THE GRASSHOPPER ESCAPEMENT

ITS GEOMETRY AND ITS PROPERTIES

by Martin Burgess, F.I.I.C., F.S.A.

A FEW years ago Colonel Quill, who has described the history of the grasshopper escapement and shown how it works (*Antiquarian Horology,* September, 1971) kindly lent me a photostat copy of John Harrison's manuscript of 1730 (Guildhall Library No. 3973). Certain clocks I have made have benefitted greatly from Harrison's inventions and by making use of his ideas I found I was beginning to see horology through his eyes. Thus I became deeply interested in the underlying principles of his inventive thought. His work cannot be understood out of the context of his age. He had a good reason for everything he did; but if we cannot put ourselves in his place there is no hope of understanding the reasons for his inventions nor even the working of the machines he created. The early regulators are especially important because everything Harrison did later developed from them. They are fully integrated machines, every part depending on every other part, and their success does not depend on very accurate workmanship. Rather they are designed to mitigate the shortcomings of the material and the methods Harrison had to use. These shortcomings were partly the result of his horological and geographical isolation in Barrow-on-Humber. His training as a carpenter and consequent preference for wood led him, at an early date, to adopt extreme solutions which no other clockmaker had thought of using. His ideas succeeded and, in spite of the use of wood, the regulators described in the manuscript were more accurate than any other clock in the world at that time.

The Geometry of the Grasshopper Escapement

The manuscript contains a description of the grasshopper escapement. Harrison was not intending that others should be able to copy it so the drawing (Fig. 1) which illustrates the description has no geometrical construction lines. I have put back these lines by methods I believe Harrison probably used. By doing this, it is possible to draw the grasshopper and make it the way he did, and consequently to have a much better understanding of what its functions really are.

The drawing of the escapement also requires the dividing of a wheel and Harrison had to mark and cut his wheels by hand. The accurate dividing of circles is fundamental to all horology, and from experience I know that even the very best protractor is an unreliable tool to use. Parallax, because of the thickness of the markings and the edge of the instrument, may introduce an error of transfer, especially on small wheels. Harrison almost certainly used a pair of dividers with fine well-sharpened perfect points and made his markings directly on the surface of the metal he was going to use. It is always more accurate to draw on a tarnished metal surface than on paper. With dividers and a straight edge the following methods can be used to divide a circle into any number of equal parts:

(1) The use of the fact that the radius of a circle will divide its circumference into six equal segments.
(2) Bisection of angles.
(3) Trial and error, i.e. pacing round the circumference with dividers. Even this method is very accurate, especially if done under a lens, though most geometers would hate to use it. (I once had to divide a small wheel into 73 equal parts in this way and it was quite satisfactory.)

The tooth form of the escape wheels of the early Harrison regulators were certainly obtained with dividers. The front of each tooth is formed by setting the dividers to two tooth spaces and drawing an arc with the tip of one tooth as centre. The back is formed by setting the dividers from the root of one tooth to the tip of the next and drawing an arc. There is no reason for the teeth to be of this form except that it is easy to mark them out this way. A curved form is as easy as a straight one to cut out by hand. For the grasshopper the shape of the teeth is of no importance so long as only their tips touch the pallets.

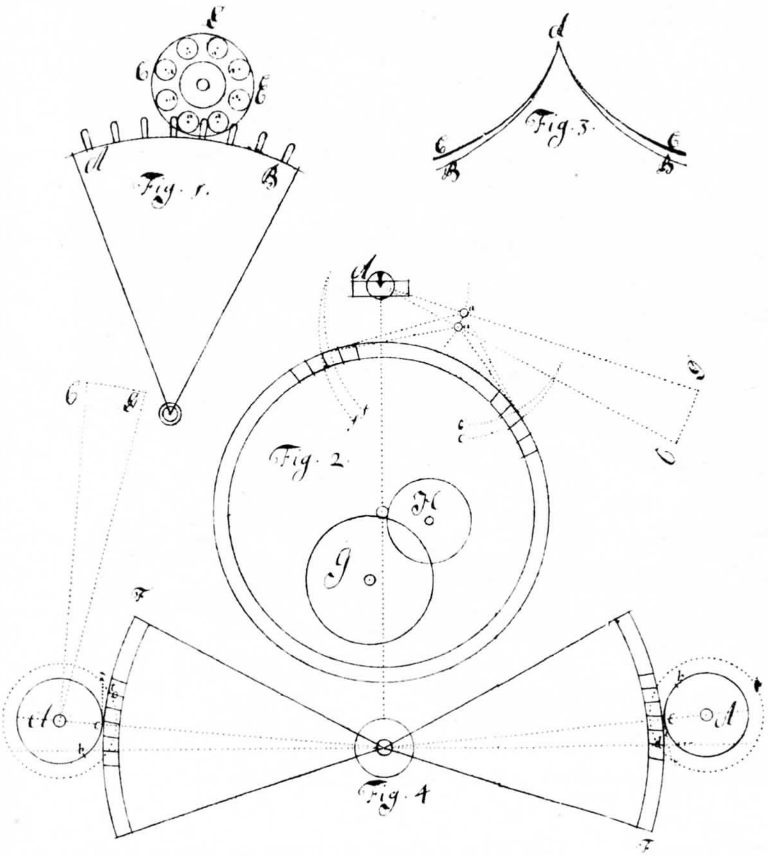

Fig. 1. Harrison's own diagrams from his manuscript of 1730.
Reproduced by courtesy of the Clockmakers' Company from their records at Guildhall Library.

Harrison would have marked out and cut the teeth as accurately as he could but in fact the grasshopper will accept quite an irregular wheel and still go on working well if there is enough supplementary arc to span the irregularities. After the clock is made the driving weight can be increased until all the teeth allow the pallets to be discharged from them.

The following method of drawing the escapement, based on Harrison's description, only requires a knowledge of elementary geometry to understand it. He used an escape wheel of 60 teeth and the pallets embraced $12\frac{1}{2}$ tooth spaces. The escaping arc was $10°$. Fig. 2 is a construction drawing with the pendulum vertical and both the pallet arms of the same length.

To find position of pallets when pendulum is vertical.

With centre O and radius the full radius of the escape wheel draw a circle to represent the tips of the wheel teeth.

From a point Z on the circumference, with radius OZ cut the circle to the right of Z at X. ZX spans 10 teeth and X is the position of entry pallet X when the pendulum is vertical.

Bisect ZX at W. ZW and WX each span 5 teeth.

Bisect ZW at V. ZV and VW each span $2\frac{1}{2}$ teeth.

With centre Z and radius ZV cut circle to left of Z at Y. XY spans $12\frac{1}{2}$ teeth and Y is the position of exit pallet Y when pendulum is vertical.

Join OX, OY and produce them.

To find the position of the pallet arms' pivot in relation to the pallets and the centre of the escape wheel.

Draw tangents at X and Y to cut each other at U. U is the position of the pallet pivot centre when the pendulum is vertical. (It is the centre of the gold pin shown as C in Col. Quill's article.) UX and UY are equal and represent the lines of compression and tension between the pallets and their pivot whatever shape the pallet arms may be.

To find the position of the crutch arbor centre.

Join OU and produce it. OU bisects angle XOY.

Push on XU should equal pull on YU and both should exert the same torque on the crutch arbor. To achieve this construct TUS perpendicular to OU then angle SUY must equal angle TUX. Both are right angles minus angles YUO and XUO respectively. And angle YUO equals angle XUO because triangles YUO and XUO are congruent (two equal sides and the included angle).

OU cuts circle centre O at R bisecting VW. VR and RW each span $1\frac{1}{4}$ teeth. Set out the positions of some of the teeth by dividing arc ZW into five equal parts by trial and error. Each side of V there will be half a tooth space and on the right of R there will be a quarter tooth space.

With radius $\frac{1}{4}$ tooth space cut circle centre O each side of X and Y. These points represent the extent of travel of pallets X and Y when in contact with the wheel teeth. With radius UX (or UY) and these points each side of X and Y as centres draw arcs to cut each other at A and B on the line OU. A will be the position of U when the pendulum is to the right. Then Y meets the next tooth and causes the wheel to recoil unlocking pallet X. B is the position of U when the pendulum is to the left. Then X meets the next tooth and causes the wheel to recoil unlocking pallet Y. It is at these instants of time that both pallets will be touching the wheel. When Us is at A the pallets will span 12 tooth spaces and when U is at B the pallets will span 13 tooth spaces. This is because as the pendulum swings the legs of the grasshopper open and shut as it walks round the wheel. As U is moving in an arc, not in a straight line, A and B will not really lie on the line OU produced but will be slightly closer to S.

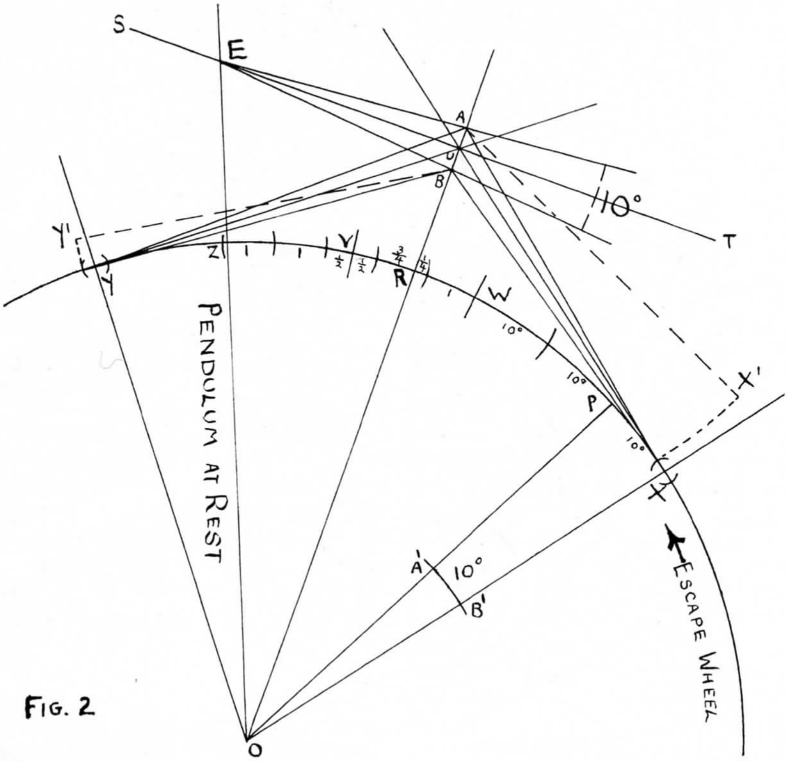

FIG. 2

Divide XW into three equal parts then angle XOP will be 10°. Mark A′ on OP and B′ on OX so that A′B′ equals AB. With radius OA′ (or OB′) and centres A and B draw arcs to cut each other on their left at E. E is the centre of motion of U and the centre of the crutch arbor. Join OE and this will be the position of the pendulum rod when at rest. OE is the distance of the escape wheel arbor from the crutch arbor. This is all the information which is required to draw out the escapement if the pallet arms are to be of equal length. It is no more complicated than a full drawing of the anchor recoil or dead beat escapements and is easy to draw accurately.

It is vital that EU is shorter than YU or the pallet Y will not lift at recoil. Even with an escaping arc of 10° the lift of Y will not be very great. The lift of X will be excessive. To find the extent of lift is easy on this drawing. Draw AX′ equal to UX so that the angle EAX′ equals angle EBX. X′ is the position of X when Y causes recoil. Draw BY′ equal to UY so that the angle EBY′ equals angle EAY. Y′ is the position of Y when X causes recoil. These positions are shown dotted on the drawing Fig. 2.

Having found the extent of lift at recoil the two pallet arms can be drawn any suitable shape and the controllers added to suit them. The under sides of the pallet arms must be arched slightly to clear the wheel teeth and this is especially true of pallet arm X, the entry pallet, because in recoil X will go well beyond the tangential point and a straight line from X to B would conflict badly with the wheel teeth. Fig. 3 shows a close up of the point U on a large working model of the grasshopper showing how the two pallet arms and their two controllers are pivoted there. Compare this photograph with Col. Quill's very clear illustrations.

To make the lift of both pallets at the recoil equal the pallet arms would have to be of unequal length, the arm Y being

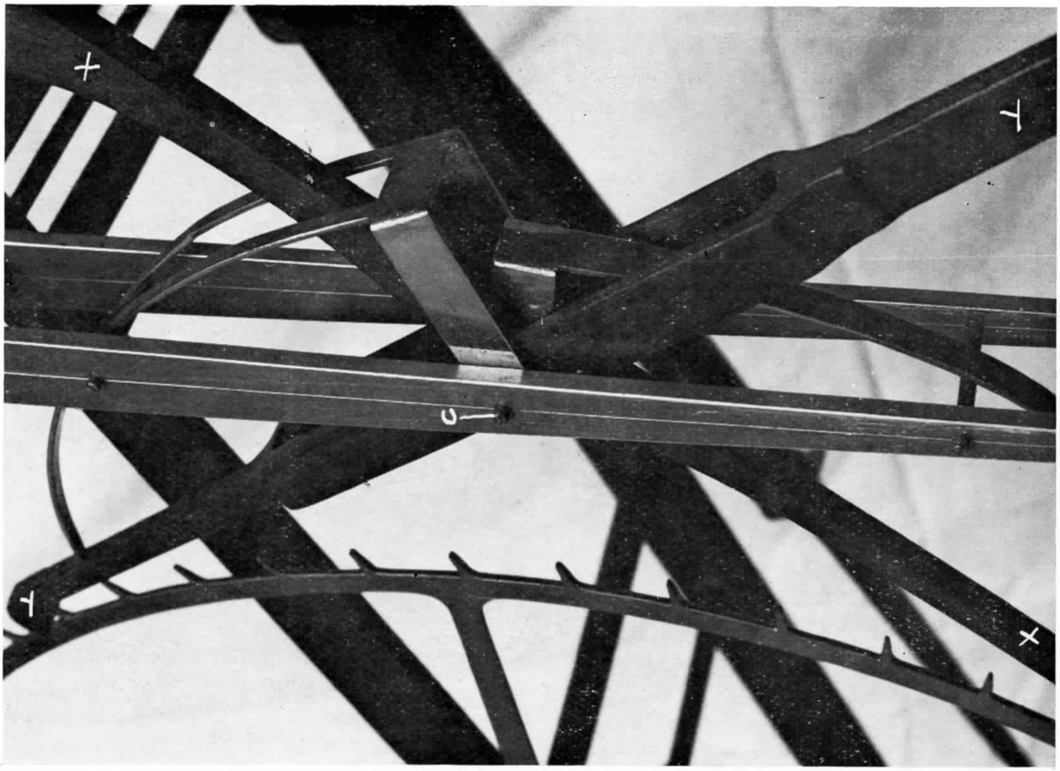

Fig. 3. Close-up of pallet pivot U showing how the two arms and the two composers are pivotted there.

much longer than X. But UX and UY would not then be tangents to the wheel rim. In the early regulators the arm Y does appear to be slightly longer than X. By reducing the lift of X it is more quickly damped by its controller and by increasing the lift of Y its depth of engagement with the wheel is greater. Both these results are an advantage and make a better functional design.

There is only one moment when the push and pull on the pallet arms is truly tangential to the wheel. This does not have to be when the pendulum is vertical. If each pallet met the next tooth at the tangential point and were carried beyond it as the pendulum moved, the pallet arm X would be shorter and the arm Y longer. The energy imparted to the pendulum would still be the same for both. Fig. 4 shows this construction. Draw the circle centre O the same size as before and the points ZXWVY as before. Draw the tangents at X and Y to cross at U. U will not now be the position of the pallet arms' pivot. Set out the teeth between Z and W to get half a tooth space each side of V. Set out half a tooth space to the left of X and also of Y. These spaces denote the distance moved by the pallets when in contact with the wheel. Next locate A, the up position of the pallet pivot, and B, its down position. B will lie on UX and A on YU beyond U, and both will lie on the same radial line from O. They must also be the same distance apart as in Fig. 2. The point E can now be obtained as before.

Properties of the Grasshopper Escapement

The grasshopper is the result of Harrison's attempts to improve the anchor recoil escapement. Therefore without a thorough understanding of the latter's properties, the properties and advantages of the former cannot be understood at all. So, although they are well known, it is vital to state them again so that there can be no doubt about what Harrison really achieved.

Like the grasshopper, the anchor escapement is closely interrelated with both its pendulum and its train. The pendulum is not free in any way and its time measurement will depend not only on the rules governing all pendulums but also on the modifications of them caused by interference from the escapement which, in its turn, is passing on some of the characteristics of the train which drives it.

The Pendulum

(a) Circular Error, All normal pendulums are subject to circular error if steps are not taken to compensate for it. It slows the rate in the longer arcs. For a given change of arc the error is much greater at a big arc than a small one. This error is theoretically the same for all pendulums and can be calculated.

(b) Energy Consumption. The energy consumption of a pendulum rises steeply as the arc is increased. A given change of energy input to the pendulum will make a much smaller change of arc at a big arc than at a small one. To change the arc by a given amount will require a much greater change of energy input at a large arc than at a small one. There is as yet no known way of calculating the energy consumption of any pendulum except by making and testing it.

Recoil Escapements

(a) Escapement Error. These escapements push the pendulum first one way and then the other. It is never free. The escapement error has a hastening effect tending to move the pendulum faster as the energy input increases thus helping to counteract the circular error. This hastening effect will depend on the weight of the pendulum, a light one being hastened more than a heavy one. If the escapement was large enough and the pendulum light enough the escapement error would counteract all the circular error over a small range of arc.

(b) Recoil. There must be supplementary pendulum arc so that the clock will continue to go under the most adverse conditions it is likely to experience. Part of the surplus energy for this is used up increasing the arc and part in pushing the escape wheel and train backwards.

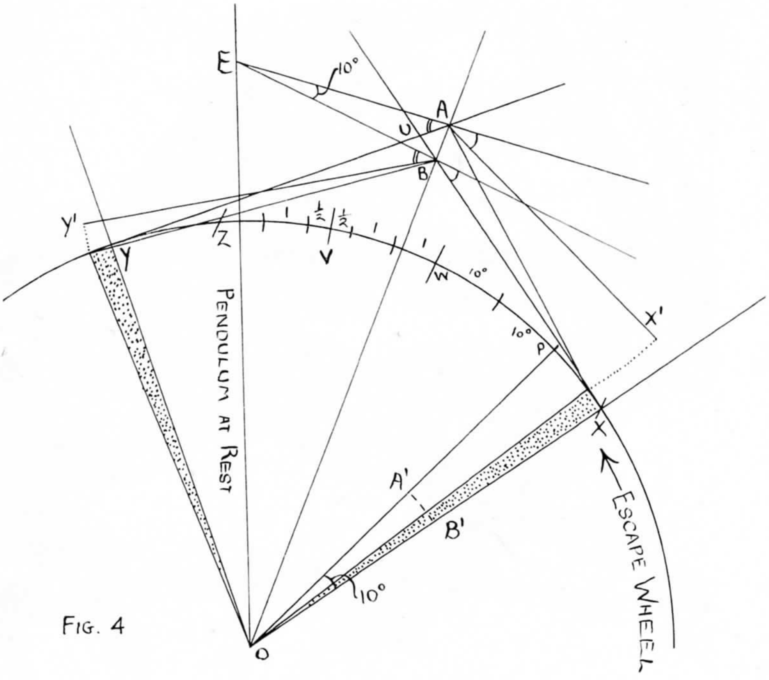

FIG. 4

The Train

All trains waste energy and if the wastage were constant this would not matter. Unfortunately the energy consumption of a train fluctuates depending on the following factors.

(a) Changing temperature, increasing age and dirt will change the effectiveness of the oil used to lubricate the bearings. 18th century oils were very poor.

(b) With time the wear in a train will increase, thus changing the energy it consumes. This is specially serious if the load on the parts is heavy, as it will have to be if the train is so inefficient that it consumes most of the energy.

(c) In recoil, when the train is being pushed backwards by the escapement most of the teeth of the wheels and pinions will experience engaging friction. To reduce friction and therefore energy consumption most clockmakers try to get all the action of the wheels on the pinions beyond the line of centres (wheel tooth and pinion tooth are in the process of disengaging when they are touching each other). This means in recoil the pinions are driving the wheels before the line of centres. This is serious, even when perfectly made and perfectly spaced high numbered wheels are used. (Harrison could not have made this kind of train in any case.)

Drop

All anchor and dead beat escapements experience drop because the tips of the escape wheel teeth must have thickness and the pallets must clear the backs of the teeth at the escape. The drop is wasted energy and is serious. The wheel teeth meet the pallets at their fastest speed and the wheel must be supplied with enough energy to overcome its own inertia. This energy is used up in noise and friction. Also the impact drives particles of dirt into the tips of the teeth and because they are oiled and slide over the pallets they soon become efficient lapping tools which wear ruts in the pallets. This becomes specially serious in recoil where the pallets are driving the wheel teeth backwards. Unequal drop due to the teeth being unevenly spaced or the wheel being out of round or mounted off centre will be made worse as wear takes place. The resulting reduction of energy reaching the pendulum will gradually reduce the arc of swing.

Harrison's system compared with others

The grasshopper in conjunction with Harrison's train and pendulum can now be compared with other contemporary systems.

In 1730 Harrison was not depending for his success on perfect craftsmanship. (Later he did and it proved to be his bane. For although the prize winning H4 showed the world that such a timekeeper could be made, it was not widely used as it was too expensive to make and adjust.) The early regulators were accurate because irregularities of manufacture and materials were allowed for in the design.

(a) The grasshopper has no drop so the escape wheel can be large and heavy. (Harrison was even able to use a large oak disc mounted on the escape wheel arbor to show the seconds.)

(b) The escape wheel teeth can be slightly irregularly spaced and, provided there is enough supplementary arc, the clock will continue to work well without additional wear.

(c) The low friction oilless train reduces the fluctuations in the energy reaching the pendulum and ensures that a large proportion of the consumed energy is used by the pendulum. This reduces the need for a large recoil arc.

(d) Because the pendulum arc is large the recoil arc is small in proportion to it. Harrison makes it quite clear in the manuscript that he thought this important.

(e) In spite of the low numbered rather crude trains, there is no serious engaging friction in recoil because the rollers and pivots only rock backwards in the side shake which must be there if they are to turn freely. Harrison also discusses, and stresses, the importance of this in the manuscript.

Energy used by the grasshopper

The friction at the pallet pivot point is not the only energy consumed by the grasshopper. The pallet arms are tail heavy to lift the pallets away from the wheel when recoil unlocks them. The shorter the period of the pendulum the faster the pallets must lift and settle on their controllers. Each time the pallet arms are drawn away from their controllers energy is consumed to lift their tails so the arms should be very small and light. Their tails should be only just heavy enough to return them to their controllers when the pallets are unlocked for, if the weight of the tails is increased, the arc of swing of the pendulum is at once reduced. The absorbed energy remains constant, however, since a constant weight is being moved through a constant distance.

Weight of the controllers and circular error

It is not important to make the controllers very light. Though they are lifted in recoil they return to their stops resting on their pallet arms thus giving the energy back to the pendulum. Increasing the weight of the controllers will only add to the escapement error, the pendulum being hastened in the long arcs as the proportion of recoil arc increases. Since the escapement error is helping to counteract the circular error, which is considerable at 10°, it is probably a good plan to make the controllers rather heavy. Harrison rendered the pendulums of his regulator clocks more isochronous by the use of cycloidal cheeks; but he says, in the manuscript, that their form had to be more open (less effective) than would be dictated by theory. This was because the grasshopper was already doing some of the circular error correction for him. So any change in the grasshopper, especially a change made to the weight of the controllers would require a readjustment to the angle of the cycloidal cheeks. Their effectiveness is the subject of research which is still going on.

In spite of the grasshopper's great

advantages, the only other horologists who have used it are those mentioned by Col. Quill; and they did not use it in the search for more accurate timekeeping. Vulliamy, great clockmaker though he was, missed the point in his version of the escapement for his controllers have no common centre of motion with the pallet arms and rubbing between them would not help the time keeping. It is also pointless to use a high numbered regulator train for some of the advantages of low friction recoil will be lost. The grasshopper has to be combined with Harrison's other inventions to achieve great accuracy: and, as I stressed above, a thorough understanding of his methods of construction and adjustment is also needed. To adopt it the clockmakers of his time would have had to change their workshop techniques and much of their horological thinking. Instead the search for accurate time keeping followed the path of heavy pendulums swinging smaller and smaller arcs, driven by smaller and better made trains, lubricated by better and better oils. In our own time there is a demand for the grasshopper from those who enjoy watching its action.

All the same I do not believe Harrison's system of accurate timekeeping has been tested since his day. The two early regulators are now too worn for a searching scientific test to produce any conclusive results. But it would be most interesting to know if Harrison's claim of a second a month was really justified. Experiments to find out more about this would have to be conducted with great care, with the 1730 manuscript in one's hand and with Harrison breathing down one's neck.

Obituary

HENRI LENGELLÉ dit TARDY

The death of Henri Lengellé in Paris on 29th September, 1971, at the age of seventy, deprives the world of a Frenchman who carved out for himself a unique niche as author, compiler and publisher of numerous reference books on horology, ivory and faïence besides the punch-marks on gold, silver and pewter. In horology, Tardy's best-known work was the three-volume *La Pendule Française* (lately brought up to date and re-issued) and his greatest unquestionably the *Bibliographie Générale de La Mesure du Temps*, first published in 1947. This tour de force was prepared or at least finished during the occupation of France in World War II. Tardy's last work was his invaluable *Dictionnaire des Horlogers Français*, of which the first part covering letters "A" to "K" was printed this year. It is very much to be hoped that a means will be found of completing the publication. Certainly it was virtually finished in manuscript form last time the present writer visited Tardy many months ago. It includes his autobiography, besides listing all his published works.

No one in England ever knew Henri Lengellé really well. He liked to work by himself, often unshaven, in a gloriously muddled and over-filled study lined with books. The floor was covered so thickly with pieces of paper snipped from manuscripts and proofs that no carpet would have been necessary. How he ever again found anything that he may have dropped by accident presented a subject for speculation that never dimmed with the years.

Alas, this "biographer" knows little of Henri Lengellé's earlier background or history, other than the self-evident fact of his scholarship. The late C. A. Ilbert and Malcolm Gardner often visited him before the war on their trips to France. It is believed that Lengellé took over the already existing "Tardy" business soon after 1930. At first he was a bookseller. His old Catalogues make most interesting reading, being very strong on the Continental horological authors, besides titles that are almost never seen today.

No one could have described Henri Lengellé as being excessively domesticated; but he liked children and would willingly take part in conversations based upon "La plume de ma tante". It was one of his endearing traits, and certainly one for which he will long be remembered.

C.R.P.A.