Bending Modes, Damping, and the Sensation of Sting in Baseball Bats

Daniel A. Russell
Science and Mathematics Department, Kettering University, Flint, MI

Abstract. The painful sensation of sting in the top hand of a player holding a baseball or softball bat may be a deterrent to enjoying the game, especially for young players. Several mechanisms for reducing the vibration of bending modes have been implemented in youth baseball bats in order to reduce sting. One method of assessing the effectiveness of these mechanisms is to compare the damping rate they provide for the first two or three bending modes in a bat. Damping rates are compared for several wood, aluminum, composite, and two-piece construction baseball bats, in addition to several bats with special damping control mechanisms. Experimental evidence suggests that damping mechanisms which reduce the vibration of the second bending mode are preferred by players. A novel dynamic absorber in the knob is shown to effectively reduce the vibration of the second bending mode and minimize the painful sting felt in the top hand.

1 The Problem of Hand Sting

The problem of sting is often a deterrent to young players who are learning how to swing a baseball bat. When they do make contact with a pitched ball, young players often hit the ball in the taper region or at the very end of the barrel. The painful sting resulting from such poor impacts can be very frustrating, and can discourage young players from continuing on in the sport. The problem of sting is not limited to young players, however, and accomplished adult players will still occasionally hit the ball badly resulting in painful sting in the hands. Discussions with players reveal that impacts near the taper region in the bat often result in a sharp pain in the fleshy region between the thumb and forefinger of the top hand. This pain is significant enough to sometimes cause bruising, and can persist for several days afterwards. Aluminum bats tend to sting more than wood bats, and while the development of specially designed padded batting gloves and special thick rubber grips on the handles of aluminum bats has improved the sensation of feel somewhat, the problem of sting still remains.

Several means of reducing vibration have been implemented. Because the problem of hand sting is more pronounced at the youth level, many of vibration reduction mechanisms only appear in youth baseball bat models. These include inserting a dynamic absorber (tuned-mass-damper) in the taper region of the barrel, inserting an elastomer plug into the knob in the handle, a two-piece construction in which the handle and barrel are

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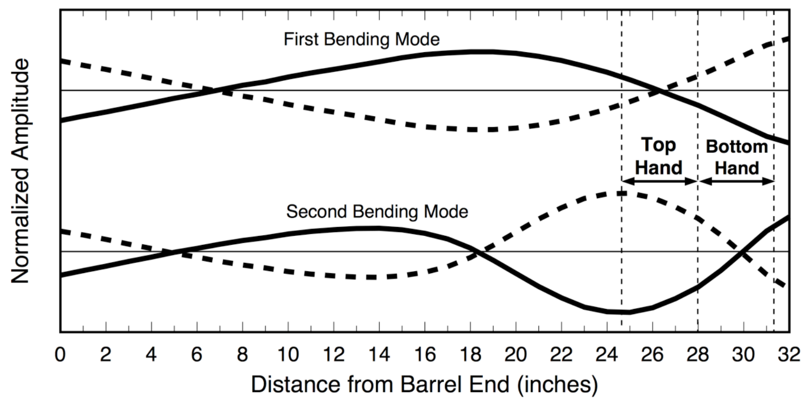

Fig. 1. Mode shapes for the first two bending vibrational modes in a 32-inch youth baseball bat. Barrel end is at the left and handle is at the right.

separate pieces connected by a rubber joint, and the injection of foam into the hollow handle.

2 Bending Modes and Hand Location

All baseball and softball bats exhibit a family of bending vibrations, similar to what one would find in a free-free beam, with nodes (locations of zero displacement) on the barrel and handle and antinodes (locations of maximum displacement) between nodes. Most of the research published on the issue of sting has focused either on the impact location relative to the nodes of the first two bending modes of vibration (Noble and Walker 1994; Cross 2001) or on the frequencies of the lowest two bending modes (Noble, Walker and Ponte 1996).

Figure 1 shows the mode shapes for the first two bending modes for a typical 32-inch youth baseball bat. The mode shapes were obtained by performing an experimental modal analysis measurement. Two features of this graph are relevant to the discussion of sting. First is the location of the nodes at the barrel end of the bat. The first bending mode has a node approximately 7-inches from the end of the barrel, and the second bending mode has a node approximately 5-inches from the barrel end. An impact at a node will prevent the corresponding mode shape from contributing to the resulting vibration of the bat. The region between 5-7 inches from the barrel end is often referred to as the "sweet zone" due to the fact that impacts within this region result in minimal vibration in the handle (Cross 1999; Cross 2001).

Of greater importance to the perception of sting is the location of the nodes and antinodes at the handle end of the bat. The bottom hand is centered on a node for the second bending mode and the fleshy part at the base of the bottom hand is at an antinode for the first bending mode. This would suggest that, if sting is the result of bending vibrations, the bottom hand should be more responsive to the first bending mode but not affected much by the vibration of the second bending mode. The top hand, meanwhile, is centered on a node for the first bending mode and the region between the thumb and forefinger of the top hand is located at an antinode for the second bending mode. This would suggest that the top hand is most responsive to vibration of the second bending mode, and less to the vibration of the first bending mode. Cross argued that the sting is the result of the impulse from the bat-ball collision traveling to the player's hands rather than the result of the bat vibrating in its various free modes of vibration (Cross 1998). However, he does point out that the impulse is indistinguishable from the vibration of the second bending mode.

3 Damping Rates for Bending Modes

It has been shown (Brody 1986) that the natural frequencies of a baseball bat are not significantly altered when the bat is gripped in the hands, thus allowing the hand-held bat to be modeled as a free-free bat (Nathan 2000). The hands do, however, add a huge amount of damping so that the natural vibrations of the bat decay very quickly. What is not known, however, is exactly how much damping the hands provide nor how much damping is inherently present in the bat itself. There are very little published data showing measured damping rates for the bending modes of baseball bats. The data that do exist suggest that damping rates for aluminum bats are roughly half those of wood bats (Collier 1992; Naruo and Sato 1998). There are no data available for composite bats, nor for youth bats with vibration reduction mechanisms. One of the aims of this paper is to provide some damping rate data.

The damping rate for a particular mode of vibration is one of the modal parameters (mode shapes, frequencies, and damping) that may be determined by curve fitting the frequency response functions (FRF) collected in a modal analysis experiment (Gade, Herlufsen and Konstantin-Hansen 2002). The analytical function used to perform the curve fitting assumes that the structure may be modeled as a 2^{nd} order time invariant system with an impulse response function of the form

$$h_{rs}(t) = \sum_{k=1}^{n} \left[\left| R_{rs}^{(k)} \right| e^{-\sigma_k t} \sin\left(2\pi f_k t + \phi_{rs}^{(k)} \right) \right] , \qquad (1)$$

where $h_{rs}(t)$ is the impulse response at location r due to an excitation at location s, and $R_{rs}^{(k)}$ is the residue (mode shape) at location r due to excitation at location s for mode k. Equation (1) indicates that the vibration resulting from an impulse is the superposition of sinusoidal oscillations, each at their own natural frequency f_k and exponential damping rate σ_k. The quantity of interest in the present analysis is the modal damping rate σ_k for the first two bending modes.

Most experimental modal analysis software packages report the modal damping in terms of a non-dimensional critical damping ratio ξ_k, usually expressed as a percentage. The critical damping ratio is related to the modal frequency and modal damping coefficient by (Formenti 1999)

$$\xi_k = \frac{\sigma_k}{\sqrt{\sigma_k^2 + (2\pi f_k)^2}} \quad . \qquad (2)$$

In our laboratory we extract the damping rate by suspending a baseball bat vertically from the knob using rubber bands. An accelerometer is attached to the knob, and the bat is impacted with a force hammer at the barrel end. The Frequency Response Function consisting of the ratio of acceleration/force is obtained using a two-channel FFT analyzer and curve fitted to extract the critical damping ratio ξ_k. The damping rate σ_k is determined from Eq.(2).

Damping rates for the first two bending modes of a sampling of youth baseball bats of varying construction are shown in Table 1. The data show that aluminum bats have very little inherent damping. Wood and composite bats have similar damping rates, both having damping rates that are approximately an order of magnitude greater than aluminum bats. The aluminum bats marked with '*' include a vibration reduction mechanism which significantly increases the damping of either the first and/or the second bending mode.

Table 1. Damping rates for wood, aluminum and composite youth baseball bats. Bats marked with '*' include a vibration reduction mechanism.

	First Bending Mode			Second Bending Mode		
Bat Type	Frequency f (Hz)	Damping Ratio ξ	Damping Rate σ (s^{-1})	Frequency f (Hz)	Damping Ratio ξ	Damping Rate σ (s^{-1})
wood – ash	187	3.368e-3	3.96	691	5.009e-3	21.7
wood – ash	212	3.916e-3	5.22	663	1.209e-3	50.4
wood – maple	175	6.713e-3	7.38	580	4.278e-3	15.6
Aluminum	229	4.654e-4	0.67	763	7.844e-4	3.8
Aluminum	190	8.428e-4	1.01	690	1.019e-3	4.4
Aluminum	201	1.326e-3	1.67	780	8.224e-4	4.0
Aluminum *	163	1.112e-2	11.39	559	2.092e-2	73.5
Aluminum *	211	1.757e-2	23.30	752	2.213e-3	10.5
Aluminum *	197	6.439e-2	79.87	697	2.309e-3	10.1
Composite	168	3.966e-3	4.19	615	3.593e-3	13.9
Composite	105	6.433e-3	4.24	405	5.702e-3	14.5
Composite	137	6.038e-3	5.20	529	6.837e-3	22.7

4 Evidence that Damping Reduces Sting

A preliminary correlation between damping and the perception of sting came from an opportunity to test three youth baseball bats for a manufacturer. Bat A was brand new (still in plastic wrapper) and served as a control while bats B and C had been modified in an attempt to reduce sting, and had each been hit by 70 players. The source providing the bats informed us that every single player preferred the same bat because it felt better, but we were not told which bat was preferred. We were asked to try to identify the preferred bat and explain why. Modal testing revealed that all three bats had nearly identical bending and hoop frequencies. The only difference between the bats was in the amount of damping for the first and second bending modes. This was immediately apparent by gripping the bat barrel lightly at the "sweet spot" and tapping the barrel. The vibration from bat C died out immediately while bat B and the control bat A rang for several seconds. Measured damping rates, shown in Table 2, show that the preferred bat (bat C) had roughly 6-8 times more damping for the first bending mode, and 20-30 times greater damping for the second bending mode.

Table 2. Damping rates for three identical youth baseball bats, with bat C being preferred unanimously by 70 different players.

	First Bending Mode		Second Bending Mode	
Bat	Frequency f (Hz)	Damping Rate σ (s^{-1})	Frequency f (Hz)	Damping Rate σ (s^{-1})
A	173	0.58	643	2.8
B	172	0.74	641	3.6
C	167	4.82	623	82.4

A second correlation between sting and the damping rate of the second bending mode is currently being investigated with the implementation of a novel dynamic absorber (Albin 2004) into the knob of aluminum baseball and softball bats. This vibration absorber may be tuned to reduce the vibration at a specific frequency by adjusting the mass of the plug and/or the stiffness of the rubber support. The knob with the absorber is larger than a normal bat handle knob, and the combined mass of the knob and absorber lowers the frequencies of the first two bending modes. Table 3 lists the damping rates for a 32-inch (81.3cm) youth senior league baseball bat without the damper and with the damper tuned to the first and second bending modes. When the vibration absorber is tuned to the frequency of either bending mode, the amount of damping for that mode is huge, while the damping rate for the other mode is not significantly altered.

Table 3. Damping rates for a baseball bat with and without a dynamic absorber in the knob that has been tuned to the first and second bending mode.

	First Bending Mode		Second Bending Mode	
Bat	Frequency f (Hz)	Damping Rate σ (s^{-1})	Frequency f (Hz)	Damping Rate σ (s^{-1})
No damper	162	1.75	582	3.3
With damper 1	146	124.6	547	8.5
With damper 2	142	1.52	573	182.0

Preliminary field tests, using bats with this absorber in the knob, indicate that the painful sting in the top hand resulting from an impact near the taper region of the bat can be greatly reduced by tuning the absorber to the second bending mode of vibration. In an attempt to further quantify the relative importance of the damping for the first and second bending modes, we have instrumented a bat, with the tunable absorber in the knob, with strain gauges on the handle in order to measure the force under the hands during and following an impact with a ball. Adjusting the tuning of the absorber allows variation of the damping rates of the first and second bending modes, to compare how either or both influence the perception of feel. This further study was still in progress at the time this paper was submitted.

As a final demonstration of how increased damping might improve the feel of a bat, Fig. 2 shows the frequency response curve of the vibration amplitude at the location of the top hand for the baseball bat in Table 3. The dashed curve is for the bat without the

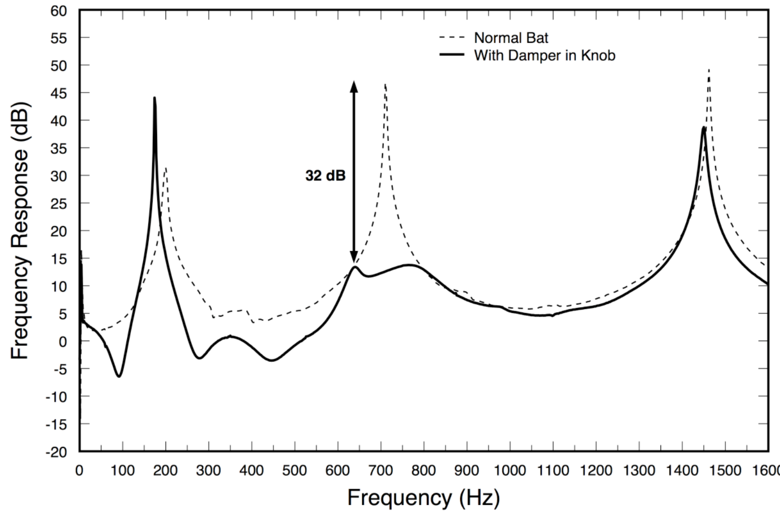

Fig. 2. Frequency response function for a baseball bat with a tuned-mass damper in the knob. Tuning the damper to the frequency of the second bending mode effectively removes that mode from the resulting vibration of the bat.

absorber, and the solid curve is for the bat with the damper inserted and tuned to the second bending mode. The dynamic absorber reduces the vibration amplitude of the second bending mode by approximately 32 dB, effectively removing this mode from the vibration of the bat following an impact with a ball away from the sweet spot.

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