Pivot Friction

Dick Stephen takes an experimental approach to reach controversial conclusions

THE THORNY SUBJECT of pivot friction is discussed from time to time in the pages of the *HJ*. This was in part prompted by my discussion on the subject in the introduction to my recent series on building a long-duration movement[1]. Control of pivot friction is absolutely essential if a long duration clock is ever to run reliably with weights of a manageable size[2]. Much of the comment was based on theoretical arguments. I certainly am not against theory, I was a theoretical physicist and as such spent much time applying theory to experimental results. I did become keenly aware that theory frequently required to be modified in the light of experimental observation. With this in mind, I decided it was time to apply a bit of practical measurement to the problem of pivot friction from a horological perspective.

The motion of the pivots in clock bearings is either a stop start motion, as in a movement with a dead-beat escapement, or a reciprocating motion as in movements with a recoil escapement. With this in mind I decided that the loss of amplitude in a pendulum attached to a pivoted arbor and given a single impulse, was the best way of comparing the friction of two pivots in different bearings.

Using a pendulum to measure the friction offers a number of advantages. First, the swing of a pendulum is similar to the motion of all the pivots in a clock train. Second, during the loss of amplitude both the average velocity of the pivot motion and the amplitude of rotation also decrease allowing the friction to be studied under changing motion parameters.

Before proceeding with any measurements, it was necessary to consider what frictional effects were likely to be encountered, and how these could affect the resulting measurements. This was a vital step as a poor experimental design could seriously affect the analysis of the results. The possible sources of friction were first the air resistance encountered by the pendulum as it swings. This frictional force would be the same for all the bearings used provided the starting amplitude of the pendulum was the same for all the measurements. At the bearing surfaces, the friction encountered would be a mixture of both sliding friction and rolling friction. The crucial question was how did the magnitude of the air resistance compare with the bearing friction? It was necessary for the bearing friction to be significantly larger than the air resistance so that subtle changes in the bearing friction could be observed as the amplitude and velocity of the pivot motion changed. Finally, it would be necessary to fit highly polished hardened end stops to prevent friction between the shoulders of the arbor and the jewel faces.

The Set Up

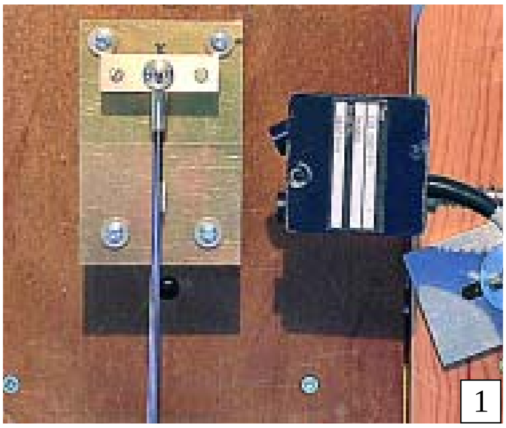
Figure **1** illustrates the experimental set up used to measure the friction. This consisted of a ‘movement’ comprising two 3.5 mm brass plates, 60 mm by 90 mm. The two plates were separated by a pillar 40 mm (±0.01 mm) in length in each corner of the plates. A back cock was fitted as shown. A 4 mm diameter hole was drilled and reamed through both plates and the back cock, to fit the arbor and the bearings. To check the alignment of the 4 mm hole a length of 4 mm drill rod was passed through the holes in the assembled plates and the back cock. The rod could easily be turned with two fingers, indicating the precision of the alignment. Once the plates were assembled there was no requirement for them to be dis-assembled in order to replace the bearings. The back cock was positioned using 1.5 mm register pins and secured with two 2.5 mm screws. Removing and replacing the back cock did not alter the precision of the alignment of the arbor.

The friction in three different bearings was compared, 1mm ID, 4 mm OD, precision ball races, 1 mm bore by 1mm thick parallel jewel holes and 1 mm bore olived jewel holes. Two arbors were used fitted with hardened and polished high-speed steel drill rod pivots of diameter 1mm and 0.92 mm. The ends of the pivots were ground to a point. The sharp ends were then domed and polished. Both bearings were fitted with adjustable polished high-speed steel end stops. The half-second beating pendulum was rigidly attached to the arbor with a 2mm locking screw. The motion of the pendulum was measured with a Micro-Epsilon laser displacement transducer and the resulting sinusoidal displacement digitally recorded, using a Nicolet Pro-10 digital oscilloscope. The traces were later analyzed using the signal analysis programme FAMOS.

Results

The loss of amplitude with the arbor with 1 mm pivots running in the 1mm ball races measured over a period of 1000 seconds is shown, **2**. Over this period the amplitude decreases by approximately 40%. With the 1mm pivots running in 1 mm parallel jewel holes, **3**, the amplitude drops to zero within 60 seconds and the pendulum comes to rest. Changing the parallel jewel holes for olived holes allows the pendulum to swing for an additional 60 seconds before finally stopping, **4**. Changing the arbor for the one with 0.92 mm pivots (a very loose fit) produces a marked change in the friction with the arbor running in the olived holes, **5**. The pendulum amplitude initially decreases at a very rapid rate for approximately 180 seconds after which the rate of decrease in amplitude slows down, almost ceasing after 1000 seconds. The slower rate of decrease in amplitude is almost identical with the rate of decrease observed with the ball races.

The final trace, **6**, shows the decrease in amplitude with the parallel jewel holes and the 0.92 mm pivots. The pendulum now takes just over twice as long to stop as it did with the 1 mm pivots running in the parallel jewel holes.



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Conclusions

The first clear conclusion is that ball races generate significantly less pivot friction than any jewel or plain bearing, a fact discovered over 200 years ago by John Harrison. The friction of an olived jewel hole is about half that of a parallel jewel hole of the same diameter. Reducing the pivot diameter further reduces the pivot friction.

From these observations the pivot friction depends on a number of factors. First, the friction depends on the total area of contact between the pivot and the bearing surface. The

Illustrations and Photographs by the author

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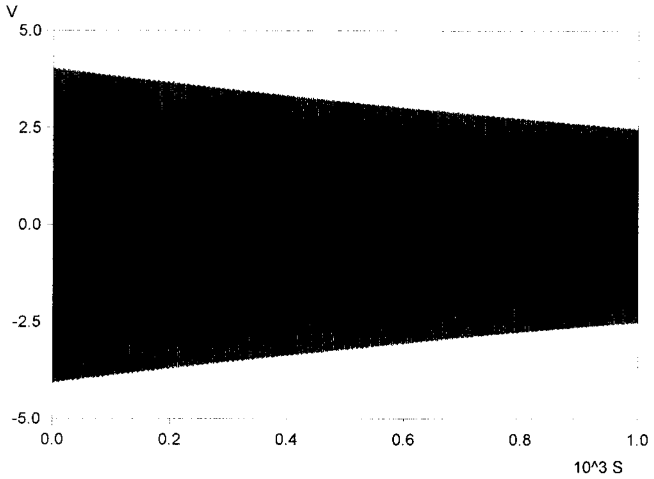
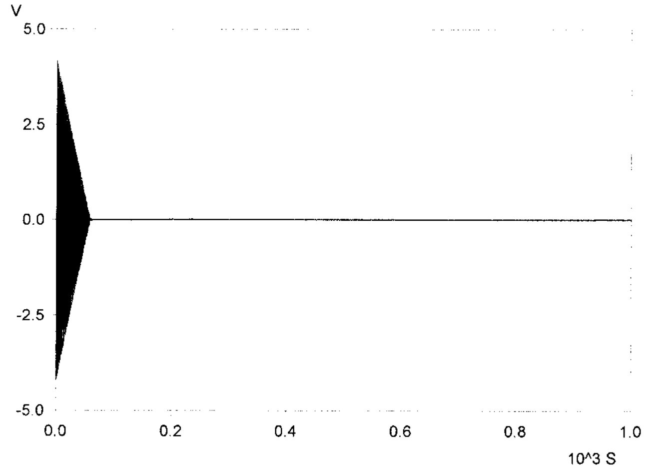
[1] p. 368, October 2004, see also p.**351**, and November p.386.

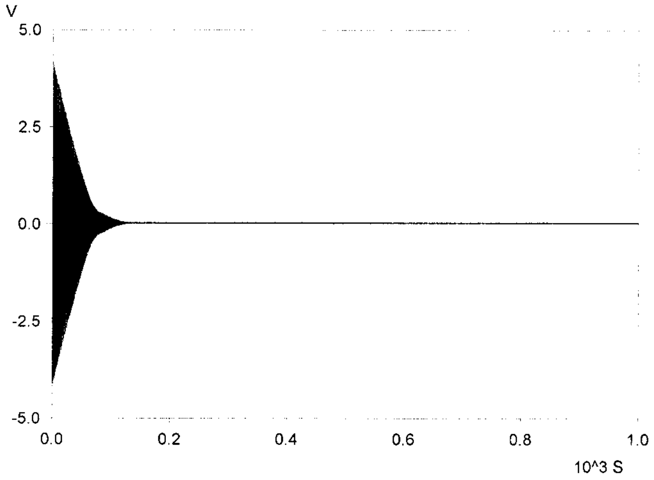
[2] p.26, Jauary 2004, also p.44 (Feb), p.120 (Apr), p.309 (Sept), p.**402** (Nov), p.423 (Dec), p.70 (Feb 2005), p.86.



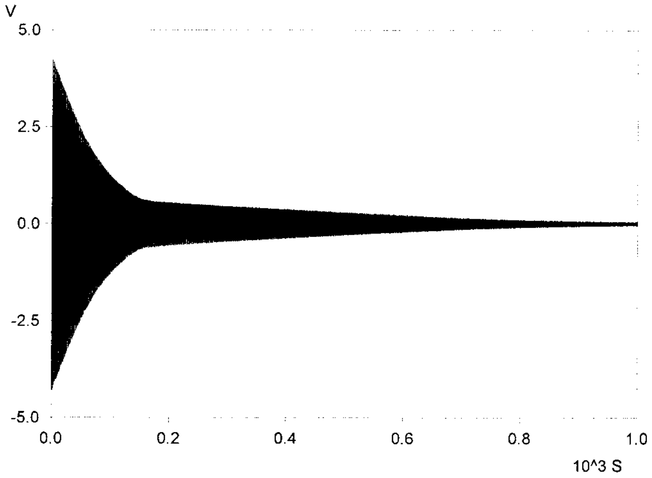
2. Pendulum coast down amplitude with 1 mm ball race bearings and 1 mm pivots.



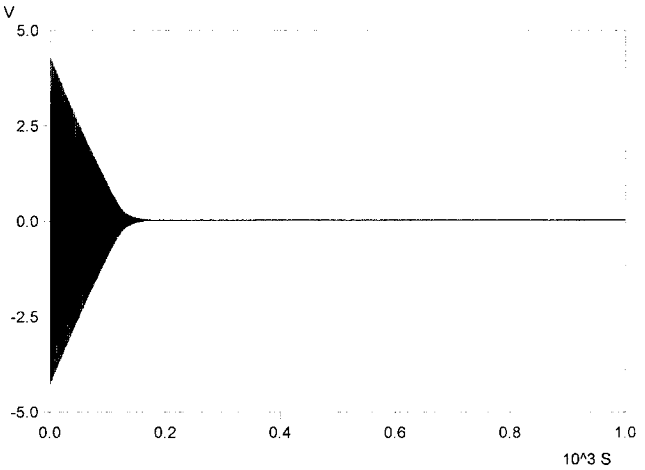
3. Pendulum coast down amplitude with 1 mm parallel jewel hole bearings and 1mm pivots.



4. Pendulum coast down amplitude with 1 mm olived jewel hole bearings and 1 mm pivots.



5. Pendulum coast down amplitude with 1 mm olived jewel hole bearings and 0.92 mm pivots.



6. Pendulum coast down amplitude with 1mm parallel jewel hole bearings and 0.92 mm pivots.

contact area depends on the relative diameters of the pivot and the jewel hole. The friction is maximal when the pivot is a close fit in the jewel hole and reduces as the pivot diameter is reduced. Second, the friction does not appear to depend on the contact pressure per unit area. The area in contact with the pivot is significantly less with an olived jewel than with a parallel jewel hole. As the pivot loading is the same for both the olive jewel hole and the parallel jewel hole it follows that the contact pressure between the pivot and the jewel hole surface is significantly larger for an olived jewel than for a parallel jewel hole; this observation probably only holds true for high-speed pivots in sapphire jewel holes.

Third, the friction generated at any pivot bearing surface will be a mixture of sliding and rolling friction. The contribution of each will depend on the amplitude of the pivot rotary motion. This is very clearly demonstrated in **5**. Initially the pivot friction is large since the pendulum amplitude decreases rapidly over the first 180 seconds. After this time the friction drops to a significantly lower value and the amplitude then decreases at the same rate as for the ball race. The friction in a ball race is almost entirely rolling friction, it then follows that with an olived jewel hole and a loose-fitting pivot for small amplitudes of rotation that the pivot friction is likely to be almost entirely rolling friction.

This conclusion agrees with the observations I have made when building long duration clocks. Frequently, there is too much friction somewhere in the train. This is, generally, due to the pivots on one or more of the arbors running in jewel holes that are too close a fit. Increasing the clearance between the offending pivots and the jewel holes always results in a dramatic reduction in the friction.

The amplitudes of rotation of the pivots in the movements is small, **5**, after the first 180 seconds. The above results indicate that it is likely that the reduction in friction in long duration movements described, is associated with a change from mainly sliding friction to mainly rolling friction. ❐