Ruminations on harpsichord building
Part 2: Jacks

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Introduction

In this second essay of this series I will analyse an aspect of the design of jacks. Some time ago I saw part of a discussion on Facebook about the fact that tongues sometimes flip backward just before the quill actually plucks the string. By pressing down a key slowly, the jack comes up and the quill will lift the string. Continue to press the key down and there will be a moment when the string leaves the quill and produces the tone. Normally, the tongue will not rotate during this process but will only move backwards at the return to let the quill pass the string without sounding it. But in some cases the tongue starts to flip backward before the pluck occurs. In this chapter of the Ruminations we will try to determine the conditions that will lead to this behaviour.

This is not to be confused with the tongue flipping backward just after the pluck (with the jack still going up). While this might also happen, the reasons for it are entirely different. Maybe I will address that question in one of the future Ruminations.

In Part 1 we became familiar with Newton's laws and how to apply them. Here we will use them again, and here too we will only be analysing situations where nothing is moving (yet) so that we don't need Newton's second law. However, for the problem at hand, we will have to extend our scientific toolkit a little bit.

Some more physics

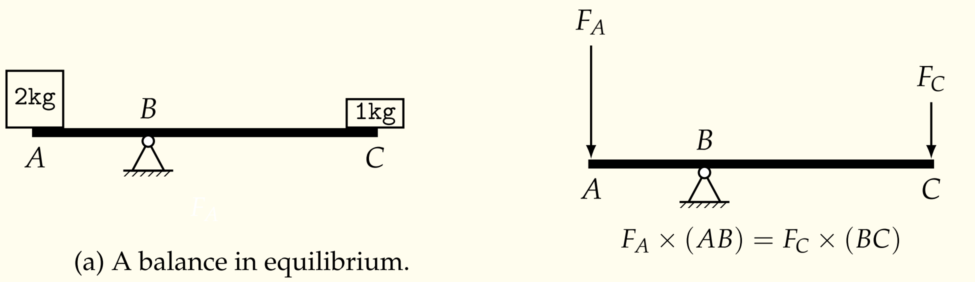
When discussing the forces on the hitch-pins in part 1, I wrote that the hitch-pin would want to topple over due to the force that the string exerts on the top of it. I left it at that without further explanations, but as it turns out, this concept of "toppling over" has been formalised in science.

Newton formulated his laws of motion in order to be able to explain the motions of the planets. The planets can be seen as very small points that interact with each other and it is not necessary to take their actual sizes as objects into consideration[1]. But

[1]To get an idea: if the earth were the size of a (European) football, about 22cm, the moon would be

when dealing with objects here on Earth we normally need to take into account their extensions in space. The problem is that most of the time the forces that act upon an object do not act on the same point of the object. In such a case an object may, apart from accelerating as a whole, start to rotate.

Consider the balance in Figure 1a. It rests on a support at point B and at both ends there are weights. If the weight at A is 2kg, the weight at C 1kg, and $A - B$ is half the length of $B - C$, nothing will move because all the forces are balanced out. We then say that the system is in a state of equilibrium. But if I place a little bit of extra weight at A, the balance will start to fall at A and rise at C, rotating around B.



(a) A balance in equilibrium.

(b) Moments of force in equilibrium.

Figure 1: Example of a lever system.

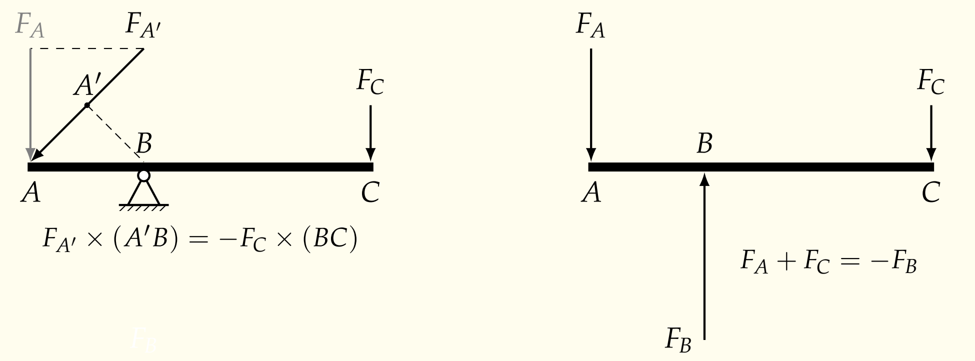
To describe this phenomenon mathematically and physically, we need the concept of the moment of a force. In Newton's laws the forces are just pushing or pulling on objects as a whole. A moment of a force gives a twist to objects and is calculated by multiplying the force with the distance to the pivot point.

Figure 1b illustrates how this works for the balance. I have left out the weights and instead show the forces F_A and F_C on the balance that result from them. If the moments of force are in equilibrium the balance will not rotate around B. For that to be true, F_A times the distance AB will have to equal F_C times the distance BC.

But we must define a bit better how one multiplies the force by its distance to the pivot point. After all, the force not only has a magnitude but also a direction. In the example of the balance, the forces were conveniently perpendicular to the lever of the balance, but what if there are forces that are not perpendicular? The rule is that you have to multiply the force by the distance from the pivot point perpendicular to the line in which the force is working. In Figure 2a I have drawn a force $F_{A'}$ at an angle. For the lever to be in equilibrium again this force needs to be bigger than F_A, because now we have to multiply $F_{A'}$ with the shorter distance $A'B$.

As an aside, we could equally well have decomposed the force into its components,

about the size of a tennis ball, 6cm, and at 13m distance. And for the case of spherical objects it can even be shown that one can just as well assume that all mass is concentrated in its centre.



(a) Moment from an oblique force. (b) Force equilibrium of the lever.

Figure 2: More on the lever system.

multiplied them with their respective distances and added them together again. The vertical component would have been F_A and the horizontal component (not shown in the diagram) would have acted along the line of the lever. That component would therefore have gone exactly through the pivot point, giving zero distance between the line of force and the pivot point, thus not contributing to the sum of the momentum of forces. Whether we decompose a force or not, that is just a matter of looking at the same reality from a different viewpoint. As long as we take all the forces and their components into account, we will end up with the same result.

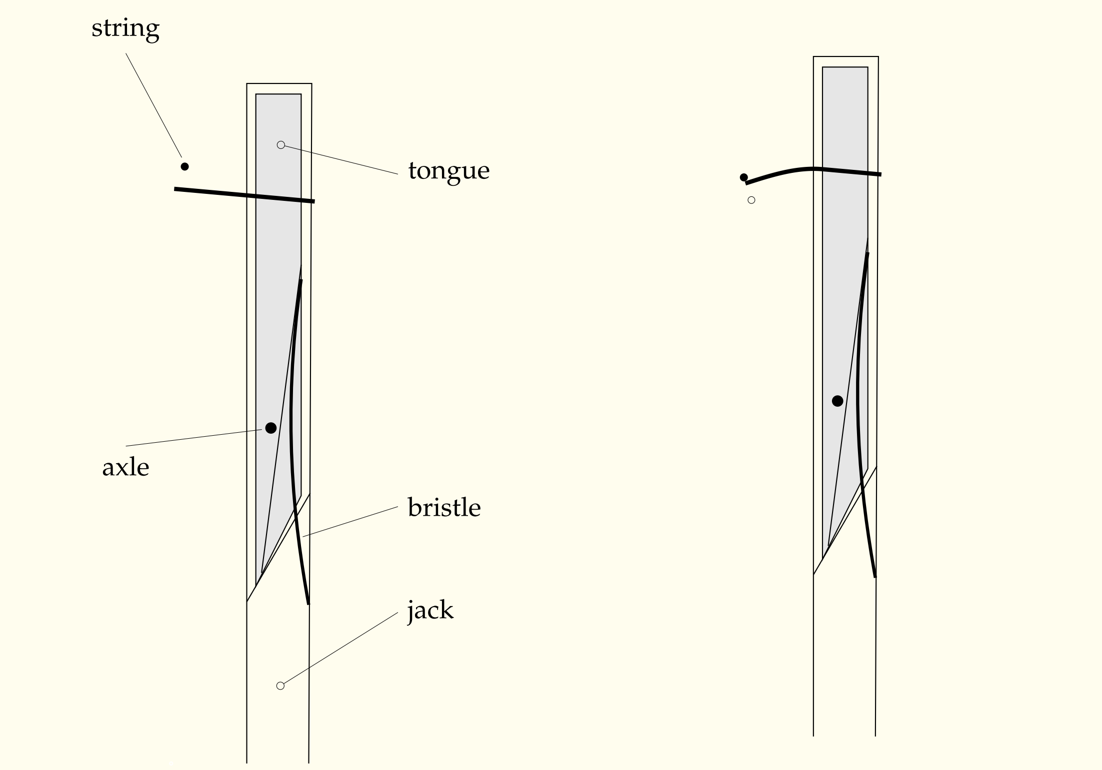
Note that the equilibrium of the moments of force is independent of the equilibrium of Newton's laws. It is not a theory that refutes them or that supersedes them. It is an addition that takes care of the rotation of objects around themselves. For the example above, the equilibrium of forces is obtained independently because the point at B will counter both the forces at A and C (Figure 2b). F_B runs exactly through the pivot point yielding zero distance to it, thus not adding to the moment of force.

Before we move on to our jack design, one last remark. The pivot point in our calculations doesn't need to be an actual physical axle or rotation point but can be at any point along the arm of the balance[2]. For example, if we take C in Figure 2b as the "pivot" point, we will also find that $F_A \times (AC) = -F_B \times (BC)$. But in general it will be most convenient to choose the physical pivot point.

[2] It can even be any arbitrary point in the plane in which the object rotates, but we will not go into that here.

Jack design

We can now turn to our problem of the backward flipping tongue. In Figure 3a I have drawn the cross section of a jack, in this case a fairly accurate representation of an 8′ jack from the 1782 Taskin harpsichord. I have not drawn the damper and other details such as chamfers as they are not necessary for our analysis.



(a) At rest.

(b) The moment just before plucking.

Figure 3: Cross sections of a jack by Pascal Taskin, 1782, scale 2:1.

Let's see now what will happen to the jack if we slowly press down the key on which it rests. It will move up vertically and nothing else happens until the quill touches the string. From that moment on, the quill will push the string up and conversely, the string will push the quill down (Newton's Third law). If we continue to move the key down, the string will be displaced upwards more and more and the quill will bend increasingly downwards. In Figure 3b I have illustrated the situation just before the string leaves the quill. The little open circle below the quill marks the original position of the string, the black dot at the tip the actual position.

Looking at the diagram you may wonder if I just drew some fancy curve for the quill that looked nice, but it is in fact a typical bend that a quill would make if it were equal in thickness and width from the front of the tongue to its tip. It was Leonard Euler[3] who derived the formulas for how beams bend under loads (a quill can be seen as a tiny beam) but for the current analysis we don't need more details. Also, the quill will probably not be of equal thickness and width over its length but will taper. We will look further at Euler's findings in the following chapter of these Ruminations.

To keep everything realistic I have given a displacement of the string just before the pluck of 1.5mm, which in my experience is about the displacement of middle C with a moderate voicing[4].

We will now analyse the various moments of force that are acting upon the tongue. In Figure 4a I have drawn all the forces but I left out the actual position of the string so that the drawing doesn't get crowded.

First we have the force of the string that acts upon the quill, F_S. The string, pushed up by the quill, will tend to return to its original position. So the force that the string exerts on the quill is going from the new position in the direction of the original position. To calculate its contribution to the equilibrium of the moments of force we have to multiply the string force by the distance between the line of force and the pivot point, to give $F_S \times (AS')$.

In this analysis I will for the moment assume that there is no friction between the quill and the string. This simplifies things a bit because we then know that the force F_S only has a component perpendicular to the quill and not in the direction along the surface. I will address friction forces in a later chapter but for now we will continue with the assumption that the quill and string slide perfectly over each other. We therefore know that the string is not only displaced vertically, but also a bit laterally, because the line of F_S will have to be perpendicular to the quill surface. With the quill bending the way it does it will therefore also push the string a bit sideways[5].

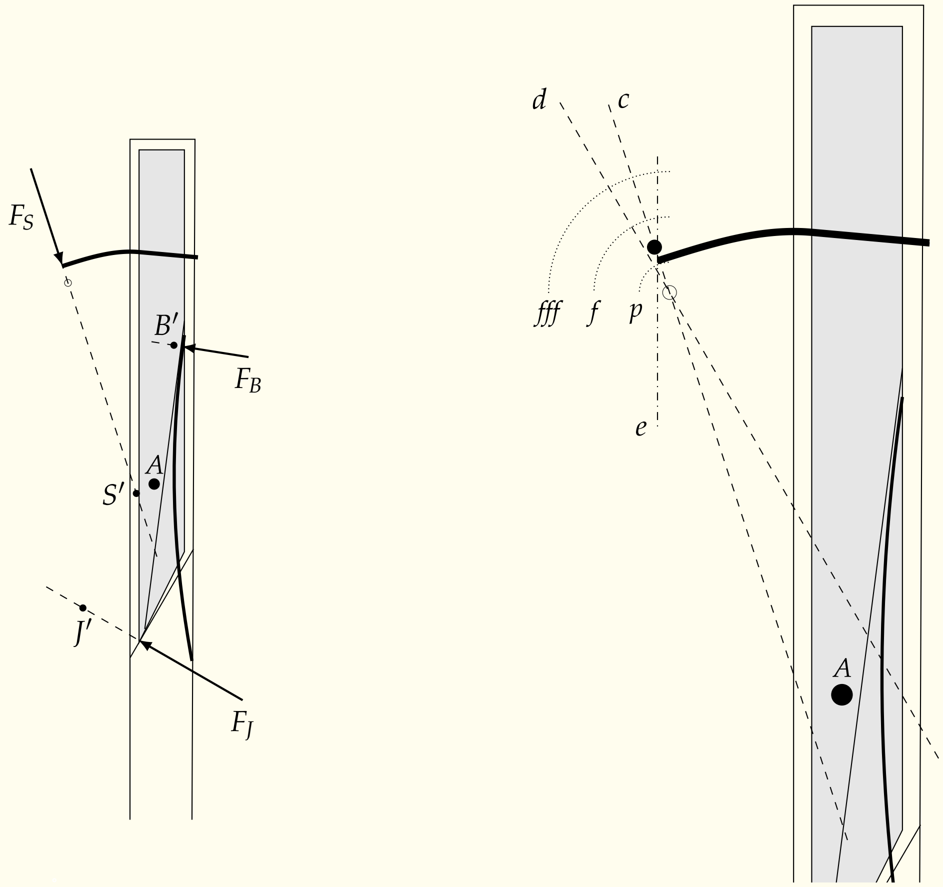
Next we have the force from the bristle, F_B. Its contribution to the moments of forces will be $F_B \times (B'A)$. Notice that both F_S and F_B will make the tongue pivot counter clock-wise though in reality the tongue sits still because its bottom is held in place by the slope of the groove in the jack. The jack pushes the tongue to produce an opposite moment, $F_J \times (J'A)$.

Now that we know which forces contribute to the equilibrium of moments of force, we can see when our tongue wants to flip back. For this to happen, the sum of the moments of force would have to act in a clock-wise direction. As noted before, the jack pushes the tongue in a clock-wise direction, but this is only because the other moments of force work counter clock-wise. As soon as the tongue starts pivoting backwards, contact between the jack and the tongue is lost, and F_J will be zero.

[3] Leonard Euler, 15 April 1707 – 18 September 1783 was a Swiss mathematician, physicist, astronomer, logician and engineer.

[4] The amount of string displacement for a certain voicing strength depends also on the string thickness, I normally use 0.27 or 0.30mm for iron strung instruments.

[5] The reader can easily verify this by trying on a real instrument.



(a) Moments of forces acting upon the tongue.

(b) Analysis of the release positions of the string. See the text for an explanation.

Figure 4: Tongue and quill just before the string releases, moments of forces and escape positions.

We are now only left with F_S and F_B. How can these forces result in a clock-wise direction of the moment? To give an answer to this question we will look at Figure 4b where I have zoomed in on the quill and string and left out the forces. I have also drawn a number of lines and arcs that will help us in our quest. This all looks all very confusing, but we will examine the ingredients one by one and everything will become clear.

Let's start with the dotted arcs. These are quarters of circles around the original string position, each arc thus indicating a constant distance to the original string position. I will assume that the strength of the voicing is determined by the total distance of the displacement of the string away from its original position. After all, this determines the amplitude of the swinging string after being released (I will say more on this topic in a later part of the Ruminations). So all the points on the same arc will therefore have the same voicing strength. So the arc p corresponds to soft voicing, f to strong voicing and fff to really very strong voicing.

Then there is a dotted-dashed vertical line labelled e at the tip of the quill. This line indicates the release points of the string for the various voicing strengths at the same distances to the tongue (e stands for equidistant). So if I make a quill of the same length but strong enough for, say, an f voicing, the string will release at the intersect of e and f (assuming of course, that the tongue doesn't pivot before).

Finally, we have the dashed lines c and d. We have seen that c represents the direction in which the force of the string is pointing at the moment of release. The line d represents the line of force that would result if the string were pushed further sideways before it is released. Remember that the line of force from the string always passes through the original string position, so a release point further left from the original string position will result in a force line that is more inclined with respect to the vertical. So c is the line of force from the string for a release point closer to the tongue, and d for a release point more distant from the tongue, whilst everything else remains the same.

Now that we understand the ingredients of Figure 4b, I will return to the question we have to answer: how can these forces result in a clock-wise direction of the moment? The answer is simple: if the line of force gets to the right hand side of the axle, it starts to act clock-wise. Then the only moment of force that acts in an anti clock-wise direction comes from the force of the bristle. Although the distance between its line of action and the axle is larger, that force is very weak, so the resulting moment will be limited[6]. So as soon as the line of force passes to the other side of A, we are in danger.

The reader has probably noticed already that this is the case for line d. This line would result if you make a quill that passes further under the string, but with the same resulting strength for the voicing. If the length of the quill passing under the string is longer, it has to bend further before it slips past the right side of the string. As the quill has to bend further, its surface will be more inclined with respect to the horizontal. The string will have a force perpendicular to the quill surface (remember we assume no friction) in a line passing through the original string position and the string force will be closer to the horizontal. The line along which the force acts can even rotate enough to pass to the other side of the axle. This means that the longer the quill is (while maintaining the same distance between jack and string in rest position), the more chances there are of the tongue flipping backward at or before the pluck. To verify this, you can do a little experiment. Put a quill in a jack somewhere at the highest note range (these strings are displaced very little when plucked) and leave it very long, passing for example some 2mm under the string. If you voice it to more or less the right strength, the tongue will almost certainly flip backwards.

[6] I will make an estimate of the magnitude of various forces in a following part of the Ruminations.

There is another way to get the line of the string force at the moment of release on the wrong side of the axle. If I place the jack closer to the string, the axle, point A, will move towards the force line. If I keep the voicing strength the same and the extra length (the amount the quill passes under the string) as well, this force line will remain the same, because it only depends on the strength of the voicing and the excess length of quill, the distance between string and jack being irrelevant. Conversely, moving the jack away from the string will create more distance between S' and the axle. So increasing the distance between the jack and the string will diminish our chances of the tongue flipping backward before the pluck.

In order to keep the line of force at the correct side of the axle, we can of course also set the axle a little bit higher. But the line of force runs only at a small angle to the vertical, so moving the axle up will only increase the distance between S' and A a little bit (please notice that as A moves upward, the point S' will also move upward along the line of force; it will always be at the shortest distance between the line of force and A). It would be more efficient to move A away from the front of the tongue, but there is simply no space to do that. Moving the axle up also has its limits: if it gets very close to the quill the tongue will have to make a large movement when the jack descends after plucking and thus compromise an efficient repetition. Jacks of 4′ registers normally do have the axles closer to the quills[7]. They are also closer to the strings as the 4′ strings are a bit to the right of the longer 8′ strings and on top of that they are voiced softer, which may also not be advantageous as we will see in the next paragraph. But the quill doesn't need to have as much excess length as for the 8′, so in the end everything plays out just fine.

Another way to keep a total anti clockwise moment of forces on the tongue would be to increase the bristle force. But that option is very limited because the tongue has to move freely backward when the jack descends, so it can never be very strong.

There's still one other observation we can make from Figure 4b: if we make a stronger voicing, there will be less chance of the tongue flipping backwards. Consider the line e. Starting at the intersection with p and moving upward along this line, we get the release points for ever stronger voicing. But we see that as we move up, at the intersection of circles of stronger voicing, *f* and *fff*, the circle is flatter at that point. We have seen already that the force of the string points down from this circle through the original position of the string, so it will be more vertical for stronger voicing, and lean more towards the axle A for softer voicing. Of course, if the voicing is extremely soft, *ppp* say, the force will be also very small and the moment induced by the bristle may counterbalance the moment from the string force.

We can do a thought experiment to verify this last result. Imagine that the quill is incredibly stiff and strong so that it doesn't bend under the force of the string. Then the string will be lifted by the quill and never be released. This is of course extreme, but sometimes it helps to imagine extremes to verify if the reasoning is correct. You can

[7] Every historical harpsichord I know of has this. Modern builders don't always follow this practice.

also do an actual experiment. By making the string tension lower, the quill becomes relatively stiffer. So if you tune a string, preferably in the tenor region where strings are long, a fifth or maybe even an octave lower and use a very strong quill, you can verify that the string is just lifted and not released. This happens when you put on a new string. When you then start tuning up, there will come a moment when the string releases from the quill. Alternatively, you can leave the string at a low pitch and start voicing the quill down, leading a moment when the quill is soft enough and starts releasing, first high up, and then lower as the quill gets softer and more flexible.

Although it is a bit outside the scope of the present analysis, I want to say a few words about yet another possibility for getting a clockwise moment. If the tip of the quill is cut very thin compared with the rest, it may not be strong enough to support the string force all the way to the very end. In this case, the tip will bend excessively, allowing the string to start returning to its original position before it loses contact with the quill.

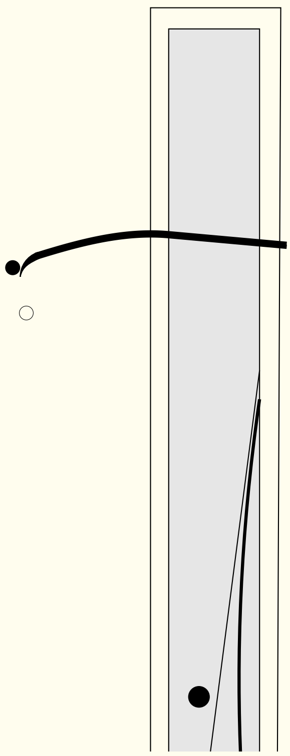


Figure 5: Quill with a thin tip.

This situation is illustrated in Figure 5. As can be clearly seen, the chance that the line of force will end up behind the axle increases. However, as the string is already moving, a static analysis (we pause pressing the key down before we assess the equilibrium of the moments of force) such as we have been applying here will not suffice and the dynamics of the system should be taken into account.

The same is true for the moment just when the string is released from the quill. While sliding past the tip of the quill, the side of the string will probably keep in contact with the tip, to some extent pushing tongue clockwise. Especially for thicker strings, this could enhance the chances of the tongue flipping backwards. Here too, a dynamic analysis is necessary to gain more insight.

Conclusion

In this Rumination we have added something to our toolkit for analysis. In the first part we became acquainted with Newton's laws and how to apply them to analyse the forces inside a hitch-pin rail. This time, we have extended our capabilities to also deal with moments of force, forces that make things twist.

We have applied our new skill to gain insight into the design of jacks, focusing on the conditions that make the tongue flip backwards just before the moment of the pluck. We have concluded that, whilst keeping everything else the same, to decrease the chances of this happening we can:

- shorten the amount of quill that passes under the string;
- increase the distance between the jack and the string;
- put the axle higher, closer to the quill;
- use a stronger voicing;
- make the quill bend as much as possible over its whole length, not just the tip (conjectural, would need to be confirmed by a dynamic analysis);

Based on the present analysis, I would say that the first and best way to avoid backward flipping tongues is to try to make the distance between the strings and the jack as long as possible. So it is of great importance to make the registers and string positions as accurate as possible to allow for this. Indeed, all historical French (and many German) harpsichords that I know have the strings of adjacent notes of the longer and shorter eight foot close together so as to have the most space possible between the strings on the same key. Also, the four foot strings are placed as close as possible to the longer eight foot strings, allowing for larger distances in that register too. This practice, by the way, obliges one to cut the dampers very short so that they will not dampen the strings when this register is not engaged thus allowing a sympathetic resonance.

In the above analysis we have assumed a static approach, so we have stopped the movement of the key and jack to make up the force balances. In practice, because the movements of all the parts are very small up to the point where the string is released, this will be a good representation of a smooth and slow (quasi static) movement. We have also assumed that there is no friction between the quill and the string. In the next part in this series of Ruminations I will, among others, address that issue.