Internal Friction in Bow Limbs

by Dick Baugh (1/10/08)

Introduction

The bow is a remarkably efficient mechanism for storing mechanical energy in about 1 pound (7000 grains) of wood and then efficiently transferring it into kinetic energy of an arrow weighing only 500 grains. All thanks to some stone age rocket scientists

A major challenge for self bowyers, those who enjoy making wood bows, is to maximize arrow speed. The "holy grail" of self bowyers is an arrow speed of 180 feet per second for a 50 pound bow with a 28 inch draw length, 6 inch brace height and a 500 grain arrow. Such a bow would have an arrow speed of 203.2 ft/sec if it were 100 per cent efficient and had a typical straight line force-draw characteristic According to Tim Baker, the best wooden straight-limbed bows today achieve a touch over 170 feet per second and that's with an extra quick draw and release. That's an efficiency of only 70 %.   Getting 180 ft/sec from this bow is equivalent to 78.5 per cent efficiency. Why is that so difficult? The stone age rocket scientists basically had a good idea but a bow has to do more than accelerate the arrow. It has to accelerate the bowstring and the bow limbs. Additional contributors to bow inefficiency are bowstring stretch and internal friction within the bow limbs. Let's examine internal friction, a major loss mechanism in bow limbs that has largely been overlooked because there was no convenient method for measuring it. The other sources of loss will be the subject of another article.

Bow limb internal friction

The fraction of the work involved in pulling a bowstring to full draw that is lost within the bow limbs and is not available to accelerate the arrow, bow limbs and string whatever the physical cause, is called hysterisis, internal friction or internal damping It is difficult to measure, partly because it is lost in a very small time interval The arrow is gone only about 0.025 seconds after the string is released. Internal friction manifests itself as a tiny increase in temperature of the bow limbs the same way that the friction of rubbing your hands together warms your hands. Don't waste your time trying to measure this temperature rise unless you have a thermometer that is sensitive to a hundredth of a degree, a temperature regulated shooting range and a lot of faith.

In *Archery-The Technical Side* Paul Klopsteg described an automated force-draw measuring system he used in 1945 to measure hysterisis in a laminated bamboo bow. It measured the draw force versus position as the bowstring was being pulled back and the force as the bowstring was being slowly returned to its brace height. It showed an energy loss of about 12% between the force-draw curve for increasing draw and decreasing draw. The measurement was not totally realistic because it used a movie camera to record the data and consequently the bow was let down slowly relative to the time taken to shoot an arrow. What is needed is a method of measuring internal friction on the same time scale used to shoot an arrow, around .023 seconds.

This article describes a dynamic method for measuring internal friction in materials used for bow limbs. It is dynamic because it tests the material under conditions that closely resemble actual arrow shooting. The percentage of energy loss due to internal friction should depend only on the nature of the material and not on the design or shape of the bow limbs. An advantage of this method is that you can do the test on a small sample of the bow limb material. You don't have to make a functioning bow to do the test.

Experiments have quantified the internal friction in test samples of red oak (Quercus spp), black locust (Robinia pseudoacacia), osage orange (Maclura spp) , yew (Taxus brevifolia) and laminated fiberglass/maple (Acerglassium laminarium).

The Experiment:

A small test sample is clamped rigidly to a heavy piece of plywood as shown schematically in Figure 1. The tip (distal end) is deflected downward a repeatable and measurable amount from its equilibrium position and released. It then is allowed to recoil If there is no internal friction then the sample will travel upward from its equilibrium position a distance equal to the initial downward deflection distance Anything less is due to internal friction in the material.

Recoil ratio = (Recoil distance)/(Initial tip downward deflection distance)

And

Internal friction = 1 - Recoil ratio

An accurate measure of the initial deflection and recoil distances must be made. This could all be done with a high speed video camera but I don't have one. Instead the height of recoil was monitored by a long thin probe constrained to move vertically above the tip of the sample. The probe is pushed up by the recoil of the sample In order to achieve an accurate measurement the probe must weigh very little and be only lightly constrained.

In order to initially deflect the sample exactly the same amount every time I use a string loop to hold the tip in position and a lanyard to release the sample. The details of the experimental setup are shown in Figure 2,.

In order to test the sample recoil in a time interval similar to that involved in shooting an arrow a weight is attached to the tip of the sample. The relationship between added weight and response time is described in the Appendices .

Caveat: The test sample must be rigidly clamped to a heavy board. Otherwise movement of the board will dampen the motion of the sample and incorrectly low values of Recoil ratio will be measured.

Discussion of the experimental data

One of the original suppositions was that internal friction would be somehow dependent on the speed of recovery. Fast recovery, characteristic of shooting a very light arrow, would cause more internal friction energy loss than the slower motion involved in shooting a heavy arrow. Consequently the data for red oak, not the best bow material in the woodpile, covers response time from less than .01 sec to .0456 sec, typical for shooting a glacially slow arrow at 80 feet/sec. Under all these conditions, for large deflections, the internal friction (1 - Recoil ratio) averaged about fifteen percent. Only when the deflection amplitude is very small, less than one inch, does the internal friction become less than ten percent. One of the big surprises from all the experiments was that internal friction energy loss didn't depend very much on speed.

The averages for "premium bow woods" were: osage orange, 9 %; yew, 8 % and black locust, 8 %. The experimental error in these experiments is probably + - 2 %. Again, there is some evidence for less internal friction at smaller strains

An additional experiment reinforced the assumption that there is less internal damping for very small amplitude deflection. A rectangular "marimba bar" with dimensions 9 in by 7/8 in by 1/2 in was made from the same sample of black locust used in the other tests. It was suspended loosely at a nodal point roughly 20 % from the end and lightly tapped with a pencil. The ringing sound it made was recorded and analyzed. The bar vibrated at 1185 Hz (cycles per second) and the amplitude decayed in half after .0291 seconds. This tells us that Recoil ratio, the amplitude after one half cycle, is 0.990, much higher than anything measured at the high strain levels experienced by a wood bow limb. The equivalent response time, equal to one quarter of a period, was only .0002 seconds. The fact that very low damping could be achieved at low strain levels and high vibration frequency tells us that the internal damping does not depend much on the frequency of vibration and that it is small for very small strain level or displacement..

The measured Recoil ratio of the laminated fiberglass/maple sample was in the range of 97-98%, barely measurable with this experimental apparatus. That means that internal friction is a very minor contributor to inefficiency in a laminated fiberglass/maple bow.

Conclusions:

A simple and unique method for evaluating the internal friction loss in bow materials has been presented. It is very convenient for testing because the bowyer does not have to make a finished bow to test the material. It works well with a sample of the material. This method for measuring internal friction in bow limbs can be used by any garage bowyer and it could have been done five hundred years ago because it uses no modern instrumentation. Implicit in the experiments is the assumption that the material characteristics governing rebound are exactly the same as those governing the initial deflection. This seems reasonable for wood and fiberglass-wood laminate but may not be a good method for composite bow limbs such as horn-wood-sinew or wood backed with sinew. An alternate method of measuring internal friction in these materials would be to make a bow, measure the area under its static force-draw curve and then shoot very heavy arrows through a chronograph. By shooting very heavy arrows the losses do to string mass, string stretch and limb vibration are greatly reduced.

The experimental data was taken for a single sample of each material. Results will certainly vary from one sample to another of the same species. Recently bowyers have observed that performance of a wood bow can be improved by "toasting" the wood on the belly. Does this process work by reducing the internal friction or is something else happening? The procedure described here would be a good way to find out. How the available energy (work used to draw the bow minus internal friction loss) is divided between arrow kinetic energy, limb vibration and bowstring vibration and stretch will be the subject of another article.

Note on the appendices: The appendices contain some of the mathematics and physics used to analyze the experimental data. You shouldn't need the appendices in order to understand the results.

Appendix A. The relationship between Recoil ratio and energy loss

Conveniently the fraction of the stored energy available for shooting an arrow is very closely equal to the Recoil ratio. If you put 50 foot pounds of work into drawing a bow and the limb material has a recoil ratio of 80 % then you have (1.0 - 0.8) * 50 = 10 foot pounds lost as internal friction in the limbs and 0.8 * 50 = 40 foot pounds of energy available to go into kinetic energy of the arrow, bowstring and bow limbs.

Why would the fraction of energy available be proportional to the Recoil ratio when the potential energy is actually proportional to the square of the Recoil ratio? The answer is that the Recoil ratio is a measure of the energy remaining after one half cycle whereas the energy available to shoot an arrow is that available after only one quarter cycle.

Appendix B. The relationship between the response time of the test sample with a weight added to the tip and the response time of a bow shooting an arrow.

The most meaningful test of internal friction is one in which the response time and strain in the test sample match those of an actual bow. In order to make the response time of the sample match that of a bow one must attach a weight to the tip of the sample so that its oscillation period is commensurate with the time required for a bow to go from full draw to release of the arrow. We know from chronograph measurements how fast typical arrows move and we know over what distance the bowstring accelerates the arrow. From those two pieces of information one can estimate the time.

T_accel = 2 * (Draw_length - Brace_height) / (Arrow_speed)

This simply says that as a rough guess the acceleration time is twice the distance the arrow travels in the bow divided by the speed.

For example, 28 inch (2.33 ft) draw length, 6 inch (0.5 ft) brace height and 160 feet per second arrow speed gives

T_accel = 2 * (2.33 - 0.5) / 160 = .0229 seconds.

We should attach a weight to the tip of the sample to obtain a response time compatible with that value. Appendix D describes the relationship between tip weight and response time. One of the revelations of the experimental work was that the internal friction didn't actually depend very much on the speed of response.

Appendix C: The Harmonic Oscillator

is just a mass connected to a spring. Move the mass away from its equilibrium position and let go. The mass bounces back and forth. If there is no internal friction in the spring and no damping due to air resistance then the mass bounces back and forth for ever and ever with the same amplitude. This mechanism describes the motion of so many things all the way from molecules to suspension bridges. The time required for one complete cycle of oscillation depends only on how stiff the spring is and how heavy the mass is.

$$Period = 2 \times \pi \times \sqrt{Mass \div Spring\_cons\tan t}$$

independent of how large the amplitude swing is. The Spring_constant, a measure of the stiffness of the spring, is equal to the applied force divided by the displacement caused by that force.

For an undamped harmonic oscillator the energy alternates back and forth between potential (stored in the spring) and kinetic (in the motion of the mass). The total energy (potential + kinetic) remains constant. What about damping? If there is air resistance, internal friction in the spring, immersion in molasses or anything else you can dream of that tends to damp the motion then amplitude of the back and forth motion will get smaller and smaller with time.

The harmonic oscillator is a very simple mechanical analog for a bow and arrow. The bow (spring) with an arrow (mass) attached is drawn (stretched) and the potential energy is transferred as kinetic energy of the arrow (mass). Ideally after one quarter cycle all the potential energy of the bow (spring) is transferred to kinetic energy of the arrow and it goes on its merry way.

Appendix D: Computing the oscillation period of the test sample with a weight attached to the tip.

Depending on the stiffness of the sample and how heavy the weight, gravity will deflect the tip downward by a certain amount after the weight is attached to the tip. If the weight added is small then deflection is small and the tip oscillates up and down rapidly. If the weight added is relatively large then deflection is large and the tip oscillates up and down more slowly. All we need to know in order to calculate the time taken for one period of the vibration is how far gravity acting on the added weight deflects the tip.

$$Period = 2 \times \pi \times \sqrt{y / g}$$

where g is the acceleration of gravity = 32.17 ft/sec^2 and y is the deflection distance. For example, a particular weight deflected the tip of the black locust sample by 0.14 inches = .0117 feet. Therefore

$$\mathit{Period} = 2 \times \pi \times \sqrt{.0117/(32.17)} = 0.1197 \sec \mathit{onds}$$

In order to simulate operation of a bow limb the test sample should have a weight attached that makes the period approximately equal to four times the time interval between release of the bowstring and the arrow leaving the bowstring (.0229 * 4 = .0892 seconds for the example described previously).

Appendix E: The raw data on Recoil ratio versus deflection and response time

The experiments showed that for the response times that are typical for shooting an arrow Recoil ratio was only weakly influenced by either amplitude or response time.

The red oak sample is 0.23 inches thick, tapers from 0.440 in to 0.270 in wide at the tip and is 15 in long.

Conditions, Red oak	**Response Time**	**Initial tip Deflection**	**Recoil**	**Recoil ratio**
No weight on tip	< 0.01 sec	3.31 in	2.69 in	0.813
Weight on tip Deflects 0.108 in	0263	0.740	0.682	0.926
Deflects 0.108 in	0263	1.855	1.608	0.867
Deflects 0.108 in	0263	2.679	2.24	0.836
Deflects 0.108 in	0263	2.782	2.195	0.789
Weight on tip Deflects 0.220 in	0.0375	3.07	2.63	0.856
Weight on tip Deflects 0.304 in	0441	0.500	0.440	0.880
Deflects 0.304 in	0441	1.607	1.395	0.868
Deflects 0.304 in	0441	2.608	2.193	0.841
Weight on tip Deflects 0.0.325 in	0.0456	1.687	1.442	856
Weight on tip Deflects 0.325 in	0.0456	2.94	2.51	0.854

The epoxy glass/maple lamination is 0.210 inches thick, tapers from 0.575 in to 0.225 in wide at the tip and is 16 inches long.

Conditions, Glass/maple	**Response Time**	**Initial tip Deflection**	**Recoil**	**Recoil ratio**

Weight on tip Deflects 0.145 in	0.0304 sec	2.73 in	2.635 in	0.965
Weight on tip Deflects 0.375 in	.0490	2.513	2.481	0.987

The black locust test sample is 0.30 inches thick, tapers from 0.675 in to 0.295 in wide at the tip and is 17 inches long.

Conditions, Black locust	**Response Time**	**Initial tip Deflection**	**Recoil**	**Recoil ratio**
Weight on tip Deflects 0.100 in	.0253 sec	2.685	2.475	9312
Weight on tip Deflects 0.115 in	0271	0.952	0.936	0.983
Deflects 0.115 in	0271	2.103	2.073	0.98
Deflects 0.115 in	0271	2.935	2.650	0.903
Weight on tip Deflects 0.178 in	.0337	2.64	2.525	956
Weight on tip Deflects 0.22 in	0375	2.880	2.530	0.879
Weight on tip Deflects 0.270 in	0415	2.550	2.350	9216

The osage orange test sample is 0.360 inches thick, tapers from 0.79 in to 0.31 in wide at the tip and is 14 inches long.

Conditions, Osage orange	**Response Time**	**Initial tip Deflection**	**Recoil**	**Recoil ratio**
Weight deflects 0.103 in	.0257 sec	2.650	2.420	0.913

The yew test sample is 0.220 inches thick, tapers from 0.835 in to 0.430 in wide at the tip and is 16 inches long.

Conditions, Yew	**Response Time**	**Initial tip Deflection**	**Recoil**	**Recoil ratio**
Weight deflects .095 in	.0246 sec	1.265	1.235	0.976
.095 in	.0246	2.44	2.243	0.919

.095 in	0246	3.408	3.165	0.929
Weight deflects 0.125 in	0283	3.720	3.335	0.0.895
0.125 in	0283	2.375	2.095	0.882
0.125 in	0283	1.395	1.315	0.943
Weight deflects 0.20 in	0358	2.306	2.235	0.969
0.20 in	.0358	3.327	3.107	0.934

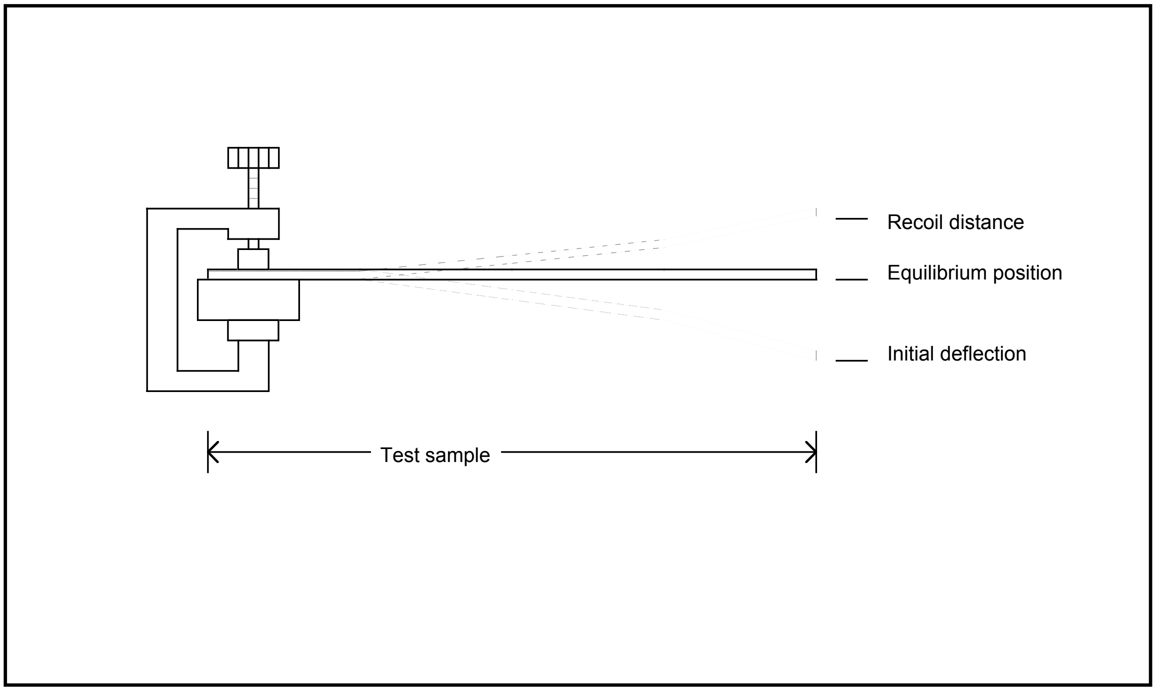

Figure 1. The test sample with one end clamped and the other end free to bounce up and down

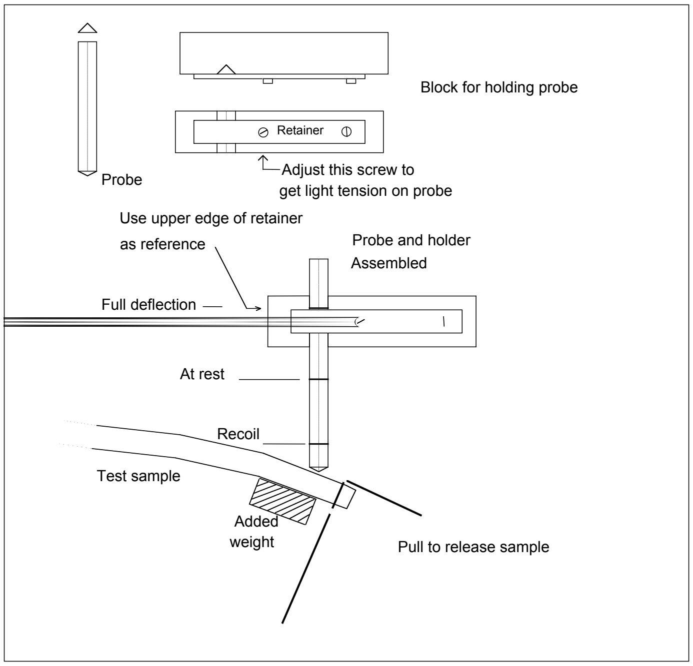

Figure 2. The experimental setup showing test sample with a weight attached to the end. The string is used to release the sample and the position sensing probe is pushed up by the tip of the test sample.

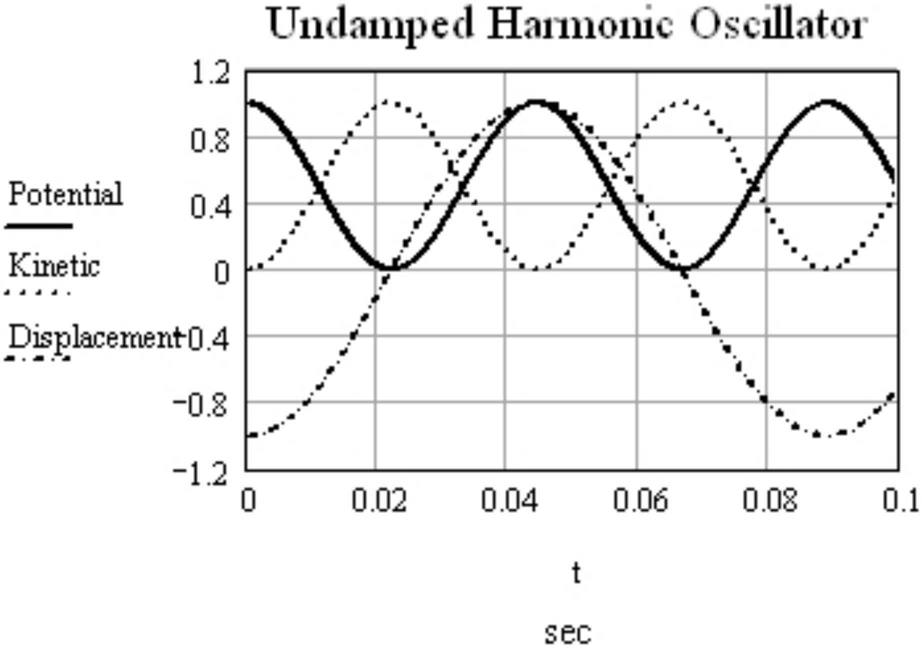

Figure 3. A plot of displacement (dot-dash), potential energy (solid) and kinetic energy

(dotted) for a harmonic oscillator.

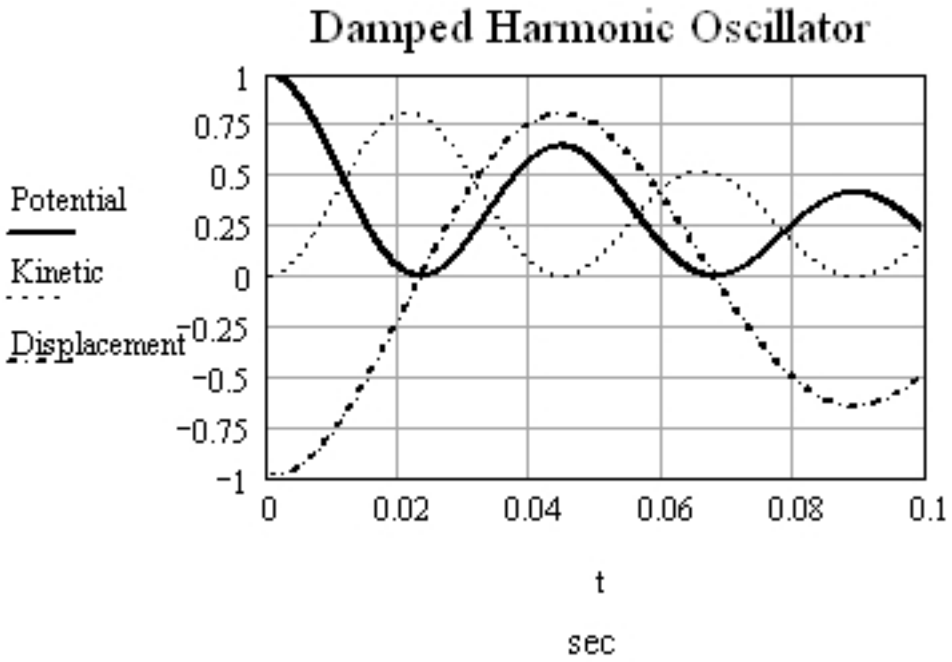

Figure 4. A plot of displacement (dot-dash), potential energy (solid) and kinetic energy (dotted) for a damped harmonic oscillator. The initial deflection is -1.0, rebounding up to +0.8, down to -0.64, etc.

E-mail your comments to "Richard A. Baugh" at oldfellah37@msn.com