

MECHANICAL OSCILLATOR SYSTEM

The present invention relates to a mechanical oscillator system comprising a balance and balance spring for use in
5 horological mechanisms (e.g. timekeeping devices) or other precision instruments. It is thought that it will be particularly applicable to the oscillator system in a mechanical watch, although the present invention is not limited to this.

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Previous mechanisms use metal alloys, in particular Fe-Ni or Ni, Cu-Be, Au-Cu alloys, for the balance spring and balance. At its most general, the present invention proposes that the balance is made of a non-magnetic
15 ceramic material and the balance spring is non-magnetic and is made of a composite material, or a polymer (including thermoset and thermoplastic polymers, esters and phenolic based resins), carbon or (non-magnetic) ceramic material, the materials having suitable
20 properties so as to compensate for thermal variation in the system.

In contrast to metals, the above materials are non-susceptible to the effects of magnetism - including
25 electromagnetic damping and magnetically induced change

of the Young's modulus. These materials have some intrinsic thermal characteristics which are better than metals and so a mechanical oscillator system having reduced variation of oscillator frequency with temperature can be made. Variation with temperature is discussed below in more detail. A balance spring of the above materials may be less susceptible to internal mechanical (e.g. friction) damping of the Young's Modulus, allowing amplitude to be maintained by the balance and a higher frequency of oscillation and therefore a more accurate horological mechanism or precision instrument than a metal spring.

The balance spring is arranged to oscillate the balance. Preferably the balance is a balance wheel; the balance spring may be arranged inside the circumference of the balance wheel so as to oscillate the balance wheel back and forth about its axis of rotation as is conventional. The balance may be coupled to an escapement mechanism for regulating rotation of an escape wheel (which is e.g. coupled to the hands of a watch), as is also conventionally known.

Preferably the balance spring works in flexion to oscillate the balance, most preferably exclusively in flexion. That is the balance spring is preferably not relying on strain or shear properties for the repeated store and release of energy during its (relatively rapid) oscillations. Preferably the balance spring coils are not in contact with each other, i.e. there is a gap between adjacent coils. This eliminates or reduces friction and allows the successive coils to act unhindered by one another.

While the main body of the balance is made of a ceramic material, it may have small appendages of other materials.

Considerations relating to the oscillator frequency and in particular its variation with temperature will now be discussed.

The accuracy of a mechanical watch is dependent upon the specific frequency of the oscillator composed of the balance wheel and balance spring. When the temperature varies, the thermal expansion of the balance wheel and balance spring, as well as the variation of the Young's

Modulus of the balance spring, change the specific frequency of the oscillating system, disturbing the accuracy of the watch. The inventor has noticed that in known systems approximately three quarters of the variation is due to thermal or magnetically induced changes in the balance spring.

Methods for compensating these variations are based on the consideration that the specific frequency depends exclusively upon the relationship between the torque of the balance spring acting upon the balance and the moment of inertia of the latter as is indicated in the following relationship

$$T = 2\pi \sqrt{\frac{I}{G}} \quad [1]$$

T : the period of oscillation, I : the moment of inertia of the balance wheel, G : the torque of the balance spring.

The moment of inertia of the balance wheel is a function of its masse M and its radius of gyration r .

The torque of the balance spring is a function of its dimensions: length l , height h , thickness e , and of its Young's Modulus E . The length l of the balance spring (which may be helical or spiral form) is the whole length of the spring, end to end, as distinct from e.g. a top to

bottom measurement that varies according to the spacing of the coils.

The relationship [1] is therefore written:

$$T = 2\pi \sqrt{\frac{12.M.r^2.l}{E.h.e^3}} \quad [2]$$

Temperature variations influence T (the period of oscillation) resulting from the effects of expansion and contraction of the system (balance spring and balance wheel) l , h and e for the balance spring, and r for the balance wheel whose mass m remains constant.

It is known how to compensate for the effects of expansion on l , h and e . However the period of oscillation is still subject to variations of r and E in keeping with the relationship expressed by:

$$\frac{r}{\sqrt{E}} \quad [3]$$

These two terms are not in a linear relationship.

It is necessary that this relationship should remain as constant as possible (so as to keep the period T of oscillations constant).

Fe-Ni metal spring alloys render an approximate solution when the alloy is perfectly de-magnetised. However, when the alloy is not perfectly demagnetized, the relationship is no longer constant: $\sqrt{E}$ changes.

The currently employed metal alloys for balance springs show an increase in E (which is considered abnormal) and also in l , for an increase in temperature, over the ambient temperature range up to 40°C. The balance wheels currently employed in precision watches are of an Au-Cu alloy with a coefficient of thermal expansion α between +14 and +17x10⁻⁶ K⁻¹ to compensate for changes in the Young's modulus of the balance spring.

In summary, the currently used metal alloys despite compensation, only allow for the stability of T (period of oscillation) over a narrow temperature range and only when the balance spring alloy remains un-magnetised. (Any watch currently employing a Fe-Ni balance spring may be stopped by a sufficient magnet).

EP 0732635 discloses a spiral spring and balance wheel made of crystalline material which is less sensitive to temperature fluctuations and magnetic fields.

According to the invention, there is provided a mechanical oscillator system as set out in claim 1.

According to a first aspect of the present invention, there is provided a mechanical oscillator system for a

horological mechanism or other precision instrument, the system comprising: a non-magnetic ceramic balance, and a non-magnetic balance spring formed of a composite material or a polymer, carbon or ceramic material, wherein the balance and balance spring are adapted such that the coefficient of thermal expansion of the balance (α_1), the coefficient of thermal expansion of the balance spring (α_2) and the thermoelastic coefficient of the balance spring ($\partial E/E$) cooperate to compensate for thermal variation in the system.

According to a second aspect of the present invention, there is provided a non-magnetic balance spring for oscillating a balance in an oscillator mechanism for a horological instrument, the balance spring formed from a composite material or a polymer, carbon or ceramic material, wherein the balance spring material has a coefficient of thermal expansion (α_2) and a thermoelastic coefficient ($\partial E/E$) arranged to cooperate with a coefficient of thermal expansion of the balance (α_1) to compensate for thermal variation in the system.

Preferably the balance spring material comprises continuous fibres extending along the length of the

balance spring from one end of said spring to the other end of said spring.

5 As the fibres are continuous extending along the length of the balance spring from one end to the other, the degree to which the spring expands (or contracts) with an increase in temperature can be controlled fairly accurately by appropriate choice of the fibre material.

10 Preferably the continuous fibres are part of a composite material, although it is possible to have a balance spring of continuous fibres in a non-composite material (i.e. without a matrix, e.g. long ceramic fibres).

15 Where the material is a composite material, preferably the matrix phase comprises a polymer (of any of the types discussed above), carbon or a ceramic. In the case of a composite material with ceramic fibres, the fibres may be continuous fibres extending along the length of the
20 spring from one end of the spring to the other as discussed above, or smaller fibres that do not extend all the way along the spring.

Where ceramic fibres are used (with or without a matrix), it is important that the ceramic is a non-magnetic ceramic. Preferably, but not necessarily, the balance spring ceramic is Alumina-Silica-Boria. Fused quartz or
5 silica may also be used for the balance.

Preferably the thermal coefficient of expansion of the balance and the thermal coefficient of expansion of material of the balance spring, in the direction along
10 the length of the balance spring, are of opposite signs and of similar orders of magnitude (i.e. the difference in magnitude between the two is not more than a factor of 6 and one of the α coefficients should not be greater than $1 \times 10^{-6} \text{ K}^{-1}$). In this way expansion of one can be
15 compensated for by contraction of the other. For example, if said thermal coefficient of expansion of the balance spring is negative and said thermal coefficient of expansion of the balance is positive then with an increase of temperature r increases, but l decreases and
20 in accordance with equation [2] these effects combine to assist in compensating for thermal variation in said period of oscillation T .

Preferably said coefficient of expansion are both very small. For example preferably the coefficient of thermal expansion of the balance is positive and less than $1 \times 10^{-6} \text{K}^{-1}$ and the coefficient of thermal expansion of the material of the balance spring in the direction along the length of the balance spring is negative, but greater than $-1 \times 10^{-6} \text{K}^{-1}$.

The variation of E (Youngs Modulus) with temperature is also important and is determined by the thermoelastic coefficient which is a measure of the unit change in Young's Modulus per unit increase in temperature. Preferably the thermoelastic coefficient of the material of the balance spring is negative ; most preferably 1% in the temperature range 0 to 60 degrees Celsius.

In general, the formula for timekeeping changes (U) consequent upon a rise in temperature of 1°C is

$$U = \alpha_1 - 3\alpha_2 / 2 - \delta E / 2E$$

Thus U can be made to tend to zero when suitable values of α_1 (balance coefficient of thermal expansion), α_2 (balance spring coefficient of thermal expansion) and the

thermo-elastic coefficient $\delta E/E$ are selected by selection of appropriate materials.

5 The tolerances represented by small α_1, α_2 (e.g. less than $6 \times 10^{-6} \text{ K}^{-1}$) and a small thermo-elastic value $\delta E/E$ allow much more readily for U to be kept low.

10 Preferably the continuous fibres are ceramic fibres or carbon fibres, most preferably carbon fibres having a graphitic carbon structure. Graphitic carbon structure has a negative longitudinal coefficient of thermal expansion. The fibres may for example be produced from a "PITCH" precursor or a polyacrylonitrile "PAN" precursor.

15 The fibres may be laid parallel to each other along their lengths, or may be twisted together. Twisting the fibres together modulates the coefficient of thermal expansion and Young's Modulus of the balance spring material and may be useful where the fibres have a high and the matrix
20 a low Young's Modulus or coefficient of thermal expansion.

Preferably the coefficient of thermal expansion of the balance spring material in the direction along the length

of the balance spring is linear up to 700° Kelvin. This allows the system to be very stable in the ambient range (0-40°C) and also to compensate for thermal variations over a large range. Preferably said coefficient of thermal expansion is negative.

Preferably the damping of the modulus of elasticity of the balance spring is of the order of 0.001 pa.

Preferably the density of the composite material of the balance spring is less than 3g/cm³.

Preferably the balance is formed by high precision injection moulding.

Further aspects of the present invention also provide a horological mechanism or other precision instrument comprising the above described mechanical oscillator system.

An embodiment of the invention will now be described.

A mechanical oscillating system for use in a horological mechanism or other precision instrument comprises a balance, in the form of a balance wheel, and a balance spring arranged to oscillate said balance around an axis
5 of rotation.

The balance wheel is made of a non-magnetic ceramic for which the coefficient of thermal expansion is, positive and less than $+6 \times 10^{-6} \text{ K}^{-1}$, most preferably less than 1
10 $\times 10^{-6} \text{ K}^{-1}$. Quartz is one example of a suitable material. Preferably high purity fused quartz is used, fused quartz has a coefficient of thermal expansion of $\leq +0.54 \times 10^{-6} \text{ K}^{-1}$. Other alternative ceramic materials include Aluminium Nitride (+5.2), Alumino-Silicate-Glass (+5), Boron
15 Carbide (+5.6), Boron Nitride (+1.6), Silica (+0.75), Silicon hot-pressed or reaction bonded (+3.5) and Zirconia (stabilised) (+5); the numbers in brackets indicate the order of magnitude of the coefficient of thermal expansion of these materials in units $\times 10^{-6} \text{ K}^{-1}$

20 The method of fabrication of the balance wheel may preferably be by high precision injection moulding.

The balance spring is shaped into an Archimedes flat spiral or helicoid form. It is made from a composite material comprising continuous carbon fibres which are either twisted or laid parallel to each other, the fibres being continuous lengths of fibres which extend from one end of the spring to the other along the length l of the spring. The fibres are derived according to the stiffness required from the precursor pitch (a mixture of thousands of different species of hydrocarbon and heterocyclic molecules) or polyacrylonitrile 'PAN' (derived from a carbon graphitic structure). The fibres are coated and set in a matrix phase of polymer (thermosetting polymer, thermoplastic polymer, ester or phenolic base resin etc), ceramic or carbon. The composite material acts in a flexural manner. The axial modulus of elasticity of the fibres is between 230 and 1000Gpa. The composite has both a lower density less than 3g/cm^3 and coefficient of damping of its Young's modulus of the order of (0.001 pa), both less than the currently employed metal alloys. Its thermal expansion coefficient (α) in the direction along the length of the spring remains both negative and stable to 700° Kelvin, and is greater than $-1 \times 10^{-6} \text{ K}^{-1}$.

This composite material is non-magnetic and obviates the negative effects of magnetism. The coefficient of thermal expansion α of the spring is negative and acts in parallel with the spring's Young's modulus which decreases linearly with a rise in temperature and is therefore negative (normal).

The values of the coefficients of thermal expansion (the α coefficients) for the spring and the balance are similar, very small and of opposite sign which further assist in the compensation for temperature variation.

The α coefficient of the spring remains the same over a wide temperature range, and the range of its use between 5° and 40°C represents only 5% at the centre of the total stable temperature range.

Thus, following the relationship:

$$T = 2\pi \sqrt{\frac{12Mr^2l}{Ehe^3}} \quad [2]$$

the numerator does not increase in value as is the case with the metal alloys when the temperature increases because the α coefficient of the fibre composite in the axial sense l is negative, and therefore it diminishes. The denominator also diminishes when the temperature rises because the thermoelastic coefficient is negative

(normal). Furthermore the height (h) and thickness (e) of the carbon fibre-matrix composite balance spring also increase with temperature which also counteracts the decrease in Young's Modulus E with rising temperature.

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By this combination of materials and their mechanical properties it is possible to obtain both greater accuracy and stability. The damping effect of the modulus of elasticity is one tenth of the value of the currently employed metal alloy and the reduced energy losses due to the decreased damping and density of the material allow to envisage maintaining stable amplitude and a significant increase in frequency and significantly reduced total energy losses in the oscillator system.

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As has been explained above the present invention can be applied to a conventional mechanical oscillator system in a time keeping device such as a watch. An example of a conventional mechanical oscillator system in a time keeping device is illustrated and described on pages 194 to 195 of "How Things Work", volume 1 published 1972 by Paladin, UK, which is incorporated herein by reference.

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CLAIMS

1. A mechanical oscillator system for a horological mechanism or other precision instrument, the system comprising:

- 5 a non-magnetic ceramic balance, and
 a non-magnetic balance spring formed of a composite material or a polymer, carbon or ceramic material,
 wherein the balance and balance spring are adapted such that the coefficient of thermal expansion of the balance (α_1), the coefficient of thermal expansion of the balance spring (α_2) and the thermoelastic coefficient of the balance spring ($\partial E/E$)
10 cooperate to compensate for thermal variation in the system.

2. A system according to claim 1, wherein the balance spring is of flat spiral or helicoidal form, and the coefficient of thermal expansion of the balance spring in a
15 direction along its length and the coefficient of thermal expansion of the balance are of opposite signs and of similar orders of magnitude.

3. A system according to claim 2, wherein the coefficient of thermal expansion of the balance is positive and the coefficient of thermal expansion of the material of the balance spring in the direction along the length of the balance spring is negative.
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4. A system according to claim 3, wherein the thermal coefficient of expansion of the balance is less than $1 \times 10^{-6} \text{ K}^{-1}$ and the coefficient of thermal expansion of the material of the balance spring in the direction along the length of the balance spring is greater than $-1 \times 10^{-6} \text{ K}^{-1}$.
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5. A system according to any preceding claim, wherein the material of the balance spring is a composite material having a matrix phase comprising polymer, carbon or ceramic.
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6. A system according to any preceding claim, wherein the balance spring material comprises continuous fibres extending along the length of the balance spring from one end of said spring to the other end of said spring.

7. A system according to claim 6, wherein said continuous fibres are carbon fibres.

5 8. A system according to claim 6, wherein the fibres are produced from one of the precursors 'PITCH' or polyacrylonitrile 'PAN'.

9. A system according to any of claims 1 to 8, wherein the material of the balance spring is a composite material having a coefficient of thermal expansion in the direction along the length of the balance spring which is negative and exhibits
10 linear thermal variation at temperatures up to 700° Kelvin.

10. A system according to the preceding claim, wherein the damping of the modulus of elasticity of the balance spring is of the order of 0.001 Pa.

15 11. A system according to any of claims 1 to 3, wherein the balance spring material comprises ceramic fibres.

12. A system according to claim 11, wherein said ceramic fibres have a coefficient of thermal expansion whose magnitude is less than $6 \times 10^{-6} \text{ K}^{-1}$.
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13. A system according to any of claims 6 to 8, 11 and 12, wherein said fibres are substantially parallel to each other.

14. A system according to any of claims 6 to 8, 11 and 12, wherein said fibres are
25 twisted together.

15. A system according to any preceding claim, wherein the balance spring is a flexion spring configured to work in flexion to oscillate the balance.

30 16. A system according to any preceding claim, wherein the density of the balance spring material is less than 3 g/cm^3 .

17. A system according to any preceding claim, wherein the balance is formed by high precision injection moulding.
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18. A system according to any preceding claim, wherein the material of the balance spring has a negative thermoelastic coefficient.

5 19. A system according to any preceding claim, wherein the respective magnitudes and thermal variations of the coefficient of thermal expansion of the material of the balance (α_1), the coefficient of thermal expansion of the material of the balance spring (α_2) and the thermoelastic coefficient of the material of the balance spring ($\partial E/E$) are selected such that, for thermal variation within a predetermined temperature range, the variation (U) in timekeeping changes for the system is
10 minimised, where

$$U = \alpha_1 - 3\alpha_2/2 - 1/2\partial E/E.$$

20. A non-magnetic balance spring for oscillating a balance in an oscillator mechanism for a horological instrument, the balance spring formed from a composite
15 material or a polymer, carbon or ceramic material,

wherein the balance spring material has a coefficient of thermal expansion (α_2) and a thermoelastic coefficient ($\partial E/E$) arranged to cooperate with a coefficient of thermal expansion of the balance (α_1) to compensate for thermal variation in the system.