THE EFFECT OF EXPERIMENTAL ERROR ON BAT PERFORMANCE MEASUREMENTS

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The performance of baseball and softball bats has improved markedly over the past four decades. This has motivated many associations to develop test methods and measures to regulate bat performance. The bat performance test involves an initially stationary bat that is allowed to recoil after being impacted by a ball. The following considers the effect of experimental error on bat performance. The error was relatively small (less than 3%) but varied significantly among currently accepted measurement techniques and performance metrics.

1 Introduction

Technology has had a measurable impact on many sports improving player performance, endurance and safety. In the case of amateur baseball and softball modern bat design and materials have had a significant impact on the game. Non-metal bats are lighter and easier to swing than their wood predecessors. The benefit of lighter bats is particularly evident with young players. Learning the fundamentals of swinging is easier with a lower weight bat. Some are concerned, however, that hollow bats hit the ball faster than wood bats, changing the competitive balance of the game. Accordingly, nearly every baseball and softball regulating association controls bat performance in some way. In professional baseball the control is by material, where only solid wood bats are allowed. In softball and amateur baseball, bat performance is controlled through experimental testing.

2 The Ball

Bat performance is strongly dependent on the properties of the ball. The coefficient of restitution (*COR* or e) is a measure of the dissipated energy from impact. Ball *COR* is regulated using a standard test method which has been developed for baseballs and softballs (ASTM F1887). The test involves firing the ball at 60 mph (26.8 m/s) at a flat rigid wall. The *COR* is found from the ratio of the rebound, v_r, and inbound, v_i, speeds as

$$e_b = \frac{v_r}{v_i}. \quad (1)$$

Balls are also regulated by their stiffness. This is particularly true for softballs, which are made from a polyurethane core that can be formulated to provide a relatively wide range of COR and stiffness. The stiffness of baseballs and softballs is most commonly measured from a compressive force to displace the ball 0.25 inches (6.3 mm) between flat platens (ASTM F1888).

3 The Bat

Bats are marketed by their weight and length. The weight distribution and length of a bat affect its mass moment of inertia (*MOI* or *I*). Although the *MOI* of a bat affects its swing speed more than weight, it is not commonly used in bat selection among players. Bat *MOI* has a measurable effect on bat performance and is commonly found from the period of oscillation, *t*, about a point 6 inches (152 mm) from the knob as (ASTM F2398)

$$I = \frac{t^2 a W}{4\pi^2}, \tag{2}$$

where *a* is the distance from the pivot to the center of gravity, and *W* is the weight of the bat.

4 Bat Speed

Laboratory measures of bat performance are of limited value without comparisons to field performance. Surprisingly little data exist to compare laboratory and field measures of bat performance, however. While the motion of the bat during the swing is complex, only its speed just prior to contact with the ball is needed. (Shaft flex prior to impact and player grip during impact are negligible [Koenig, *et al*., 2004].) Since the bat-ball contact duration is short (~1ms) the bat's motion may be described by an instantaneous center of rotation over this period. Field studies have shown this instantaneous center to be close to the knob, near the batter's lower wrist (Crisco, *et al*., 2000, Smith, *et al*., 2003).

Bat speed decreases with increasing *MOI* and has a large effect on the batted-ball speed in play. Accordingly, an understanding of the effect of *MOI* on bat speed is needed. Unfortunately the dependence of bat speed on *MOI* is non-trivial. Empirical studies have shown bat speed, v_b, to depend on *MOI* according to

$$v_b = v_n \frac{q}{q_n}\left(\frac{I_n}{I}\right)^n, \tag{3}$$

where v_n and I_n are the nominal bat speed and *MOI*, respectively (Smith, *et al*., 2003, Cross and Bower, 2006). The impact location, *q*, is taken from the center of rotation and q_n is the location where v_b=v_n with I=I_n. The exponent *n* is approximately 0.25.

5 The Apparatus

A schematic of the bat test apparatus used herein is shown in Fig. 1. After the ball exits the air cannon, it passes through light screens which measure its inbound speed. The bat pivot is positioned along two axes to achieve the prescribed impact location along its length and a co-linear (line drive) rebound. From the conservation of angular momentum about the pivot we obtain

$$r(v_i - v_r) = V_r, \tag{4}$$

where V_r is the bat rebound speed at the impact location,

$$r = \frac{mq^2}{I}, \tag{5}$$

and m is the ball mass. Accordingly, the bat-ball test involves measuring five parameters: the ball mass, bat *MOI*, inbound and rebound ball speed and the recoiling bat speed. Ball mass and bat *MOI* are readily measured to a greater accuracy than ball or bat speed. Since angular momentum about the pivot point of the ball-bat system is conserved during the impact, two speeds are typically measured and Eq. (4) is used to determine the third. The preferred approach is to measure the rebound ball speed as it passes back through the light screens after impact. Since the ratio of the ball speeds is used to describe performance, error in the light screen spacing cancels. In some cases the rebound ball speed is too slow to pass through the light screens, necessitating a bat-speed measurement.

6 Bat Performance Metrics

The foregoing has described how a bat may be tested in a laboratory environment. Equally important is determining how the data from the test may be used to quantify and compare performance. This topic has been addressed in detail elsewhere (Nathan, 2003), and will be briefly reviewed here for completeness. The *COR* of a two impacting bodies is the ratio of their speed after impact to before impact. For a bat-ball impact this may be described as

$$e_{bb} = \frac{V_r - v_r}{v_i - V_i}, \tag{6}$$

where e_{bb} is the bat-ball *COR*, v and V are the ball and bat speeds at the impact location, respectively, and the subscripts i and r refer to inbound and rebound, respectively.

The speed of a ball hit by a bat in play, v_h, may be found from (Nathan, 2003)

$$v_h = e_a v_p + (1 + e_a) V_b, \tag{7}$$

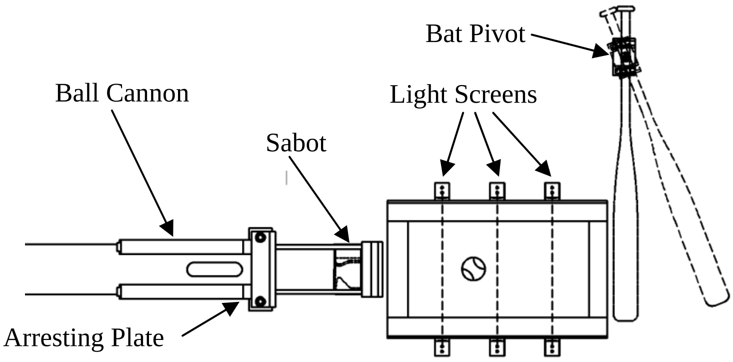

Fig. 1. Schematic of bat test apparatus.

where v_p and V_b are the pitch and bat speeds of interest on the field, respectively, and e_a is the so-called collision efficiency. The collision efficiency may be found from the bat-ball *COR* as

$$e_a = \frac{e_{bb} - r}{1 + r}. \tag{8}$$

More conveniently e_a may be found from the ball inbound and rebound speeds from an initially stationary laboratory bat test as

$$e_a = \frac{v_r}{v_i}. \tag{9}$$

The measures used to quantify bat performance (e_{bb}, v_h and e_a) may be distinguished by the effect of changing the bat's *MOI*. The bat-ball *COR* is independent of *MOI* for a given bat model (Adair, 2002), while e_a and v_h have a nonlinear dependence. Bat speed will increase with decreasing *MOI*. Consider a player who swings a high *MOI* bat and an otherwise identical bat with low *MOI*. It is not obvious if the angular momentum (and in turn v_h) of the low *MOI* bat will be higher due to a faster swing speed or lower due to its reduced *MOI*. The competition between swing speed and angular momentum has been considered in field studies (Smith, *et al*., 2003), where angular momentum had a slightly larger effect than swing speed. The effect of *MOI* on v_h is determined by the empirical exponent, n, in Eq. (3). Thus, to achieve higher v_h, a batter should select a high *MOI* bat. The ideal bat *MOI* is limited by the ability of a player to make contact with the ball.

The collision efficiency is related to the bat-ball *COR* through Eqs. (5) and (8) so that e_a increases as the bat *MOI* increases. Thus, two bats with the same collision efficiency will only have the same field performance if their *MOI* is also the same. In other words, if two bats have the same collision efficiency but differ in *MOI*, the bat with the lower *MOI* will have the higher field performance.

7 Effect of Measurement Error on Bat Performance

The following considers error in the five measured parameters used in Eq. (4). Accordingly, a representative error, with a normal distribution for each measure, was applied. The *COV* from redundant ball speed measurements were used for v_i and v_r (0.05% and 2%, respectively). The *COV* for ball mass, *MOI* and impact location (0.4%, 0.2%, and 0.15%, respectively) were taken from the calibrations of these measures.

The error in bat speed is primarily due to a non-integer number of oscillations and their magnitude over the period that the bat speed is measured. Bats impacted near their sweet spot typically have a vibrational amplitude less than 2°. Consider a bat with a swing speed of 2000 °/s, a vibrational amplitude of 2° and a frequency that varies from 120 to 200 Hz (a common range for bats). The slope of the oscillating bat at different frequencies provides an estimate of the bat speed error. For the range of frequencies considered the *COV* of the bat speed was 4%.

The performance (e_{bb}, e_a, and v_h) of a representative softball bat (I = 9500 oz in^2 = 0.174 kg m^2, v_i = 110 mph = 49 m/s, v_r = 18 mph = 8 m/s, m = 7 oz = 200 g, and q = 21 in = 533 mm) was computed. The performance was again computed by adding one standard deviation to each of the measures in Eq. (4). The percent change in performance for each measure is reported in Fig. 2 for the cases of measuring the ball rebound speed, the bat rebound speed and the ball and bat rebound speed. Error in ball weight was observed to have the smallest effect, while error in the rebound speed (ball or bat) had the largest effect. Of the three performance measures, e_a was the most sensitive to experimental error while v_h was the least sensitive. Measuring the bat rebound speed was most sensitive to error, while measuring the ball rebound speed was the least sensitive. Note that a positive error in the measurement can produce a positive or negative change in performance.

8 Summary

Significant effort and progress have been made in measuring the performance of baseball and softball bats. Bat performance found from the rebound ball speed was shown to be less sensitive to experimental error than from the bat rebound speed. Of the three commonly used bat performance measures, v_h was the least sensitive and e_a was the most sensitive to experimental error. In spite of the noted sensitivities to experimental error, bat performance measures have remarkable repeatability and reproducibility, which is generally within 1%.

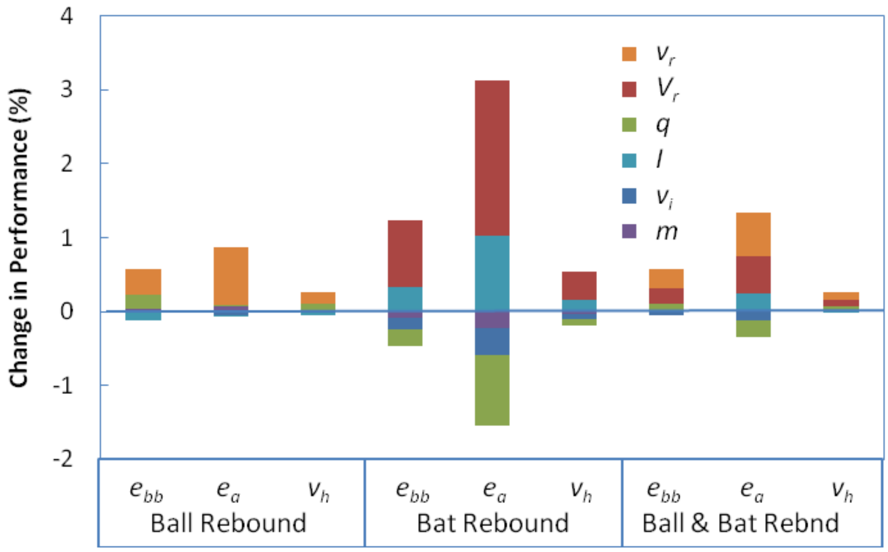

Fig. 2. The effect of test measurement error on bat performance (e_{bb}, e_a, v_h) for tests where either the ball rebound speed, bat rebound speed or ball and bat rebound speeds were measured.

9 References

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