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Do All Wood Bats Perform Identically?

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Abstract

This paper investigates whether seemingly identical wood baseball bats perform identically. A collection of 18 wood bats with essentially identical inertial properties (length, weight, moment of inertia, and shape) were investigated. The sample included six each of ash, birch, and maple that were specially constructed for this project. The studies included modal analyses to determine the frequencies and shapes of lowest bending vibrations, high-speed ball-bat collisions, and computer simulations. The results show that these bats do not perform identically and that the differences occur mainly for impacts further from the barrel tip than the sweet spot. At these locations the ball-bat coefficient of restitution, the metric of performance, is correlated with the frequency of the lowest bending vibration, a surrogate for the bat bending stiffness, or Young's modulus, with higher frequency bats performing better. The physics underlying these observations is explored. For given stiffness, no appreciable differences are found among the three wood species.

Keywords: Baseball bat performance, bending vibrations, ball-bat coefficient of restitution

1 Introduction

After several decades of research, a good understanding has emerged about the physics of the baseball-bat collision [1, 2]. In particular, it is now very well established how to characterize, measure, and (in the case of non-wood bats) regulate the performance of a bat [3, 4]. Most of the research has concentrated on non-wood bats, which are the bats of choice at essentially all levels of the game other than the professional level. That research has led to an excellent understanding of the factors that contribute to the performance of a bat in a game-like situation. This has resulted in the establishment of performance standards for non-wood bats, such as the Ball-Bat Coefficient of Restitution (BBCOR) standard used at the high school and college levels [5] and the similar standard used for Little League and other youth leagues [6].

But this research, while shedding much light on the performance of non-wood bats, has not yet addressed the factors affecting the performance of wood bats. In particular, the research has yet to address the question posed in the title, “Do all wood bats perform identically?”. To bring this question into sharper focus, consider the following hypothetical. Suppose we have two nominally identical bats, labeled A and B, where “nominally identical” means they have the same length, weight, balance, weight distribution, and shape. Will these bats perform identically in a game situation? Are there differences due to the species of wood? If there are differences in performance, what is the underlying physics that explains these differences? We address these questions in this paper.

It should be pointed out that differences in performance among nominally identical wood bats is more than just an academic interest. A professional baseball player usually has a large selection of identical bats at his disposal but wants to use the best-performing bat in a game situation, thereby giving him a small edge over the course of a long season.

51 The paper is organized as follows. In Sec. 2, the necessary background information is
 52 presented with emphasis on the features of a bat that affect its performance. The experi-
 53 mental procedures are given in Sec. 3 and computational simulations in Sec. 4. Results are
 54 discussed in Sec. 5; and conclusions are summarized in Sec. 6

55 2 Background

56 For the purposes of this investigation, we will specify that bat A will outperform bat B if the
 57 exit velocity of A is higher than that of B under some range of standard game conditions.
 58 The exit velocity, a commonly used term among baseball people, is the speed of the batted
 59 ball just after it loses contact with the bat. From the point of view of the game itself, it is a
 60 sensible definition of performance. Generally speaking, if you want to improve your chances
 61 of getting a hit, then you want to maximize the exit velocity, regardless of whether you are
 62 swinging for the fences or just trying to hit a well-placed line drive through a hole in the
 63 infield. The faster the ball comes off the bat, the better are the chances of reaching base
 64 safely, as confirmed by a large body of data from Major League Baseball games [7].

65 With that definition of performance, it is useful to ask what the exit velocity depends
 66 on. Following the work of Nathan [3], the batted ball speed v_f can be expressed as follows:

$$v_f = qv_{pitch} + (1 + q)v_{bat} , \quad (1)$$

67 where v_{pitch} and v_{bat} are the speeds just prior to impact of the pitched ball and bat, respec-
 68 tively. The “collision efficiency” q is a dimensionless quantity that is a joint property of
 69 the ball and bat. Using conservation of energy, momentum, and angular momentum, it is
 70 straightforward to express q as follows:

$$q = \frac{e - r}{1 + r} , \quad (2)$$

71 where e is the BBCOR and is discussed more fully below. On the other hand, the so-called
 72 recoil factor r is given by

$$r = m/M_{eff} \quad (3)$$

73 where m is the ball mass and M_{eff} is the effective mass of the extended bat which depends
 74 on the actual mass, the moment of inertia about the center of mass, and the impact location
 75 relative to the center of mass [3].

76 We next examine the implications of the preceding equations for the relative performance
 77 of our nominally identical bats A and B. These equations tell us that the exit velocity under
 78 standard game conditions depends only on these factors: v_{pitch} , v_{bat} , m , M_{eff} , and e . The
 79 standard conditions mean that v_{pitch} and m will be the same for bats A and B. Moreover,
 80 since the bats have the same inertial properties, they will necessarily have both the same
 81 M_{eff} and the same moment of inertia about a point on the handle, commonly referred to as
 82 the “swing weight” [8]. The latter means that the bats will be swung identically so that v_{bat}
 83 will be the same. Therefore the *only* factor that will result in a difference in performance
 84 between A and B is the factor e [9], on which we now focus in some detail.

85 The BBCOR e is a measure of the elasticity of the collision, since $1 - e^2$ is the fraction
 86 of the initial kinetic energy in the center of mass frame that is dissipated in the collision
 87 (i.e., appearing neither in the kinetic energy of the rebounding ball nor in the translational
 88 or rotational energy of the recoiling bat). It is a joint property of the ball and bat and is
 89 distinguished from e_0 , which is a property of the ball alone. The latter, which is often referred
 90 to as the ball COR, is the elasticity of the ball when impacting a massive rigid object, such
 91 as a solid steel block, and is simply the ratio of rebound to initial velocity. Quantitatively
 92 at speeds relevant to the game of baseball, $e_0 \approx 0.5$, meaning that 75% of the initial kinetic
 93 energy is dissipated in the ball. When the ball impacts a solid wood bat, energy can also
 94 be dissipated in the bat in the form of bending vibrations, so that in general e is less than
 95 e_0 . In our stipulation of standard game conditions, we will assume that the ball is identical
 96 in all respects, including e_0 . Therefore, the expectation is that differences in the bending

97 vibrations will be the primary factor that affects performance differences between bats A
 98 and B.

99 The bending vibrations of a wood bat and their relevance for the ball-bat collision have
 100 been extensively studied by Van Zandt [1] and Nathan [2]. We postpone a detailed discussion
 101 of this topic to Sec. 4. For now the essential points to emphasize are summarized below and
 102 in Fig. 1, based on simulations of the ball-bat collision [2] for a pair of 0.86 m (34-inch)
 103 bats that are nominally identical except for bending stiffness. These points will serve as
 104 guidelines in designing our experimental program:

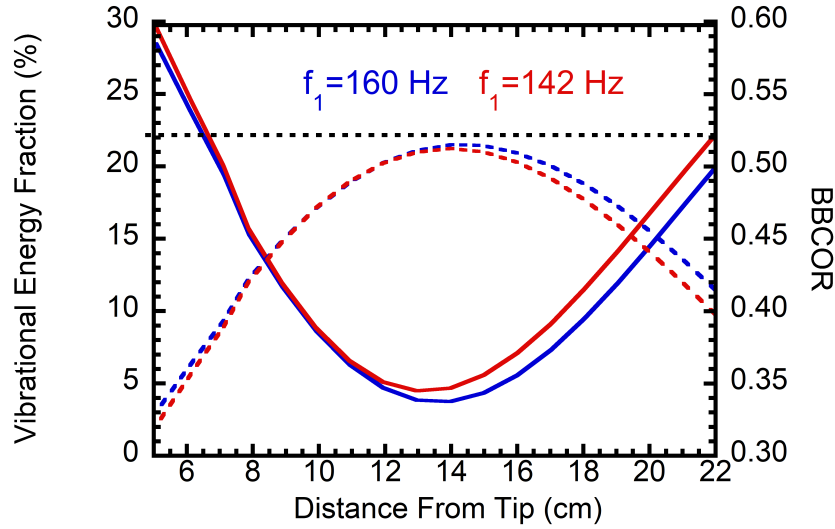


Fig. 1: Simulation of the ball-bat collision, where the ball is incident at 44.7 m/s (100 mph) on two nominally identical bats at rest. The blue and red curves are for bats with frequencies for the fundamental vibrational mode of 160 and 142 Hz, respectively. The solid curves and the left scale are the fraction of the initial kinetic energy resulting in bat vibrations. The dashed curves and right scale are the BBCOR. The black dotted line is the ball COR e_0 . The simulation shows that the BBCOR peaks close to the impact location where the vibrational energy is minimized. Differences between the two bats are most apparent for impact locations further from the tip than the sweet spot, as discussed more fully in Sec. 4

- 105 • The BBCOR is maximized and slightly less than e_0 at the location along the axis of
 106 the bat where the vibrational energy is minimized (the “sweet spot”, which for these

107 bats is approximately 14.5 cm [5.7 inches] from the tip). For locations removed from
 108 the sweet spot, the vibrational energy increases, resulting in the BBCOR decreasing.

- 109 • The simulations suggest that differences in BBCOR for the two otherwise identical bats
 110 are due to their differences in bending stiffness. This is reflected in the frequency of the
 111 fundamental bending mode f_1 , which approximately scales as the square root of the
 112 bending stiffness.
- 113 • For impacts at the sweet spot, the BBCOR is expected to be only weakly dependent
 114 on f_1 , since the vibrational energy fraction is very small there.
- 115 • The greatest difference in bat performance is expected to occur for impacts further
 116 from the tip (i.e., closer to the handle) than the sweet spot, where the vibrational
 117 energy fraction is much greater and more sensitive to differences in bending stiffness.
 118 At these locations, the bat with the lower f_1 will result in greater vibrational energy
 119 and therefore a smaller BBCOR. The reasons for this behavior are subtle and discussed
 120 at length in Sec. 5.

121 3 Experimental Procedures

122 A set of 18 nominally identical wood bats were sourced from a bat manufacturer and specially
 123 constructed for these experiments, including six bats each of ash, birch, and maple, which
 124 are the most popular wood species currently used by professional batters. The bats were
 125 nominally 0.861 m (33.9 inches) in length, 0.897 kg (31.6 oz) in weight, identical shape
 126 profiles, and specific properties given in Table I. These properties are typical of bats used
 127 by professional batters. A two-part program of experiments was conducted, as described in
 128 Sections 3.1 and 3.2.

129 3.1 Modal Analysis

130 Experimental modal analysis is a technique that determines the dynamic properties of a
 131 structure, namely its natural frequencies, mode shapes, and damping, from experimentally

Table 1: Measured properties of the bats, where I_6 is the moment of inertia about a point on the handle of the bat located 15.2 cm (6 inches) from the knob end and f_n is the frequency of the n th bending mode. The letters A, B, and M designate the wood species: ash, birch, and maple, respectively. Since all bats have the same shape profile with assumed uniform density, the density of each bat is $795(\text{Mass}/0.891) \text{ kg/m}^3$. The right-most two columns are the Young’s and shear moduli, respectively, as discussed in Sec. 4

Bat	Mass (kg)	Length (m)	I_6 (kg-m ²)	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_4 (Hz)	E 10^{10} N/m^2	S 10^{10} N/m^2
A1	0.808	0.959	0.206	146.3	505.1	1021.1	1611.1	1.65	0.13
A2	0.798	0.962	0.204	152.3	524.8	1056.1	1663.5	1.76	0.14
A3	0.800	0.959	0.204	134.6	469.9	966.5	1551.9	1.38	0.25
A4	0.808	0.962	0.207	121.6	418.7	853.7	1380.1	1.14	0.16
A5	0.792	0.962	0.202	138.9	481.9	980.5	1564.7	1.48	0.17
A6	0.803	0.962	0.204	149.7	521.4	1056.8	1669.1	1.69	0.18
B1	0.795	0.959	0.203	149.6	511.3	1052.6	1633.5	1.69	0.14
B2	0.800	0.959	0.204	144.9	500.6	1020.9	1636.2	1.60	0.19
B3	0.795	0.959	0.204	157.7	551.6	1121.1	1783.7	1.89	0.27
B4	0.798	0.962	0.203	159.7	558.9	1128.4	1804.8	1.94	0.27
B5	0.798	0.962	0.204	142.0	500.5	1026.6	1629.7	1.53	0.26
B6	0.805	0.962	0.206	155.4	542.3	1095.7	1749.6	1.85	0.21
M1	0.798	0.962	0.203	140.1	490.9	1012.3	1634.1	1.49	0.42
M2	0.792	0.962	0.200	145.2	510.8	1055.3	1671.9	1.59	0.33
M3	0.800	0.959	0.204	144.0	500.8	1024.2	1658.7	1.58	0.29
M4	0.808	0.959	0.206	157.1	558.2	1115.0	1792.0	1.90	0.29
M5	0.795	0.962	0.201	155.6	552.9	1108.8	1770.3	1.83	0.30
M6	0.805	0.959	0.205	146.6	506.7	1049.2	1658.5	1.65	0.20

collected data [10–12]. This technique is well documented in the literature and has a broad range of applications across many industries including sports equipment [13, 14]. The collection of data involves applying an input force at a given point on a structure and recording the vibration response at another point on the same structure to obtain a frequency response function that represents the response of the structure at one location to a force input at another location.

For the present study, each bat was suspended at the barrel and handle ends using rubber-bands. This provides some stability, so the bats won’t bounce around during testing, while allowing the bats to vibrate freely. In effect, on the short time scale of the input force,

141 the bats are essentially free, a boundary condition which has been shown to closely match
 142 the hand-held condition for baseball bats [15], cricket bats [16], and even tennis rackets [17].
 143 The input force was provided by a special impact hammer which has a force transducer in
 144 the head to measure the time history of the force impulse when the hammer impacts the
 145 bat. The vibration response of the bat was measured with a 0.5-gram accelerometer, which
 146 was attached to the barrel of the bat 2.5 cm (1 inch) from the tip, a location that allowed
 147 measurements of the first seven bending modes. A roving-hammer technique was used in
 148 which the bat is impacted at 2.5-cm (1-inch) intervals along the length of the bat, keeping the
 149 accelerometer fixed, thus collecting a measurement of both the force input and acceleration
 150 response for every pair of points along the length of the bat. Since batters generally orient
 151 the bat so that the ball strikes it on the edge grain for ash and on the face grain for birch
 152 and maple [18], those same orientations were used for both the modal analysis and the impact
 153 studies discussed in Sec. 3.2. The signals from the hammer and accelerometer were input to
 154 a 2-channel frequency analyzer, where they are transformed from the time to the frequency
 155 domain. By dividing the frequency response from the accelerometer by that of the hammer,
 156 the frequency response functions for each impact were obtained. Commercial software was
 157 used to post-process and curve-fit the frequency response functions to generate mode shapes
 158 and frequencies.

159 The frequencies of the lowest four bending modes are given in Table I, while the variation
 160 in the lowest frequency for the bats is shown in Fig. 2. It is remarkable that there is such a
 161 large variation, from 122 to 160 Hz, among these nominally identical bats, even within the
 162 same wood species, which is presumably due to the variation in the stiffness of the wood.
 163 Despite this large variation, the shapes of the lowest modes are essentially identical, as shown
 164 in the example of Fig. 3. This is a consequence of both the identical shape profile among
 165 the different bats and the uniformity of the mass density along the length of each bat. The
 166 nodes closest to the barrel tip for the lowest four bending modes are nearly identical among

the bats: 17.3, 13.5, 10.9, and 9.1 cm (6.8, 5.3, 4.3, and 3.6 inches) for modes 1, 2, 3, and 4,
 respectively, as measured from the barrel tip .

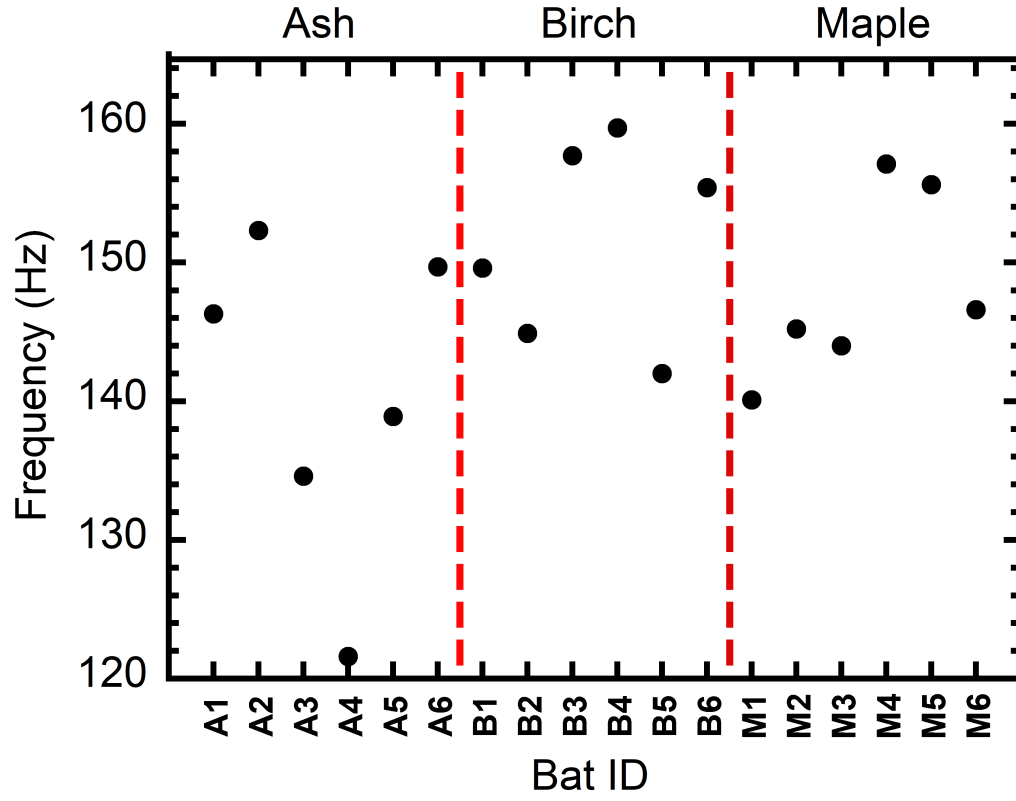


Fig. 2: Frequency of lowest bending mode, where the dashed line separates bats of different wood species. Note that on average, the birch and maple bats have similar frequencies whereas the ash bats have a bit lower frequency.

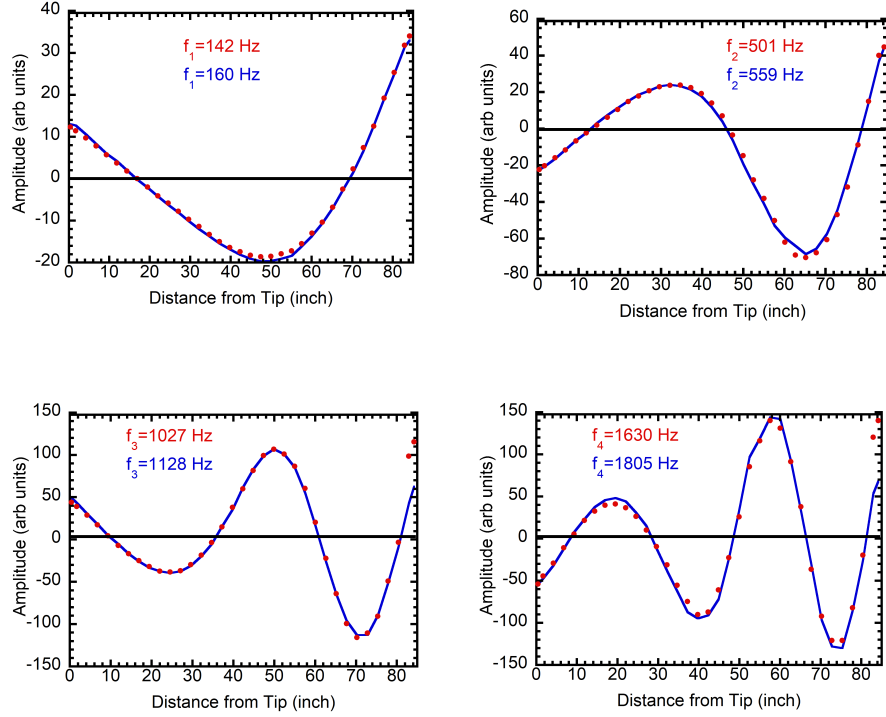


Fig. 3: Comparison of the lowest four bending modes between two birch bats with different bending frequencies, as indicated on the graphs. The red points and blue curves are the lower and higher frequency bats, respectively.

169 3.2 High-Speed Impact Studies

170 The technique for measuring the BBCOR of a bat in the laboratory has been described
 171 by Smith [4]. The measurements consist of firing a baseball from a high-speed air cannon
 172 onto a stationary bat. The bat is mounted horizontally and supported by clamping it at the
 173 handle to a structure that is free to pivot about a vertical axis located on the handle, 15.2
 174 cm (six inches) from the knob end. Three light screens located between the cannon and bat
 175 are used to measure the speed of the incoming and rebounding ball, v_i and v_f , respectively.
 176 Ideally v_i would be typical of professional game conditions, approximately 67-74 m/s (150-
 177 165 mph). However to prevent breakage, especially for impacts greater than 5 cm (2 inches)

178 from the sweet spot, it was necessary to lower the speed to 44.7 m/s (100 mph), independent
 179 of impact location. An initial test was performed on bat M1 at 61 m/s (136 mph) impact
 180 speed and the bat broke shortly into the testing at the impact locations away from the sweet
 181 spot. Because the purpose of the study focused on the performance at impact locations off
 182 the sweet spot, it was deemed better to use this lower impact velocity than to risk breakage
 183 of the bats.

184 The ball-bat impact location could be varied between 8.9 and 21.6 cm (3.5 and 8.5 inches)
 185 from the barrel tip. This range of impact location was largely guided by the simulations
 186 shown in Fig. 1, which indicate that the location most sensitive to differences in bending
 187 stiffness is a few inches farther from the tip than the sweet spot. For each bat, impacts were
 188 performed at a minimum of six locations along the barrel. First, impacts were performed
 189 15.2 cm (6.0 inches) from the barrel tip, which is close to the expected location of the sweet
 190 spot. Then, impacts were performed at 1.3-cm (0.5-in) intervals around the 15.2 cm point
 191 to isolate the sweet spot location. Finally, impacts were performed 5 cm (2 inches) on either
 192 side of the sweet spot.

193 From Eq. 1, the collision efficiency q for a baseball impacting an initially stationary bat
 194 is the ratio of outgoing to incoming ball speeds v_f/v_i . By rearranging Eqs. 2 and 3, the
 195 BBCOR e can be obtained from the measured quantities [3]

$$e = \frac{v_f}{v_i}(1 + r) + r, \quad (4)$$

196 where r is defined in Eq. 3. For each bat, the variation of e with impact location looks very
 197 similar to that shown in Fig. 1, with a peak near the 15-cm (6-inch) point and a falloff on
 198 either side. A sampling of the results for three representative bats spanning the range of f_1
 199 values is shown in Fig. 4.

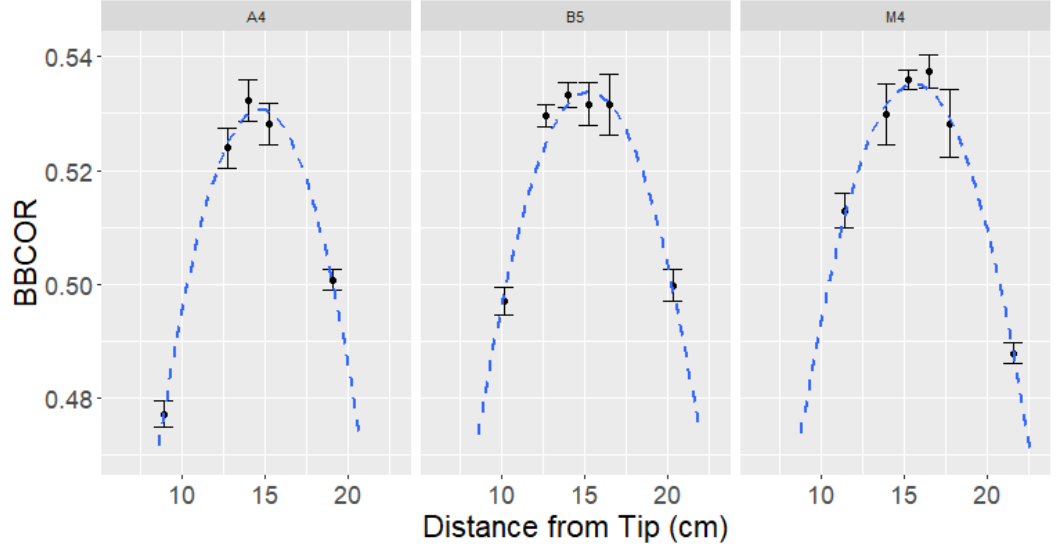


Fig. 4: BBCOR measurements from impacts of a 44.7 m/s (100 mph) baseball with bats A4, B5, and, M4, with f_1 values 122, 142, and 157 Hz, respectively. Each point represents the mean value of individual measurements at that location along with the standard error. The latter falls in the range 0.003-0.005, depending on the number of impacts at that location. The curves are parabolic fits to the data.

For each bat, the BBCOR data are fitted to a parabola, as shown for three of the bats in Fig. 4. The parameters of the parabola are then used to find the location of the peak BBCOR, which we identify as the sweet spot. Guided by the discussion in Sec. 2 and particularly Fig. 1, the parabolic fit was used to find the BBCOR value at the sweet spot and at a location 5 cm further from the tip than the sweet spot. These results are plotted versus the fundamental frequency f_1 in Fig. 5 along with a linear trendline.

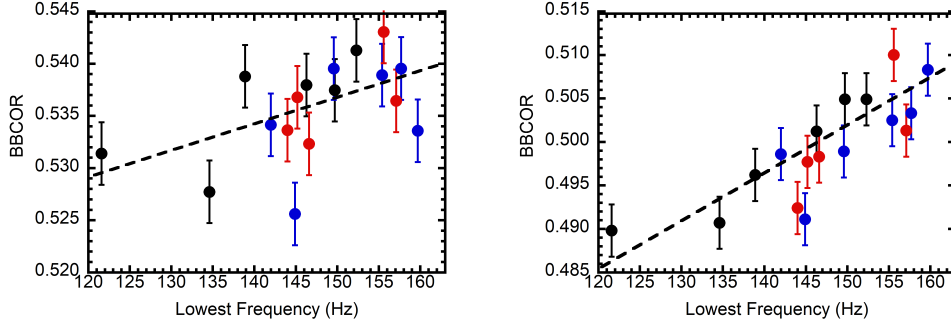


Fig. 5: Experimental results for BBCOR vs. the lowest bending frequency at the sweet spot (left) and two inches further from the tip than the sweet spot (right). The black, blue, and red points are for ash, birch, and maple, respectively. The line is a linear fit to each plot, with $R^2=0.27$ (left) and 0.66 (right).

4 Computer Simulations

The simulation of the baseball-bat collision uses the technique developed by Van Zandt [1], as modified by Nathan [2], and will be described briefly here. It is a two-part process. First, the Timoshenko beam equations for a free bat, as modified for the non-uniform shape profile of a bat, are utilized to find the frequencies and shapes of the bending modes for each bat. Since the shape profile of each bat and its inertial properties are known, the only unknowns are the Young's modulus (or "bending stiffness") E and the shear modulus S . The procedure used was to adjust E to reproduce the experimental value of the lowest bending frequency f_1 and to adjust S to reproduce the experimental value of the frequency of the fourth bending mode f_4 . The values of E and S for each bat determined from this procedure are given in Table I. A comparison of model to experiment for the lowest four bending modes is shown in Fig. 6 for the frequencies and Fig. 7 for the shapes. In both cases, the agreement is excellent.

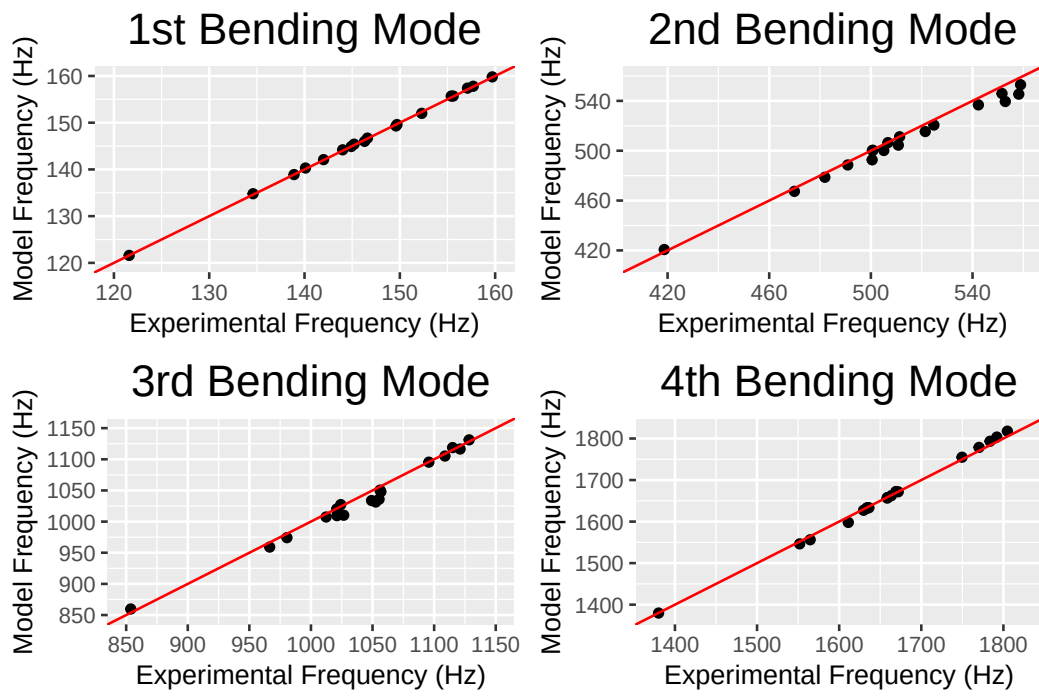


Fig. 6: Model-vs-Experimental bending mode frequencies.

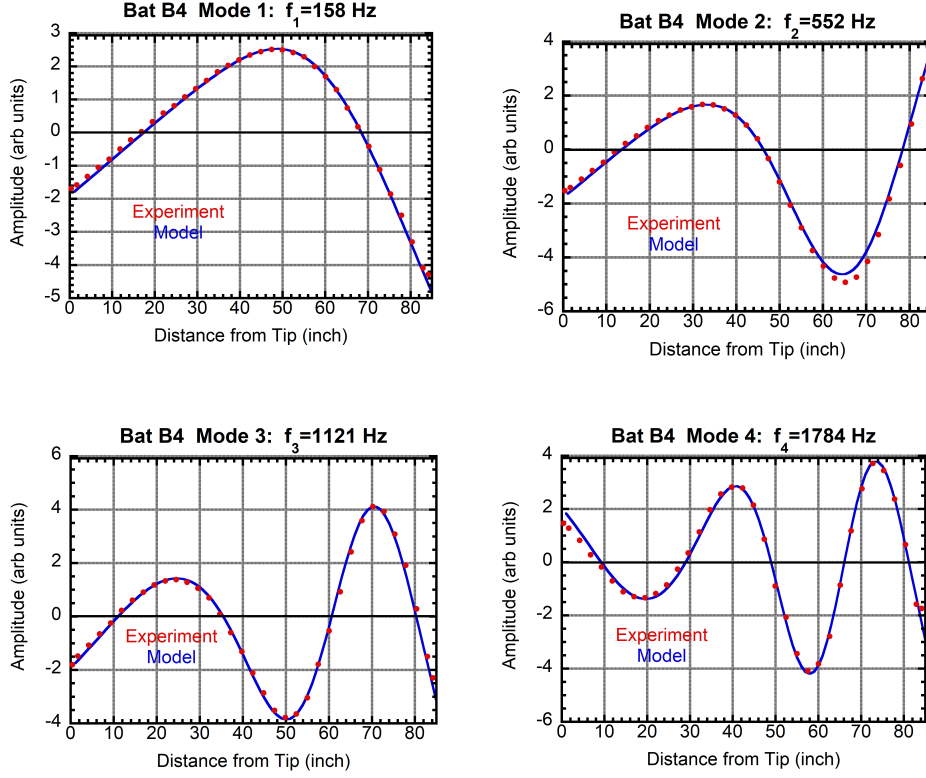


Fig. 7: Bending mode shapes, experimental (points) and model (curves) for bat B4.

Second, the ball is coupled to the bat via the force they mutually exert on each other. The ball is modeled as a lossy, non-linear spring, the properties of which are determined by the experimentally measured COR and dynamic stiffness of the ball [4]. These properties determine the ball-bat force. The motion of the bat is expanded in a complete set of normal modes for the free bat, including the two rigid-body modes (translation of and rotation about the center of mass), and the collision is tracked until the spring relaxes to its equilibrium position as the ball leaves the bat. The ratio of final to initial speed of the ball is thus determined, from which the BBCOR can be found via Eq. 4.

The simulation was performed by impacting a baseball at 44.7 m/s (100 mph) onto each of the bats at a range of locations along the barrel. Following the discussion in Sec. 2 and

228 especially Fig. 1, the resulting BBCOR values at the sweet spot and at 5 cm (2 inches)2
 229 further from the tip than the sweet spot are plotted versus the fundamental frequency f_1
 230 in Fig. 8. The general trend discussed earlier is confirmed by this more extensive set of
 231 calculations. Namely, the BBCOR of each bat increases with the bending stiffness of the bat,
 232 where f_1 is a surrogate for bending stiffness. While the BBCOR at the sweet spot changes
 233 by only 1.9% over the full range of frequencies, the change is much greater, 8.9%, two inches
 234 further from the tip than the sweet spot, in accordance with expectations based on Fig. 1.

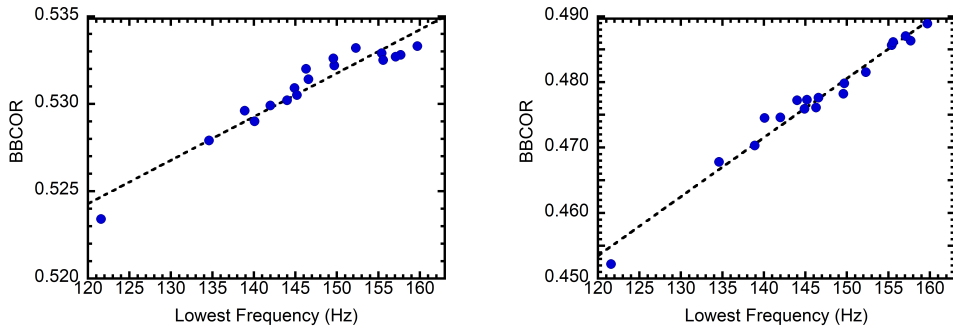


Fig. 8: Results from the bat-ball simulations of BBCOR vs. the lowest bending frequency at the sweet spot (left) and six cm (two inches) further from the tip than the sweet spot (right). The line is a linear fit to each plot. Note that the BBCOR axes are different from those in Fig. 5

235 5 Discussion

236 The data in Fig. 5 show that there are indeed differences in performance among these
 237 nominally identical bats. The differences are small at the sweet spot and larger at locations
 238 further from the barrel tip than the sweet spot. Moreover, the differences in the data are
 239 correlated, at least in part, with the bending stiffness of the bat, in qualitative agreement
 240 with the simulations shown in Fig. 8. At the sweet spot, the spread of BBCOR values is
 241 $\approx 2.1\%$, in excellent agreement with the simulations, albeit with considerable scatter about

the trendline. At six cm further from the tip than the sweet spot, the spread of BBCOR values is $\approx 4.9\%$, nearly a factor of two less than predicted by the simulation, albeit with less scatter than at the sweetspot. The reason for the disagreement between data and simulation is not presently understood. We conclude that, while the differences in BBCOR among the bats are due in part to differences in bending stiffness, there are other factors, as yet unknown, that also contribute.

It is instructive to ask why the differences in performance between bats with different bending stiffness primarily occur at impact locations further from the barrel tip than at the sweet spot. This question can be addressed by referring to Nathan, Sec. IID [2], in which it is shown that the energy dissipated in a vibrational mode is the product of two factors. One factor is proportional to the square of the vibrational amplitude at the impact location. As previously discussed (see Fig. 3), those amplitudes are essentially the same for each bat regardless of stiffness and therefore do not distinguish among the bats. The second factor, $g(\omega\tau)$, is given by

$$g(\omega\tau) \equiv \left| \int_0^\tau \mathcal{F}(t)e^{i\omega t} dt \right|^2, \quad (5)$$

where $\mathcal{F}(t)$ is the time-dependent ball-bat force normalized to unit impulse, $\omega=2\pi f$, and τ is the collision time. Given that g is the squared modulus of the Fourier transform of $\mathcal{F}(t)$, it has the property that it varies between 0 for $\omega\tau \gg 1$ and 1 for $\omega\tau \ll 1$. For the ball-bat force modeled in the simulation, where $\tau \approx 0.7$ ms, $g(\omega\tau)$ is plotted in the right panel of Fig. 9, along with the values of $\omega\tau$ appropriate for the lowest four modes of bats B4 and B5. It is $g(\omega\tau)$ that accounts for the performance difference between bats of different bending stiffness.

Looking at the left panel of Fig. 9, we see that the energy fractions in the lowest two bending modes are essentially identical for the two bats, independent of impact location, a reflection of the very small fractional difference in g for these two modes. Moreover, for impact locations closer to the tip than 15 cm (6 inches), the energy fraction for modes 3 and 4 are small due to the small vibrational amplitude at these locations (Fig. 3). As a result, the

total vibrational energy and therefore the BBCOR is the same for the two bats. However, for impact locations greater than 6 inches from the tip, not only is the vibrational amplitude greater for modes 3 and 4 (Fig. 3) but there is also a greater fractional difference in g for the two bats. As a result, there is more energy dissipated in modes 3 and 4 for B5 (lower f_1) than in B4 (higher f_1), leading to greater total vibrational energy and smaller BBCOR.

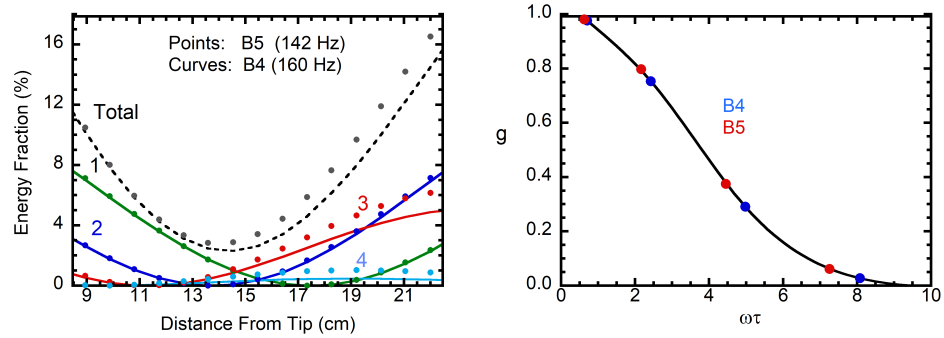


Fig. 9: Left: The fraction of initial energy deposited in the lowest four vibrational modes for bats B4 (curves) and B5 (points). The contributions of the individual modes and the total are indicated on the graph. Right: The squared Fourier transform of the ball-bat force, normalized to unit impulse, as a function of $\omega\tau$. The points represent values of $\omega\tau$ for the lowest 4 modes of bats B4 (blue) and B5 (red)

Finally we address whether there are systematic difference in performance among the three wood species studied. The results are presented in Table II and show that there are no systematic differences among the three species.

6 Conclusions

The high-speed impact studies have shown that wood bats that have the same shape and inertial properties do not necessarily perform alike. Differences among the bats are due to variation in the ball-bat coefficient of restitution, which in turn depends on the stiffness of the bats to bending vibration. At the sweet spot, both the data and simulations show that

Table 2: Average BBCOR for each wood species at the sweet spot (e_{max}) and at 5 cm (2 inches) further from the tip than the sweet spot (e_2)

Species	e_{max}	e_2
Ash	0.537 ± 0.001	0.501 ± 0.001
Birch	0.535 ± 0.001	0.499 ± 0.001
Maple	0.537 ± 0.001	0.504 ± 0.001

the dependence of BBCOR on stiffness is weak. However, at impact locations further from the tip than the sweet spot, bats that are stiffer (i.e., greater vibrational frequency) have a larger BBCOR than those that are less stiff. However, the data show less dependence on stiffness and more variation due to other unknown factors than the simulation. Finally, the data show no evidence for differences among the ash, birch, and maple that are not attributable to differences in bending stiffness.

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Declarations

Author Contributions. All authors contributed to the study conception and design. BC supervised the bat construction. DR performed the modal analysis. PD performed the high-speed measurements of BBCOR. AMN performed the simulations. All authors contributed to the final analysis and preparation of this document.

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Data Availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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