering of Sport 5, Vol. 2.* International Sports Engineering Association, Sheffield, UK, pp. 641-647.

Russell, D. A. (2006). Bending modes, damping, and the perception of sting in baseball bats. In Moritz, E. F., and Haake, S. (Eds.), *Engineering of Sport 6, Vol. 1 Developments for Sports.* Springer Science+Business Media, New York, pp. 11-16.

Russell, D. A. (2012). Nondestructive testing detects altered baseball bats. *NDT Technician* 11(4), 1-5. Available at https://goo.gl/VUwEUu. Accessed August 27, 2017.

Smith, L. (2008). Progress in measuring the performance of baseball and softball bats. *Sports Technology* 1(6), 291-299. doi:10.1002/jst.70.

Smith, L. V. (2001). Evaluating baseball bat performance. *Sports Engineering* 4, 204-214.

Sutton, A. D., and Sherwood, J. A. (2010). Using vibrational analysis to investigate the batted-ball performance of baseball bats. *Procedia Engineering* 2, 2687-2692. doi:10.1016/j.proeng.2010.04.052.

Wang, B.-T., and Wu, G.-Z. (2005). Modal properties of golf club wood driver in different boundary conditions. In *Proceedings of Thirteenth National Conference on the Society of Sound and Vibration* C10.