<u>High Precision Mechanics (HPM):</u>
<u>A self-winding mechanical movement with quartz precision.</u>

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Abstract

A self-winding movement has been developed with the accuracy of an electronic quartz movement [1]. This is achieved by replacing the escapement mechanism and the balance wheel/hairspring resonator by an electromechanical escapement and a quartz tuning fork resonator. At the end of the gear train is a miniature generator turning constantly at a speed of about 7 revolutions per second. This micro generator supplies the energy to operate an integrated circuit containing a quartz oscillator. The frequency of the AC generator signal is compared to the frequency of the quartz resonator and the generator is electrically synchronised to maintain its speed according to the quartz resonator's signal.

The generator being driven by the main spring through the gear train coupled to the hands, this principle leads to a perfectly constant speed of the hands and a totally quiet movement. The energy for the movement being stored in the main spring, the timepiece has no primary or rechargeable battery or similar electrical energy storage means (″Supercapacitor″). An operating temperature range of -50°C to + 90°C has been observed. The wear tests pursued since over two years show excellent reliability and confirm the quartz accuracy of the timepiece.

Résumé

Le mouvement mécanique à remontage automatique HPM (aussi dénommé "Salto" [1]) présente la précision d'un mouvement à quartz. Cette caractéristique est obtenue en remplaçant l'organe régulateur d'une montre mécanique à balancier-spiral ainsi que l'échappement à ancre par une microgénératrice qui fournit l'énergie nécessaire à l'alimentation d'un circuit intégré de régulation de sa vitesse de rotation. Ce mouvement possède une autonomie équivalente à celle d'une montre mécanique automatique car le stockage d'énergie se fait également par le ressort de barillet. Il ne contient de ce fait ni batterie, ni accumulateur, ni aucun autre élément électrochimique. Ce dispositif démarre instantanément, même après un stockage prolongé de la montre, par un simple remontage de la couronne, de façon analogue à une montre mécanique automatique conventionnelle. L'aiguille des secondes se déplace avec une vitesse quasi-constante, se distinguant du mouvement saccadé d'une montre mécanique traditionnelle. Grâce au principe du mouvement, une marche plus silencieuse que tout autre calibre à affichage analogique à aiguilles est obtenue, accompagnée d'une plage de fonctionnement de -50°C à +90°C et d'une sécurité de fonctionnement remarquable. Plusieurs centaines de prototypes ont été réalisés et les tests au porter démontrent qu'ils satisfont bien les spécifications de précision d'une montre à quartz, soit une précision 100 fois meilleure que celle d'une montre à balancier-spiral. D'apparence identique à celle d'une montre mécanique automatique, ce mouvement à microgénératrice dispose de la facilité de réglage de la marche d'une montre à quartz.

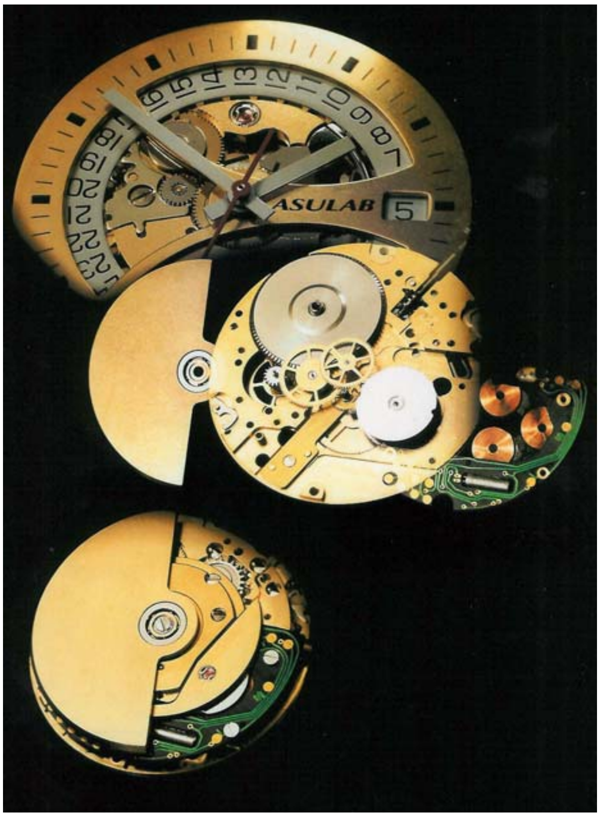

Fig. 1: High Precision Mechanics (HPM) movement. Centre view, the bridges and the self-winding mechanism are absent.

1. Introduction

The problems created by the power source and its inherent limitations often cause the most difficult to solve design problems for portable electronic products and are limiting the users possibilities significantly.

We all are aware of this and are buying with portable electronic equipment several sets of batteries, a line adaptor, etc. and the ″battery-low″ sign is constantly observed during the operation of the device. For watches this is even truer, since the replacement procedure often requires a specialists service in order to guarantee the water resistance of the product.

Considering this, our elders who developed the self-winding watch deserve particular respect: using the body movement as a primary energy source and mechanical storage means that are sufficiently large for practical use of the product. They created a product [2] which (compared to a battery operated device) rightfully deserves the reputation of an ever lasting product, reliable enough for expeditions to the North Pole or the moon.

The mechanical energy storage offers autonomy – largely enough if the product is worn – and the user only reaches the autonomy limit if he chooses not to wear the watch and can very easily take the corrective action himself in a few seconds by wearing the watch and setting the time.

This situation is very different from watches with electrochemical energy sources or storage: the electrochemical autonomy is much larger, but the effort needed to correct an end of life situation of the battery is significantly larger too.

From a user standpoint, the self-winding watch would be a perfect product, if the accuracy of the classical resonator (hairspring/balance wheel) and its associated escapement would not periodically lead to the need of time adjustments. It is well known that the accuracy limits depend on factors, which cannot be controlled by the user. Even a careful user cannot avoid resetting the time at intervals beyond his control, imposed on him by the product.

The development outlined in this paper presents a product which preserves all the advantages of the classical self-winding mechanical watch but avoids its only disadvantage (the limited accuracy) by replacing the spring/balance wheel resonator and its associated escapement by a (mechanical) quartz tuning fork resonator and a corresponding escapement. It's noteworthy that this basic idea is not new at all; several attempts have been made to improve the classical resonator/escapement system e.g. by using special alloy tuning forks [3]. These developments did lead to a power consumption of the resonator, which required a battery power source thus offering no advantage over the classical battery operated quartz watch.

The idea to use the energy available at the escapement to drive a quartz resonator is quite old as well and has first been described by J.Cl. Berney in 1978 [4]. The use of a modified stepping motor as escapement generator has been presented in 1987 [5]. The power consumption of the associated electronic circuit and the basic choice of the generator principle did lead to sophisticated micromechanical solutions, difficult to industrialise.

A new generator concept together with a novel electronic approach [6] has now led to a reliable movement suitable for mass production and maintaining the mechanical aspect of the product as shown in fig. 1.

2. Working Principle

High Precision Mechanism (HPM) basically is a self-winding mechanical movement. The development presented in this paper is based on a modified version of ETA's Calibre 2824. From the ETA movement the calendar mechanism, the time setting mechanism as well as the self-winding mechanism have been used, the spring and gear train have been adapted, but have the same functionality as in the normal mechanical movement. A normal gear has replaced the escapement wheel and the generator is at the location of the classical resonator.
The modifications to the ETA 2824 Calibre are illustrated in fig.2. The figure shows the functional and design similarities between the two movements.

The generator is mechanically coupled to the spring and the hands and turns permanently with an angular velocity corresponding approximately to the peak velocity of the classical spring/balance wheel resonator (but always in the same direction).

The generators AC voltage is used for two functions: first of all it is rectified and powers the integrated circuit containing the quartz oscillator thus eliminating the need of an electrochemical power source (battery, rechargeable battery or supercapacitor). In addition the AC-signal is used to control the generator speed and thus the time keeping function of the watch movement. For this, the AC frequency is compared to the (divided) 32'768 Hz frequency of the quartz tuning fork. If the generator runs too fast, the IC short-circuits the generator for a short time in order to reduce the generator velocity to the nominal value.

It may be seen, that the micro generator and its associated integrated circuit performs the three classical tasks of the mechanical escapement:

- Supply the energy to the resonator
- compare the speed of the gear train with the resonator frequency
- control the gear train speed according to the resonator frequency

Since quartz crystal tuning fork is used as a time keeping resonator, the movement has the time keeping accuracy of a normal quartz watch using the same resonator.

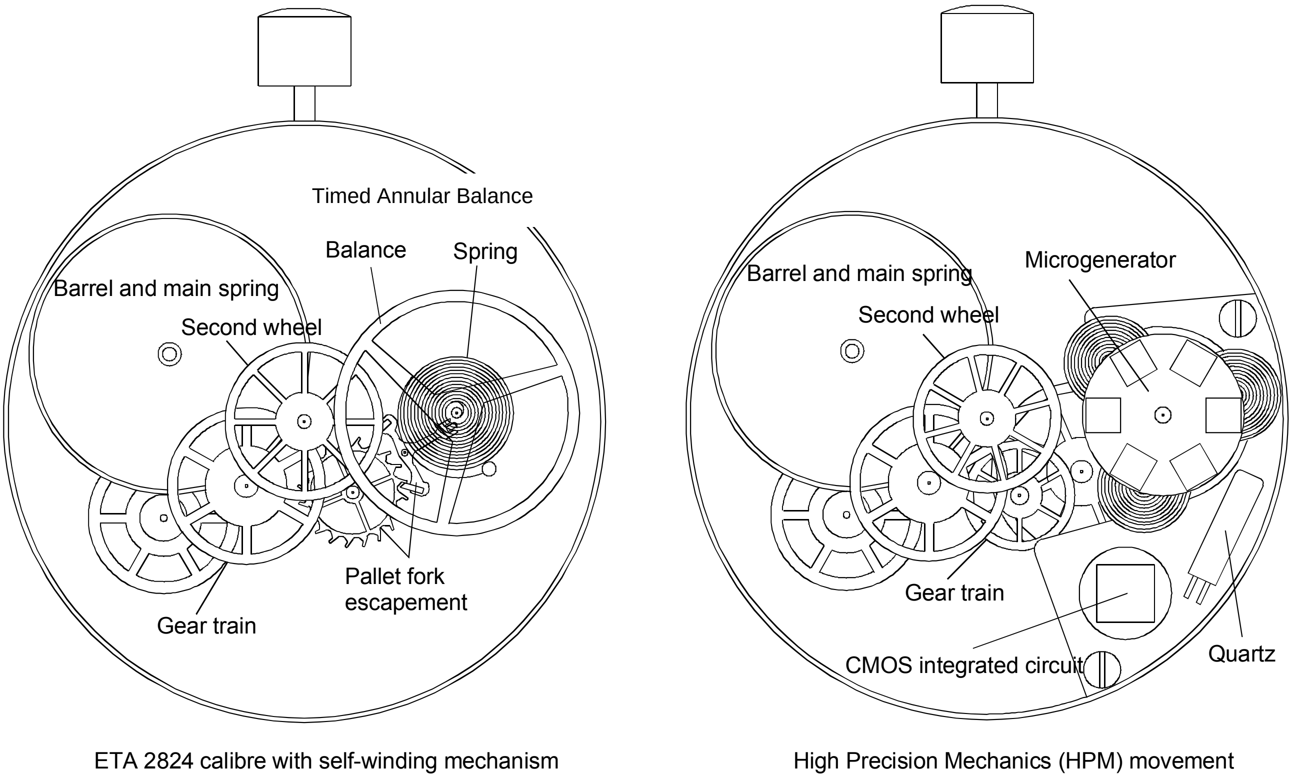

Fig. 2: Comparison of the layout between ETA 2824 self-winding mechanical calibre (left) and the High Precision Mechanics (HPM) movement (right). The self-winding mechanism as well as time setting and calendar part are not shown.

It is of course possible to design a rigid speed control of the generator, e.g. by using a phase locked loop between the generator signal and the (divided) quartz frequency. This is the case in a classical mechanical movement (and in a normal electronic quartz movement as well) and leads to the situation that a momentarily disturbed generator movement (e.g. in case of a shock) will lead to time loss. For this reason the HPM electronics uses logic acting on the mean value of the two frequencies only. To do this, the generator frequency and the quartz resonator frequency (divided in such a way that the two frequencies are equal) are fed into an up/down counter and its output is used to control the short circuit function of the generator. This allows the generator to turn too slow or too fast for periods of time largely exceeding shocks or fast arm movements, etc. without any loss of the time keeping performance of the movement over long periods of time.

The design principle outlined above leads to a quasi-continuous regular displacement of the second hand and to an absolutely noise-free movement.

Most of the elements and subassemblies of the HPM calibre are well known and may be found in classical mechanical movements, only the generator design and the integrated circuit are discussed in more detail hereafter.

3. Microgenerator

In order to allow an easy start-up of the movement (with little torque on the spring), the generator must not show any electromagnetic torque (positioning torque) at standstill. That means that during start up only forces and torques are coming from the friction effects similar to a classical mechanical movement and a start up behaviour identical to a normal mechanical watch will result.

Our early designs [4] were based on Lavet type motors used as generators. This principle however needed perfectly symmetrical designs to avoid magnetic standstill torques and did lead to very tight manufacturing tolerances. For this reason, we selected a generator design based on an ironless stator having no magnetic standstill torque. Fig. 3 shows a schematic cut away view across the generator.

The rotor consists of the main shaft with the drive pinion and two iron flasks holding six Samarium-Cobalt magnets each. The magnets have their magnetic direction parallel to the rotor shaft and are assembled to the flasks, in order to always alternate the magnetic field direction in the coil area. The rotor bearings are similar in design to the bearings of the spring/balance wheel resonator of a classical mechanical movement. The stator consists of 3 ironless coils in 120° connected in series. The coils are assembled on the printed circuit board, which also contains the quartz resonator and the integrated CMOS circuit.

The generator design produces a sinewave voltage Ui according to [7]:

$$U_i = N \cdot \frac{d\Phi}{d\varphi} \cdot \omega = \gamma \cdot \omega \qquad (1)$$

where: N is the number of turns of the coils,
Φ is the magnetic flux of the magnets,
φ the angular position of the rotor,
ω its angular velocity, and
γ the electromagnetic coupling constant.

With the actual design of 3'500 turns per coil, the electromagnetic coupling constant γ becomes 17.5 mVs/rad with an angular speed of 7.11 revolutions per second. The induced voltage Ui according to eq. (1) becomes 1.5V peak-peak, which is sufficient to directly power a low voltage, low power CMOS circuit.

The generator speed has been chosen in order to produce a voltage sufficiently high to drive the integrated circuit and also to produce a generator signal far beyond the electrical noise level to avoid time loss due to electric interference signals. The lower speed limit is also given by the user movements at the wrist especially during sports activities such as tennis, etc. where angular velocities between 1 and 5 per second have been observed [8].

On the other hand the generator speed should be as low as possible to avoid wear on the pivots and excessive energy loss due to bearing and air friction.

Considering these criteria, a rotation frequency of 7.11 Hz has been chosen which is easily obtainable from the 32'768 Hz oscillator. The electrical generator frequency, which is three times the mechanical rotation frequency, is obtained by dividing the 64 Hz signal of the division chain by a factor of three.

The microgenerator delivers a power of 480 nW with the main spring wound at 1.5 turns, which is normally the starting point of the movement. The power consumption of the integrated circuit being much smaller, this figure shows the losses due to the rectifier circuit actually of the order of 50%.

The use of more sophisticated rectifying techniques (such as active diodes) could substantially improve this situation and allow further miniaturisation of the movement.

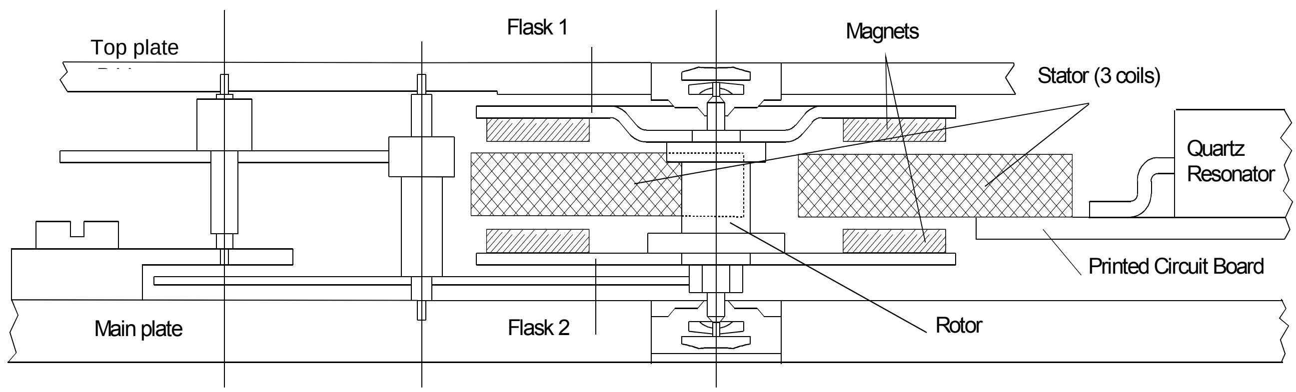

Fig. 3: Sectional view of the micro generator with the rotor, the stator (coils) between the main plate and the top plate.

4. Integrated Circuit

Fig. 4 shows the functional blocks of the integrated circuit with a schematic indication of the mechanical parts of the movement (without the self-winding block). The 32'768 Hz quartz crystal is a standard tuning fork type watch resonator. This allowed using existing designs for the oscillator, the dividing chain as well as the 6-bit EEPROM inhibition logic. The 64Hz signal is further divided by 3 to obtain 21.33Hz.

The other blocks had to be designed for this circuit and will be described in more detail.

The generator signal first needs some signal conditioning by a Schmitt-Trigger type circuit. In the same time this circuit performs digital filtering functions to avoid electronic interference together with the up-down counter [9].

An almost standard up/down counter now compares the pulses from the 21.33 Hz quartz reference and the generator. The counter has a capacity of ± 512 pulses changing its output at 0 to trigger the short circuiting logic of the generator. This means that the watch movement can accumulate up to 24 seconds of integrated time loss (or gain) and compensate for this as soon as the disturbance is over.

The counter output triggers a short circuiting logic that acts on the generator with a CMOS power transistor for a small period of time every cycle. The braking period is selected to avoid short circuiting the generator during the periods needed for the IC's power supply (the peak periods of the signal), but sufficiently long to ensure effective generator braking for fully wound main spring conditions.

The circuit also contains an ″end of energy″ logic block. If the counter reaches the 24-second time loss limit, it is assumed that the watch is in fact not worn and the spring is at the end of its capacity. To make sure that the user does not get erroneous time information, the logic then short-circuits the generator permanently, which causes the second hand to stop. The user taking a watch that has not been worn will be able to detect at the second hand movement whether or not the ″end of energy″ condition has been reached.

The circuit has been designed in EM-Marin HCMOS 1.95 µm technology [10] for optimum IC and design costs. The IC has about 3600 transistors and a surface of about 4.5 mm^2. Fig. 5 shows the IC's layout. It should be noted that this is a ″Multi Project Wafer″ layout and not yet optimised for area and pad count, etc.

The IC's power consumption is about 180 nA at 1.3 V (the nominal operating voltage) in the above (non-optimised) layout. This shows the very favourable overall power consumption of this movement principle. The power consumption of this circuit is more than 2 times smaller than the lowest power consuming Lavet type watch motor with a very optimised control circuit [11], which typically uses 400 nA at 1.5 V operating voltage (neglecting all other functions except the motor and drive circuit).

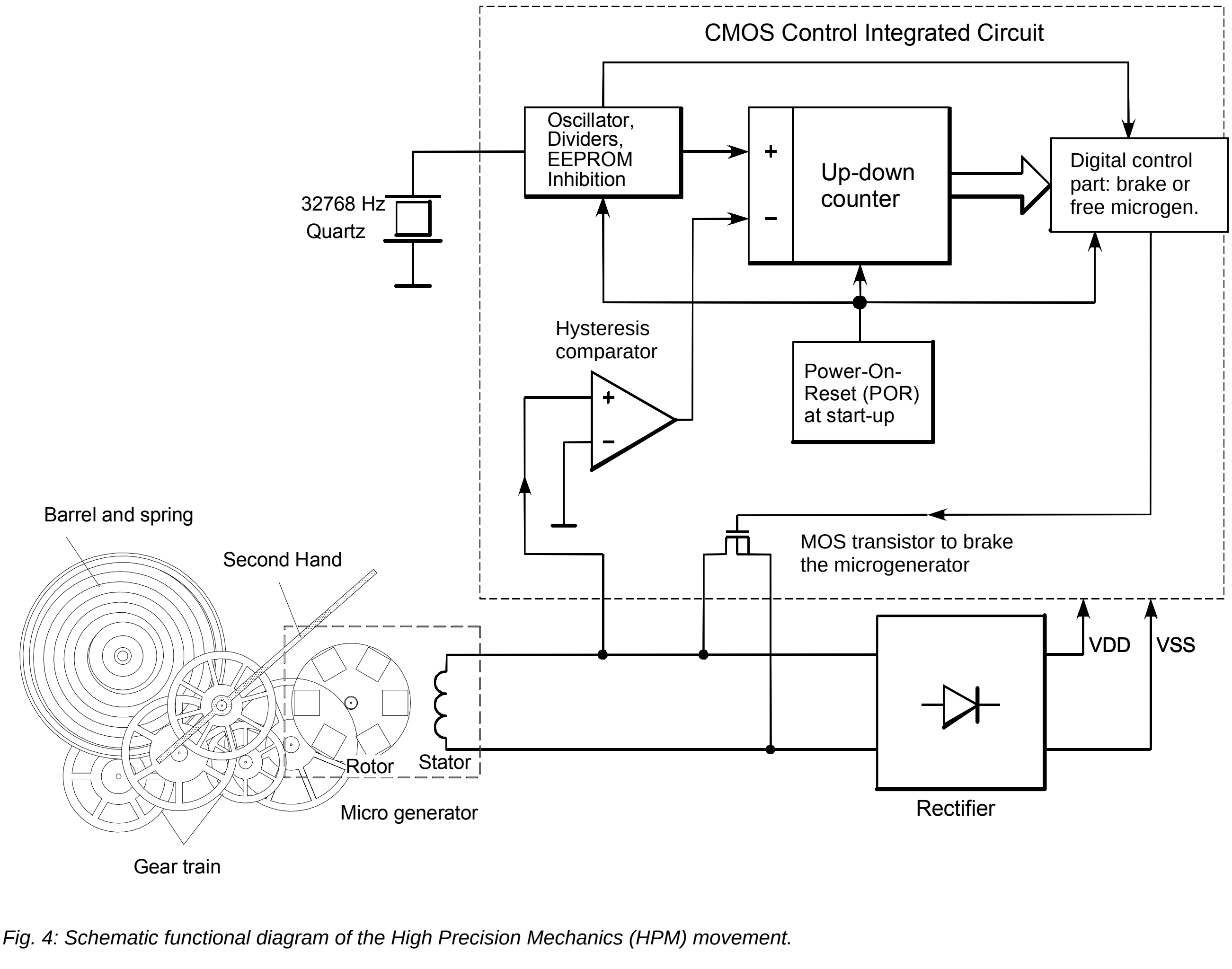

Fig. 4: Schematic functional diagram of the High Precision Mechanics (HPM) movement.

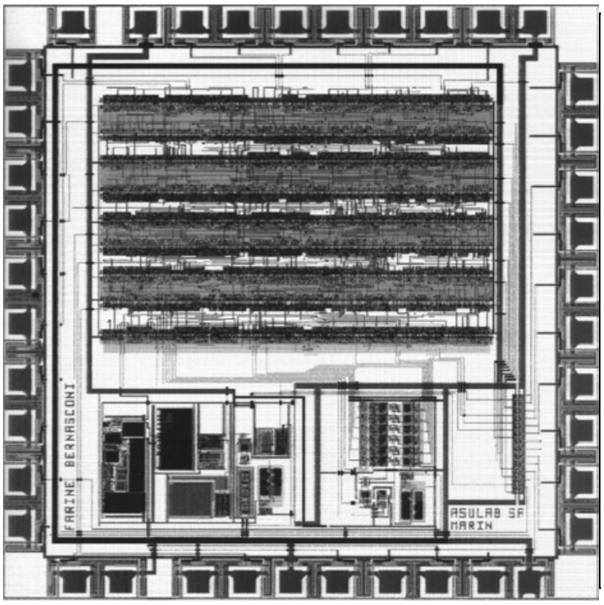

Fig. 5: HCMOS integrated circuit in EM-Marin 1.95 µm technology for the High Precision Mechanics (HPM) movement.

5. Results

150 HPM movements according to fig. 1 have been made and passed through ETA's standard movement test programme, extended temperature testing, noise measurement and extensive wear tests. The standard test programme has been successfully passed including the 5000-g shock tests and repetitive small shock testing.
Some movements have been used to perform extended temperature testing. Using special low temperature oils (such as Moebius ″Arctic″) the movements operate from -50°C up to +90°C. The higher temperature limit is due to the Schottky type diodes used to rectify the generator voltage which show increased leakage current at high temperatures. Active rectifier diodes could eliminate this effect.

Noise measurements

Noise measurements of a HPM movement in a Swatch Irony stainless steel case (with organic glasses on top and as a bottom cover) have been performed and compared with an Omega Seamaster (electronic quartz movement) and a Omega Speedmaster Professional (mechanical calibre) both in the original stainless steel case with sapphire glasses.

The microphone was placed at a 2mm distance from the watch glass and the results are as follows.

Omega Speedmaster Professional	48 dBA
Omega Seamaster	36 dBA
HPM in Swatch Irony case	< 28 dBA

The measurements show that the HPM movement is at least 8 dBA quieter than a practically inaudible watch. The noise measured at a HPM movement is due to the drive gear of the generator and at 80Hz where the human ear is less sensitive than for the noise due to the Lavet motor or the mechanical escapement. This shows that the HPM movement clearly is inaudible.

Wear test

The established test procedures normally show the weaknesses of products designed using known principles (they have been developed using the experience made with these known products), but for new concepts they may not reveal all the defects. For this reason extensive wear tests have been performed with Asulab people selected among sportsmen (tennis, squash, volley-ball, etc) and people often serving vibrating power tools or doing arc welding, etc.
The watches have been compared daily and/or weekly to the caesium standard (HBG signal of the Neuchâtel Observatory) with an optoelectronic comparator using the second hand position. This method has a statistical error estimated at ±0.01 seconds.

Fig. 6 shows the absolute time error rate with respect to the HBG signal over a two-year period. The measurements essentially show a linear behaviour that reveals the initial adjustment error of the quartz resonator.

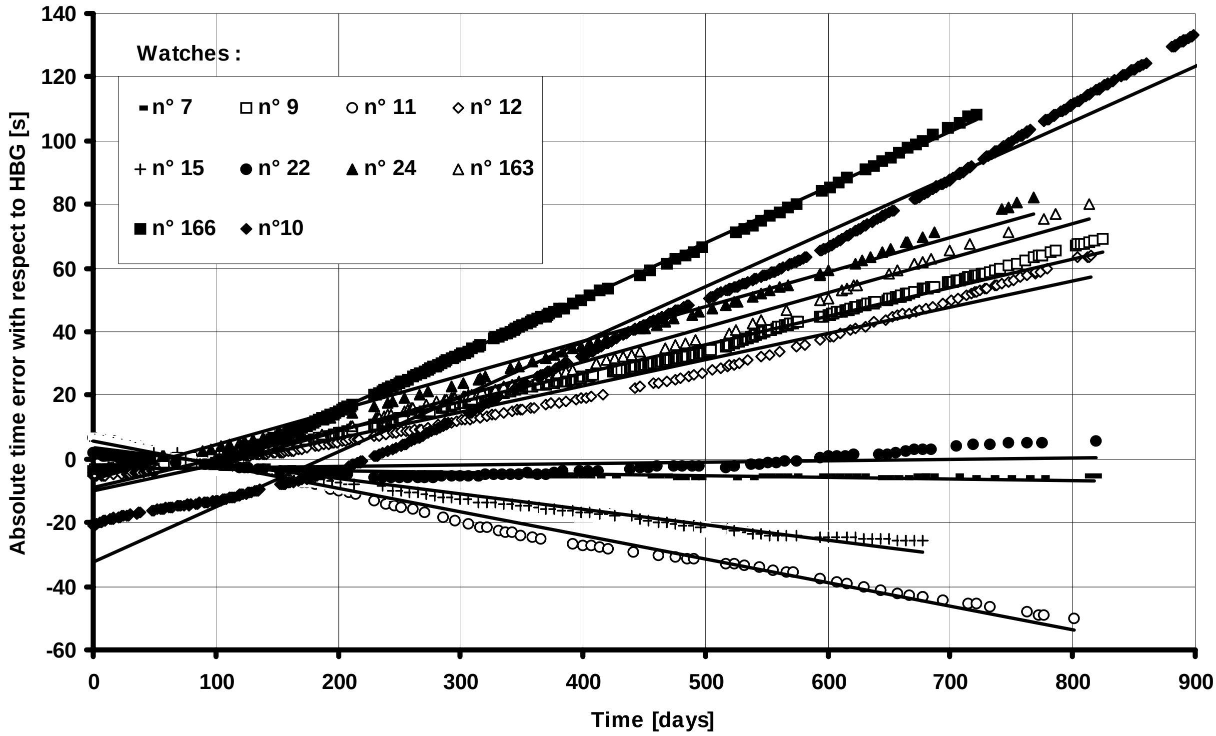

Fig. 6: Absolute time error with respect to the HBG Caesium standard clock during wear test over two years period for 10 HPM watches.

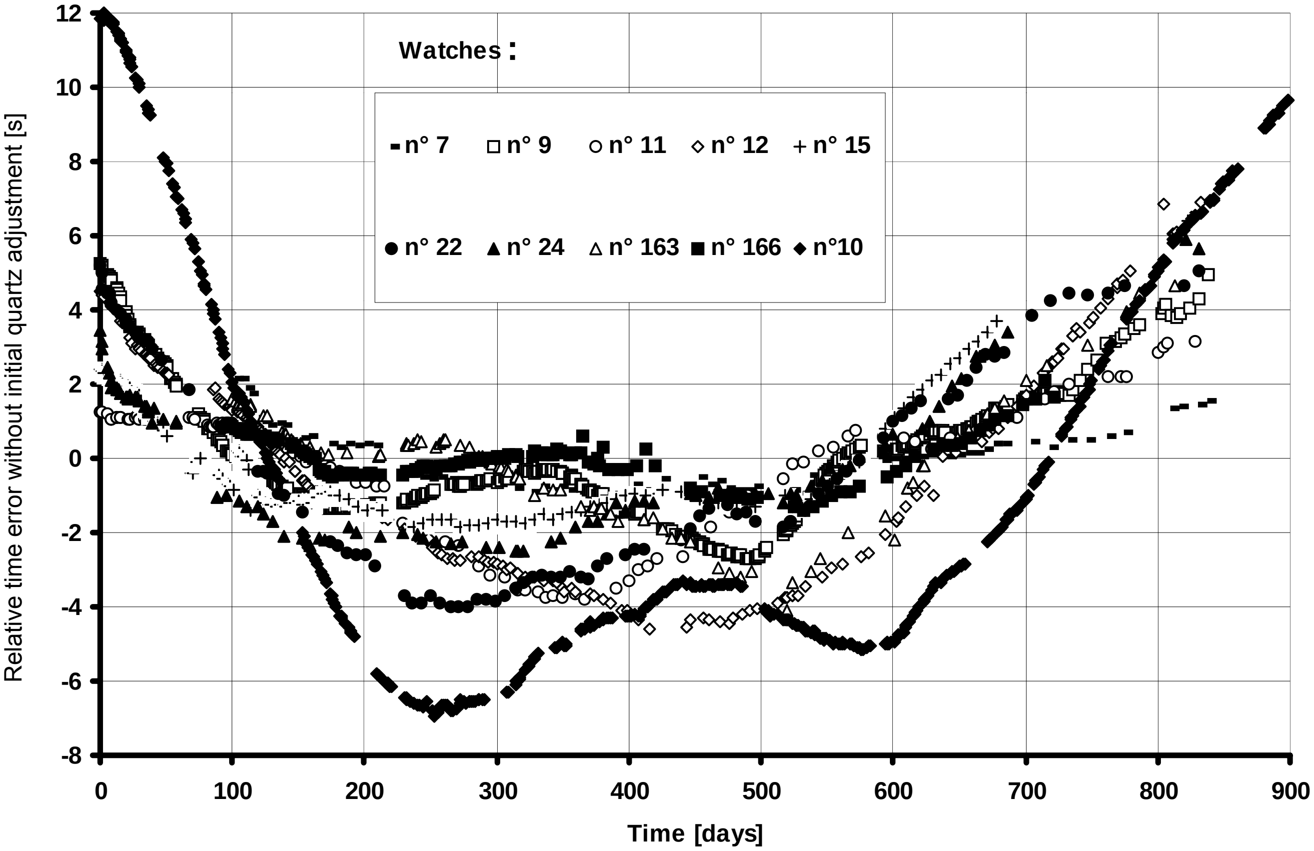

Figure 7: Measured relative time error without the initial adjustment error of the quartz resonator during wear test over a more than two years period for 10 HPM watches.

In order to reveal real time keeping errors of the HPM movement, a linear regression was made with the data of Fig. 6 and removed from the recorded data. The result is shown in Fig. 7. The figure shows, that no sudden ″jumps″ occur, which means that if the HPM movement would have shown time keeping errors, caused by the movement principle itself (and not due to errors inherent to the quartz resonator) these are in any case substantially below the aging and temperature effects of the quartz resonator.

The curves show in fact, that there are no mechanical movement errors at all. If the generator would have been blocked (e.g. by the service movement of a tennis player) and the IC goes through its ″power on reset″ cycle (otherwise no information is lost anyhow), this leads to a time loss of 0.5 seconds at least. Such a sudden offset of any of the curves of Fig. 7 would be easily visible and is obviously absent.

Electrical noise could create smaller time losses. Fig. 7 proves however that – if there are any electric interference losses present – they are far below the time keeping errors inherent to the quartz resonator.

In conclusion, the wear test have over a period of more than two years not revealed any time keeping errors other than the natural errors of the quartz resonators used.

The figure 7 shows that for some watches, the effect of the temperature variation on the quartz crystals frequency dominates. For some persons wearing the watch permanently, this effect and the unavoidable ageing of the resonator are very small. The watch with the most stable resonator is the watch n° 7 (which is worn permanently) and the curve in Fig. 8, which shows this watch n° 7 alone, still does not reveal any time keeping error not due to the quartz resonator.

Autonomy

The movement has been designed to reach the same autonomy as for a classical mechanical movement. With horizontal gear shafts 45 hours are reached with these 13''' size movements.

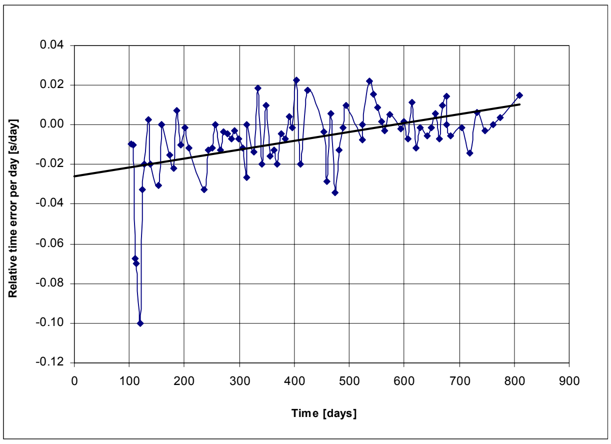

Fig. 8: Evolution of the relative time error per day on a worn HPM watch during 800 days. Seasonal temperature effects on the quartz (sinus wave) and ageing itself (slope of the curve 0.2 ppm/year for watch n°7) are very small and seem to be negligible here.

Accuracy check procedure

Any new watch movement principle leads to the development of appropriate instrumentation to measure its accuracy and correct time keeping performance especially for after sales service conditions. The test of the HPM movement is rather straightforward: the measurement equipment used to detect the analogue quartz movements by their motor stray-field also detect the braking pulses of the generator and allow to measure the HPM movement within three minutes to an accuracy of 1 ppm or to calculate the resulting accuracy in a few seconds by additional external electronics as the braking pulses are modulated the EEPROM inhibition values.

6. Conclusions

High precision mechanics (HPM) – a self-winding mechanical movement having the precision of an electronic quartz watch - has been developed. This performance is achieved by replacing the spring/balance wheel resonator and its associated escapement mechanism by a quartz tuning fork resonator and an electromechanical escapement (a micro-generator and an integrated control circuit).

It has to be noted that the escapement generator creates the electric energy needed for the resonator and escapement functions. For this reason, there is no need for electrochemical energy storage of any kind (rechargeable battery, supercapacitor, etc.) and the energy to operate the movement comes from the main spring as in any other mechanical timepiece.

The self-winding mechanism and the mechanical energy storage in the main spring give the user a reliability and comfort which is significantly better than both, the traditional mechanical movement (because the most critical elements – resonator and escapement – have been replaced by more reliable and more precise ones) and the traditional electronic quartz movement (because its most unreliable element – the electrochemical power source – has been replaced by a system of constant availability and unlimited lifetime).

The quartz movements cannot achieve this performance with a kinetic generating system recharging the accumulator or supercapacitor [12, 13]. On the other hand these movements offer the significantly larger autonomy (if not worn after a long wearing period) due to the relatively high-energy storage capacity of a rechargeable battery. It should, however, be considered, that no system can create energy. A much larger energy storage capacity needs to be ″filled up″ in order to be able to deliver its capacity and when empty often needs a much more uncomfortable handling than a mechanical watch in order to run again normally.

The large operating temperature domain together with its reliability makes this movement an ideal choice for extreme conditions such as expeditions, etc.

7. Acknowledgements.

The authors would like to thank E. Favre from ETA S.A. for the encouraging discussions and performing the test programme on the HPM movements. The HPM development has been carried out by an interdisciplinary team at Asulab and the authors would like to thank their colleagues E. Bernasconi, F. Chabloz, R. Froidevaux, R. Frossard, J. Labourey, S. Rota, R. Viennet, J.-P. Wattenhofer and F. Wiget for their very significant contribution.

8. References.

[1] J.-J. Born, R. Dinger et P.-A. Farine, Salto – Un mouvement mécanique à remontage automatique ayant la précision d'un mouvement à quartz, Journée d'Etude 1997 de la Société Suisse de Chronométrie SSC, Le Sentier, Suisse, 2 octobre 1997.

[2] L. Defossez, Théorie générale de l'horlogerie, Chambre suisse de l'horlogerie, Volumes I et II, La Chaux-de-Fonds, Suisse, 1950.

[3] M. Hetzel, Le diapason et son influence sur l'horlogerie, bulletin annuel de la société suisse de chronométrie, vol IV-1962, juin 1962, p. 666-679.

[4] J.-C. Berney, Mouvement d'horlogerie mû par un ressort et régulé par un circuit électronique, brevet suisse n° 595 636, Ebauches S.A., avril 1978.

[5] M. Tu Xuan, D. Taghezout, Mechanical to Electrical Energy Converter, United States Patent Number 4,799,003, January 17, 1989.

[6] F. Wiget, Timepiece driven by a source of mechanical energy and regulated by an electric circuit, United States Patent Number 5,517,469, May 14, 1996.

[7] M. Jufer, Transducteurs électromécaniques, Traité d'électricité de l'EPFL, Volume IX, Editions Georgi, St-Saphorin, Suisse, 1979.

[8] Ph. Marmy, E. Favre, Chocs et accélérations de la montre portée, 6ème congrès européen de chronométrie, Bienne, Suisse, octobre 1996, p. 141-144.

[9] P.-A. Farine, F. Pellandini, On the behaviour of quasi-continuous digital filters, Digital Signal Processing – 84, Florence, Italy, 5 – 8 September, 1984, pp. 27-31.

[10] HCMOS 3µm - R 35% Shrink, Low Voltage Electrical Parameters, Specification 050325, EM Microelectronic-Marin S.A., Marin, Switzerland, 1997.

[11] E. Bernasconi, J.-P. Wattenhofer, P.-A. Farine, D. Taghezout, COCA - An On Line Control IC for Watch Stepping Motors, Proceedings of the 22nd European Solid-state Circuits Conference ESSCIRC'96, Neuchâtel, Switzerland, September 1996, pp. 180 - 183.

[12] T. Hara, Seiko Kinetic Quartz, 63ème congrès de la société suisse de chronométrie, Granges, Suisse, octobre 1995, p. 71-74.

[13] B. Gilomen, J.-L Béguin et R. Bugmann, Autoquartz - Le mouvement à quartz dont l'énergie est fournie par une génératrice, Journée d'Etude 1997 de la Société Suisse de Chronométrie SSC, Le Sentier, Suisse, 2 octobre 1997.