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Flexural vibration and the perception of sting in hand-held sports implements

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In the sports of baseball, softball, and field hockey a player swings a bat or stick held in both hands to hit a relatively hard ball. Poorly hit impacts often result in painful sting in one or both hands. Experimental modal analysis is used to reveal the flexural mode shapes contributing to sting. This paper compares the flexural mode shapes responsible for causing sting in each sport, highlighting differences in hand positions between sports. Two-piece construction, material selection, and vibration absorbers have been used to reduce sting in metal and composite baseball and softball bats and in composite field hockey sticks. Damping rates for various bat and stick compositions will be compared. Recent success in the reduction of sting in bats and sticks using vibration absorbers will be discussed.

1 INTRODUCTION

When the impact between a ball and a baseball or softball bat occurs at the so-called "sweet spot" of the bat, the resulting vibration in the bat handle is minimized and the player holding the bat feels no painful sting. However, for impacts away from the sweet spot, the resulting vibration can result in significant pain in one or both hands, and repeated painful impacts have been known to result in prolonged discomfort and even bruising. Similar complaints regarding sting are reported by field hockey players, since impacts between ball and hockey stick almost always occur on the face of the head away from the "sweet spot" on the shaft.

The convention for describing hand positions in baseball and softball is that the bottom hand (called the "action" or "guiding" hand) is closest to the knob end of the bat while the top hand (called the "power hand") is closer to the barrel end of the bat. The opposite convention is used for field hockey sticks (and also golf clubs) where the reference to "top hand" and "bottom hand" (also known as leading and trailing hands) refers to the position of the hands when the stick is held in normal playing position with the head on the ground and the handle pointing up. To avoid the confusion between these two conventions, it is preferable to identify the *proximal* hand as being the hand in closest proximity to the knob end of the handle, and the *distal* hand is the hand farthest from the handle toward the barrel of the bat or the head of the stick. Figure 1 shows the

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profiles of a 34-inch baseball and softball bat and a 36-inch field hockey stick with the relative positions of the proximal and distal hands.

Studies of the threshold of sensitivity and the sensation of pain humans[1-2] have shown that the human hand is most sensitive to frequencies within the range of 200-400 Hz, with sensation becoming increasingly less sensitive to frequencies above 800 Hz. For an analysis of the role of flexural bending vibration on the perception of sting, our discussion of bending vibrations in bats and sticks will focus on mode shapes with natural frequencies below 1000 Hz.

2 FLEXURAL VIBRATION OF BASEBALL BATS AND HOCKEY STICKS

2.1 Experimental Modal Analysis

Mode shapes and frequencies of baseball bats and hockey sticks can easily be obtained through experimental modal analysis. The bat or stick is horizontally supported at each end by rubber bands, essentially providing a free-free boundary condition. When a bat or stick is held in the hands, the hands provide a significant amount of damping, but the natural frequencies of a hand-held bat are close enough to the free-free condition (as compared to a clamped-free boundary condition) that we may assume the free-free condition to be a valid predictor of actual behavior.[3] An impact hammer with force transducer in the tip is used to impact the bat or stick at 1-inch intervals along its length (in the case of a bat) or over its surface (in the case of a stick). The impulse response of the bat or stick is measured using a small 0.5gram unidirectional accelerometer. For this experiment, a fixed-response method was used, where the accelerometer remains attached at one location while the hammer location is varied. A dual channel FFT analyzer was used to record a Frequency Response Function (consisting of the ratio of acceleration response to force input) for each impact location. Post processing of FRF data was done with STAR Modal software to extract mode shapes and natural frequencies.

2.2 Bending Mode Shapes and Hand Positions for Baseball and Softball Bats

The natural frequencies of the bending modes of a baseball or softball bat depend on the length, weight, material properties, and specific profile of the bat. Table 1 lists typical frequency ranges for adult baseball bats, slow-pitch softball bats and youth baseball bats. For longer adult sized bats, the second bending modes have frequencies within the sensitive range, while for youth bats the first bending mode falls within the sensitive range. The frequencies of the third bending modes are above the range of hand sensitivity, so most of the effort toward reducing sting due to vibration in baseball and softball bats has focused on targeting the first and second bending modes.

Figure 2 shows the mode shapes for the first three bending modes of for typical 34-inch, adult sized wood baseball and softball bats. Mode shapes for aluminum and composite bats are very similar, though extreme variations in handle stiffness, shape profile, and weight distribution can cause locations of nodes and antinodes to shift perhaps as much as 0.5 inch in either direction. The batter's hand positions are also indicated in Fig. 2; the proximal hand (blue shaded region) is closest to the knob end of the handle, and the distal hand (red shaded region) is farthest from the knob end of the handle.

Also indicated on the plots in Fig. 2 is a 2-inch wide region in the barrel, surrounding the node location, within which impacts would produce only minimal vibration at the handle. The so-called "sweet spot" on the barrel is often taken to the region approximately 5-7 inches from the end of the barrel that includes the nodes of the first two bending modes, since impacts within this region result in minimal vibration at the handle.[4]

The important interpretation from Fig. 2 is the fact that the if bending vibrations are the cause of the pain resulting from impacts outside the sweet spot on a baseball bat, then it would appear that the second bending mode of vibration is primarily responsible for pain felt in the fleshy region between thumb and forefinger of the distal hand, since this location on the handle is near the antinode of the second bending mode but near a node for this first bending mode. Both the first and second bending modes have large vibration amplitudes at the knob end of the handle and could contribute to pain felt in the heel of the proximal hand. The third bending mode has a node at the distal hand farthest from the knob, and its frequencies tend to be above the range of sensitivity so it is less likely that the third bending mode contributes significantly to sting.

2.3 Bending Mode Shapes and Hand Positions for Field Hockey Sticks

Figure 3 shows the first three bending modes for a composite field hockey stick. There are also several torsional mode shapes, but for this paper we are primarily interested in mode shapes with significant transverse vibration amplitude in the handle. Hockey players usually hold and carry the stick with the proximal hand at the knob end. For guiding the ball, the proximal hand grips the handle end at the knob and the distal hand holds the stick somewhere further down the handle toward the head. However, when the stick is swung to strike the ball, the distal hand usually grips the handle adjacent to the proximal hand, similar to the two-hand grip used for baseball. The hand positions are indicated in Fig. 3. Impacts between stick and ball almost always occur at the face of the stick in the U-shaped curved portion of the head, rather than near the nodes of the bending modes. Thus, almost all impacts result in vibration at the handle.

Sting is usually felt most strongly in the proximal hand, especially in the heel but also in the fleshy webbing between thumb and forefinger. However some players also report discomfort in the knuckles and fingertips of the distal hand. Looking at the bending mode shapes for a typical hockey stick in Fig. 3, we see that the first bending mode could be responsible for the pain in both locations of the proximal hand, since the vibration amplitude is large over this entire region. However, the first bending mode has a node near the knuckles of the distal hand and so would probably not be responsible for discomfort at this location. The second bending mode has sizeable amplitude at both the knob end and at the location of the knuckles on the distal hand and could contribute to sting at both locations. The third bending mode has an antinode close to the knuckles of the distal hand, but the frequencies are higher than 800 Hz so we would expect these modes to contribute less to the problem of sting.

3 COMMERCIAL METHODS OF MINIMIZING STING IN BATS AND STICKS

3.1 Vibration Reduction in Baseball Bats

Attempts by manufacturers to reduce sting in baseball bats is not widespread; relatively few bat manufacturers have attempted to modify bat designs specifically reduce vibration and sting. Aluminum bats are always sold and used with a thick rubber grip covering the handle, and most players wear batting gloves to further reduce sting. However, there are a few notable examples of bat designs with damping mechanisms to reduce sting. In the early 1990's Easton implemented a Vibration Reduction System in some of their aluminum youth baseball bats.[5] This device consisted of a cantilever mass-spring system inserted into the taper region of the bat and it essentially acted as a tuned-mass vibration absorber tuned to the frequency of the first bending mode. This absorber effectively reduced the vibration of the first bending mode, but was discontinued because the additional absorber weight became undesirable as the trend in youth bats moved toward increasingly lower bat weights. From the mid 1990's to the present, several Louisville Slugger youth baseball bat models have incorporated a "Sting Stop" absorber in the knob of the bat. This device is a rubber mass-piece that fits inside the hollow knob, and effectively reduces the vibration of the first bending mode. For several years Easton and DeMarini have both made two-piece bats in which the handle and barrel are separate pieces joined together, with the handle often being made of relatively flexible composite material. Depending on the nature of the joint, and the material properties of the handle, this construction can reduce the sensation of sting in the hands.

In 1998, Worth introduced the ACX Copperhead baseball bat, which used a piezoelectric damper to convert vibrational energy into electrical energy which was then dissipated in an electrical circuit causing a red LED in the knob to glow.[6] The following year, the NCAA implemented new bat performance standards and Worth chose not to use this piezoelectric damper in subsequent models. However, this particular bat is interesting because of the location of the piezoceramic damper; it was positioned at the location of the antinode of the second bending mode on the handle, approximately 7-8 inches from the knob, right where the player's distal hand holds the handle. In fact, the reduction in vibration amplitude for the second bending mode is almost twice that of the first bending mode.[6]

The most recent attempt at minimizing sting in baseball bats was introduced in 2007 by Marucci Sports in their line of aluminum baseball and softball bats. The knob of these bats is completely redesigned to contain a dynamic absorber (patented as the Albin Harmonic Damper) consisting of a metal mass cylinder surrounded by a rubber spring.[7] The system is tuned to the frequency of the second bending mode and almost completely eliminates it from a measured impulse response. The damper also provides significant damping for the third bending mode, but leaves the first bending mode essentially untouched. Anecdotal feedback from players is very favorable for this bat model, with players expressing an ease at locating the sweet spot on the barrel but without feeling pain for poorly hit balls.

3.2 Vibration Absorbers for Field Hockey Sticks

The use of vibration absorbers to reduce sting is not as prevalent in the sport of field hockey, as many players still use solid wood sticks. Most manufacturers of hollow composite sticks do not implement any sort of damping mechanism to reduce sting. One exception is STX, who patented a vibration absorber for hollow composite sticks.[8] This vibration absorber is similar to that used for baseball bats in that it consists of a cylindrical metal plug surrounded by a rubber elastomer sheath, and acts essentially as a dynamic vibration absorber tuned to a frequency between that of the first and second bending modes.

4 COMPARISON OF DAMPING RATES FOR BATS AND STICKS

4.1 Measuring Damping Rates

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 obtained through experimental modal analysis.[9] The analytical function used to perform the curve fitting assumes that the structure may be modeled as a 2nd order time invariant system with an impulse response function of the form

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

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 of vibration.

Most experimental modal analysis software packages report the modal damping in terms of a non-dimensional critical damping ratio ζ_k, usually expressed as a percentage. The modal damping rate for a particular bending mode may be obtained from the critical damping ratio and the natural frequency[10]

$$\sigma_k = \sqrt{\frac{\left(2\pi f_k\right)^2 \zeta_k^2}{1-\zeta_k^2}} \quad (2)$$

Extracting model damping rates from modal analysis data is problematic in that the exponential window used to reduce leakage error adds an artificial damping that can be several orders of magnitude larger than the inherent damping in the structure under test. This can be avoided by measuring the frequency response function without using an exponential window, and using the cursor tools on the FFT analyzer to extract the critical damping ratio from the –3dB points on either side of the peaks in the frequency response spectra. To minimize the effect of damping from the supports, the bat or stick is hung vertically from the knob using rubber bands. An accelerometer is attached to the knob end, and the bat or stick is impacted with a force hammer at the barrel or head. 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 ζ_k. The damping rate σ_k is determined from Eq. (2).

4.2 Comparison of Damping Rates for Baseball Bats and Hockey Sticks

Table 2 compares damping ratios ζ and exponential damping rates σ for a variety of typical wood, aluminum and composite baseball bats. Typical aluminum bats tend to have damping rates approximately an order of magnitude lower than wood bats; this agrees with the perception among players that aluminum bats sting more than wood. Single-piece composite bats tend to have damping rates equivalent to wood bats.

The four aluminum bats marked with '*' include a vibration reduction mechanism which significantly increases the damping of either the first and/or the second bending mode. The piezoelectric electric circuit damper reduces the second bending mode more than the first, as would expected because it is located at the antinode of the second bending mode and the node of the first bending mode. The Vibration Reduction System formerly used by Easton in youth baseball bats and the Sting Stop used in Louisville Slugger youth baseball bats both target the first bending mode, significantly increasing the damping rate for the first bending mode while only minimally increasing the damping rate for the second bending mode. The bat with the Albin Harmonic Damper, demonstrates a huge amount of damping for the second bending mode. This is to be expected since this vibration absorber was tuned to the frequency of the second bending mode of vibration.

Table 3 compares damping ratios ζ and exponential damping rates σ for two composite field hockey sticks with and with vibration absorbers in the handle. The mass-loading of the absorber lowers the frequencies slightly. Absorber #1 is equally effective at increasing the damping for the second bending mode for both sticks A and C. However, the while the same absorber provided a huge increase in damping of the third bending mode of stick A it only slightly increased the damping for the third bending mode of stick C. This discrepancy is likely due to the absorber fitting snuggly in the handle of stick A, but not as snuggly in the handle of stick C. Absorber #2 was most effective at increasing the damping for the second mode of vibration of stick A, while absorber #3 was most effective at increasing the damping for the first mode of vibration of stick C. These results demonstrate that vibration absorbers tuned to different frequencies can be used to target specific bending modes. Field studies and player feedback may then be used to determine which absorber players prefer.

4.2 Effectiveness of Vibration Absorbers for Baseball Bats and Hockey Sticks

Figure 4 shows the frequency response function (the ratio of acceleration at the handle to a force at the barrel end) for a baseball bat with the Albin Harmonic Damper in the knob tuned to the second bending frequency. The plot clearly shows the reduction in vibration amplitude for the second bending mode while the amplitudes and frequencies of the first and third bending modes are not significantly altered.

Figure 5 shows the acceleration time signal measured at the handle end of a field hockey stick resulting from an impact at the face of the head. The time signal was filtered with a band-pass filter centered on the frequency of the second bending mode. The black signal is for the stick without any absorber, and the vibration slowly decays with time. The red trace is for the same stick with a vibration absorber tuned to the second bending frequency. The absorber clearly prevents the amplitude from reaching the same peak value as the normal stick and causes the amplitude to decay very quickly.

Both of these results clearly indicate an increase in damping that correlates to a reductionin the vibration in the bat or stick that is most likely responsible for sting.

5 CONCLUSIONS

For baseball bats, the second bending mode of vibration is suspected of playing the primary role in causing the sensation of sting since it has an antinode at the location of the fingers, and a frequency within the range where the hand is most sensitive. For field hockey sticks, the first and second bending modes may both contribute to sting, though the third bending mode may also influence the perception of feel. Vibration absorbers in the handle of a baseball bat or hockey stick can dramatically increase the damping rates associated with the bending mode to which the frequency of the absorber has been matched. Initial field testing and anecdotal feedback from players suggests that the use of dynamic absorber tuned to the right frequency can effectively minimize the problem of painful sting for poorly hit balls in both of the sports of baseball and field hockey.

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Table 1 – Typical frequencies for bending vibrations in baseball and softball bats.

Bat Type	First Bending (Hz)	Second Bending (Hz)	Third Bending (Hz)
Adult Baseball (33-inch)	90-175	350-630	850-1300
Slow-pitch Softball (34-inch)	100-220	450-750	900-1300
Youth Baseball (30-inch)	170-230	600-800	1050-1400

Table 2. Damping rates for the first two bending vibration modes of several wood, aluminum and composite baseball bats. Bats marked with '' include a vibration reduction mechanism.*

	First Bending Mode			Second Bending Mode		
Bat Type	Frequency *f* (Hz)	Damping Ratio ζ	Damping Rate σ (s^{-1})	Frequency *f* (Hz)	Damping Ratio ζ	Damping Rate σ (s^{-1})
wood – ash	187	3.368e-3	3.96	691	5.009e-3	21.7
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
Composite	137	6.038e-3	5.2	529	6.837e-3	22.7
Aluminum * *ACX Piezo*	184	1.630e-3	1.9	672	6.160e-3	**26.0**
Aluminum * *V.R.S.*	211	1.757e-2	**23.3**	752	2.213e-3	10.5
Aluminum * *Sting Stop*	197	6.439e-2	**79.9**	697	2.309e-3	10.1
Aluminum * *AHD*	170	1.510e-3	1.6	782	5.970e-2	**294.0**

Table 3. Damping rates for two models of composite field hockey sticks with and without a vibration absorber in the knob.

	First Bending Mode			Second Bending Mode			Third Bending Mode		
Stick	*f* (Hz)	ζ	σ (1/s)	*f* (Hz)	ζ	σ (1/s)	*f* (Hz)	ζ	σ (1/s)
A (no absorber)	146	2.32e-3	2.1	421	2.49e-3	6.6	824	2.95e-3	15.3
A (absorber #1)	136	5.80e-3	5.0	404	3.85e-2	**97.9**	826	6.36e-2	**330.6**
A (absorber #2)	136	1.80e-3	15.4	424	7.46e-2	**199.3**	826	1.42e-2	73.5
C (no absorber)	169	1.29e-3	1.4	463	1.34e-3	3.9	885	1.92e-3	10.7
C (absorber #1)	156	1.06e-2	10.4	472	3.58e-2	**106.1**	890	5.21e-3	29.2
C (absorber #3)	154	7.11e-2	**69.0**	468	1.25e-2	36.8	888	4.41e-3	24.6

Fig. 1 – Profiles and relative hand positions for a 34-inch baseball and softball bat (left) and a 36-inch field hockey stick (right).

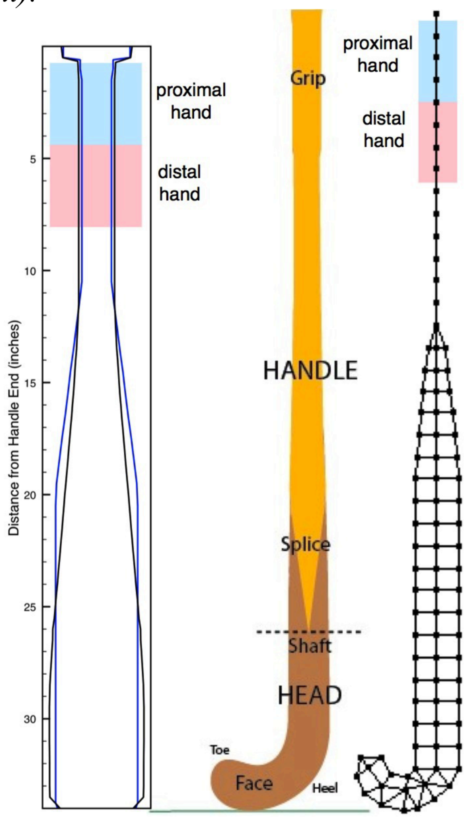

Fig. 2 – Mode shapes for the first three bending modes of a typical wood baseball and softball bat, showing hand locations.

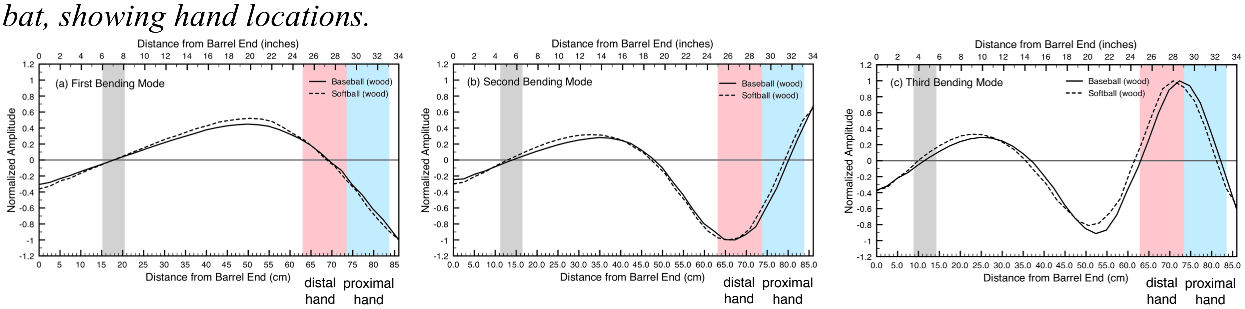

Fig. 3 – Mode shapes and frequencies for the first three bending modes of a typical composite field hockey stick, showing hand locations.

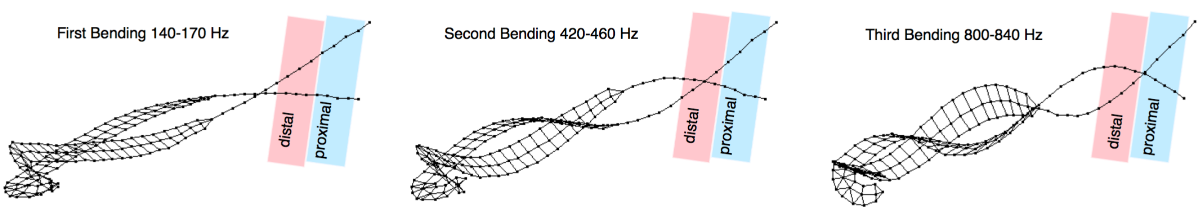

Fig. 4 – Frequency response function (force at barrel end, acceleration at knob of handle) for a 34-inch baseball bat with and without the Albin Harmonic Damper in the knob.

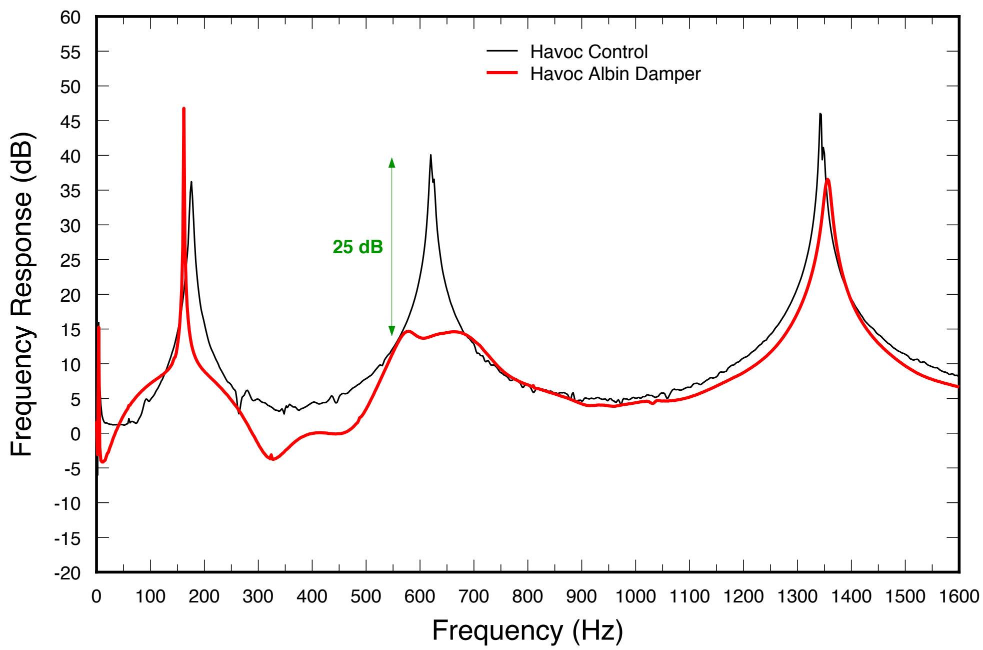

Fig. 5 – Time history of acceleration measured at knob end of a field hockey stick in response to impact at the face of the head, showing the effect of the vibration absorber.