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Mechanism Balancing Taxonomy for the Classification of Horological Oscillators

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L'équilibrage des mécanismes consiste à distribuer leurs masses, inerties et éléments élastiques de manière à leur octroyer des propriétés mécaniques spécifiques, telles que l'insensibilité à la gravité, l'insensibilité aux vitesses et accélérations linéaires et angulaires de leur châssis, ou encore l'annulation des forces et moments exportés. Cet article présente une nouvelle taxonomie de l'équilibrage des mécanismes, structurée en 15 types distincts, qui clarifie les concepts d'équilibrage « statique » et « dynamique ». Elle révèle des aspects inexplorés de l'équilibrage qui sont pertinents pour la conception de mécanismes soumis à de fortes perturbations inertielles, tels que les oscillateurs des horloges de marine ou des montres-bracelets ; la précision chronométrique de ces bases de temps composées d'un corps inertiel – généralement un balancier – et d'un ressort de rappel – généralement un spiral – est en effet affectée par les mouvements de leur châssis. La classification de divers oscillateurs mécaniques horlogers selon cette nouvelle taxonomie met en évidence leurs principales propriétés. Sept mécanismes sont sélectionnés : l'oscillateur du pendule de Huygens, les oscillateurs de trois des chronomètres de marine de Harrison (H1, H3 et H4), ainsi que trois oscillateurs à guidages flexibles développés par l'Instant-Lab (EPFL) destinés au remplacement des balanciers-spiraux classiques : Quadrivot (oscillateur à 1-degré-de-liberté (DDL) équilibré en force), Wattone (oscillateur à 1-DDL équilibré inertiellement) et Wattwins (oscillateur à 2-DDL, de type IsoSpring® planaire, équilibré inertiellement).

The balancing of mechanisms consists in distributing their moving masses, inertias, and elastic components in order to achieve key mechanical properties, such as the insensitivity of the mechanism to gravity and to the motions of its chassis, or the elimination of the shaking forces and moments exported onto their supporting structure. This article presents a new taxonomy of mechanism balancing that is structured into 15 distinct types. The proposed classification clarifies the concepts of « static » and « dynamic » balancing, and reveals unexplored aspects of balancing that are relevant to the design of mechanisms exposed to high inertial disturbances, such as the oscillators of marine clocks and mechanical wrist-watches. The chronometric precision of these time-bases that are composed of an inertial body – typically a balance wheel – and a restoring spring – typically a hairspring – is indeed affected by the movement of their chassis. The classification of various mechanical horological oscillators according the new taxonomy reveals their key mechanical properties. Seven mechanisms have been selected : the oscillator of Huygens' pendulum clock, the oscillators of three of Harrison's marine chronometers (H1, H3 and H4), and three flexure-based oscillators developed by Instant-Lab (EPFL) dedicated to the future replacement of the traditional balance springs: Quadrivot (1-Degree-of-Freedom (DoF) force balanced oscillator), Wattone (1-DoF inertially balanced oscillator) and Wattwins (2-DoF planar IsoSpring® inertially balanced oscillator).

Introduction

Balancing is a fundamental field of mechanical engineering: it enhances the static and dynamic performance of mechanisms ranging from simple rotating shafts to complex robotic systems. Balancing is used for example to counteract the gravitational forces affecting heavy portable devices such as movie cameras, making them easy to handle at arm's length. For space applications, balancing is required for example in order to mitigate shaking forces and moments that mechanisms may export onto the satellite's chassis as they move. In horology, the chronometric performance of mechanical watches is affected by the orientation of gravity as well as by linear and angular accelerations resulting from the wrist movements: balancing is a means for decreasing the sensitivity of the oscillators to these external disturbances.

In the existing literature, balancing is generally classified in 4 types: static balancing, shaking force balancing, shaking moment balancing, and dynamic balancing. However, a closer examination reveals gaps in these classifications, inconsistencies in terminology between «static» and «force» balancing, and ambiguities concerning the properties associated with dynamic balancing, particularly when considering rotating reference frames. To overcome these issues, we established rigorous definitions of the main balancing types, listed their intrinsic properties, and introduced a new balancing taxonomy [1]. This taxonomy is composed of 4 primary types (**S***, **F***, **M*** **a**nd **I***), whose 15 combinations yield to 4 *pure balancing types* (**S, F, M** and **I**) and 11 *blended types* (**SF, SFM, SFMI, SFI, SM, SMI, SI, FM, FMI, FI, MI**). The **FMI*** balancing type - inertial balancing - is of particular interest for watchmaking. Indeed, if an oscillator satisfies the inertial balancing conditions, it is completely decoupled from the motion of its chassis, *i.e.*, it is insensitive to linear and angular accelerations as well as angular velocities.

Mechanical watch oscillators are, in their vast majority, balance and hairsprings. Theoretically, these oscillators have a low sensitivity to the orientation of gravity and to linear accelerations, but they are highly sensitive to angular accelerations of the watch around axes parallel to their axis of rotation. Angular shocks therefore interfere with the harmonic motion of the oscillators, which affects the timekeeping accuracy.

In order to understand how to design new oscillators that are robust to angular accelerations as well as to angular velocities, we have selected seven horological oscillators and classified them using the new proposed taxonomy.

The first oscillator is the one used in the Huygens' pendulum clock [2, App. 2]. The second, third and fourth oscillators are the H1, H3 and H4 of Harrison's marine chronometers [3]–[5]. The fifth, sixth and seventh oscillators are flexure-based mechanisms developed at Instant-Lab (EPFL) - named Quadrivot, Wattone and Wattwins - having no solid friction, no lubrication, and a drastically reduced number of parts [6]. The Quadrivot is a one-degree-of-freedom (DoF) oscillator with theoretically zero parasitic shift and a high radial stiffness that makes it less sensitive to radial accelerations than the known flexure-based watch oscillators [7]. The Wattone is a 1-DoF oscillator that is fully decoupled from all motion of the wrist, paving the way to better timekeeping accuracy. The Wattwins is a 2-DoF planar inertially balanced oscillator based on the IsoSpring® concept [8]–[10] using a simple driving crank (Figure 4) instead of an escapement. Using the introduced taxonomy, we will discuss the placement of these seven oscillators within the classification and discuss the advantages and potential drawbacks of balancing oscillators.

Balancing taxonomy

The new mechanism balancing taxonomy is illustrated by a 4-set Venn diagram (Figure 1). Each set, which is represented by an ellipse, corresponds to a *primary balancing type* (**S***, **F***, **M*** and **I***). The latter can combine, resulting in 15 distinct types of balancing, including 4 *pure balancing types* and 11 *blended balancing types*. Among the *blended types*, we highlighted two important subsets: the **FM*** subset, called *dynamic balancing*, and the new **FMI*** subset, called *inertial balancing*.

For the design of mechanical oscillators, it is essential to know which balancing type is required to withstand which kind of excitation: linear accelerations, angular accelerations, and angular velocities.

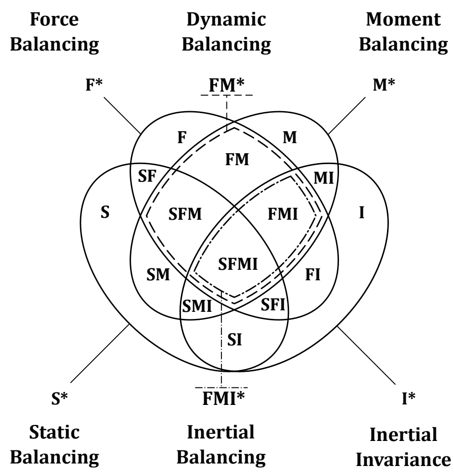


Figure 1: Mechanism balancing taxonomy structured as a 4-set Venn diagram [1].

Static balancing (**S***) is satisfied when a mechanism has constant potential energy over its workspace. Since such mechanisms are zero-force, they cannot be used as oscillators: indeed, a restoring force is required in order to produce oscillation.

Force balancing (**F***) is satisfied when the linear momentum of a mechanism is constant over its workspace. During motion, a type **F** mechanism has its center of mass (CoM) fixed. The mechanism is insensitive to linear accelerations. Force balanced mechanical watch oscillators are theoretically insensitive to changes in gravity orientation as well as to radial shocks. However, they are sensitive to angular accelerations and velocities.

Moment balancing (**M***) is satisfied when the angular momentum of a mechanism at an arbitrary point (A) is constant over its workspace. The relevant property of a type **M** mechanism is its insensitivity to angular accelerations around point A. For practical reasons, moment balancing is frequently combined with force balancing, leading to what is commonly referred to as *dynamic balancing* (**FM***). In this case, the force and moment balancing properties add up, and the dynamically balanced mechanism is insensitive to linear and angular accelerations around any axis. A dynamically balanced oscillator is insensitive to angular shocks but is nevertheless sensitive to angular velocities.

Inertial invariance (**I***) is satisfied when the angular momentum as well as the inertia tensor of a mechanism at an arbitrary point (A) are configuration-invariant. A type **I** mechanism is insensitive to angular velocities only around point A. When combined with force balancing, the type **FI** mechanism is insensitive to linear accelerations as well as angular velocities around any axis. On the other hand, a type **MI** mechanism is insensitive to angular accelerations and velocities around point A. Finally, a **FMI** mechanism combines all the balancing properties and is said to be *inertially balanced*. Such mechanisms are insensitive to linear and angular accelerations as well as to angular velocities around any axis. Hence, an inertially balanced watch oscillator is theoretically fully decoupled from the wrist movements.

The insensitivity properties associated with each balancing type are summarized in Table 1.

Balancing taxonomy applied to horological oscillators

To help the reader better understand how mechanisms can exhibit typical balancing properties, we propose to apply the balancing taxonomy to specific mechanical watch oscillators. With oscillators we selected from 4 well-known horological projects as well as from 3 designs of Instant-Lab, we explain how they are coupled with the motions of their chassis and where they should be located within the balancing taxonomy (see Figure 6).

Huygens' pendulum

The Huygens' pendulum-regulated clock was invented in 1656 (Figure 2). By definition, a pendulum is not balanced: it's center of mass moves, it is composed of single rotating body, and its inertia tensor varies during movement. This oscillator is therefore very sensitive to changes of gravity orientation, linear and angular accelerations, as well as to angular velocities. Within the balancing taxonomy (Figure 6) the Huygens' clock is therefore located outside of the 4-set Venn diagram. Indeed, Huygens sent several of his clocks on ships, with the intention of calculating the longitude at sea. In calm seas, the longitude was accurately estimated, but during stormy weather, the movements of the ship affected the pendulum's swing [11].

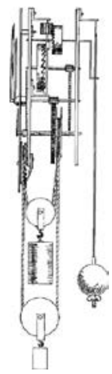


Figure 2: Huygens' pendulum-regulated clock [2, App. 2].

H1: Harrison's first marine chronometer

H1 is a marine chronometer designed by John Harrison in between 1730 and 1735 in response to the British government's Longitude Act, which offered a substantial reward for a solution to accurately determine a ship's longitude at sea. H1 has an oscillator composed of two dumbbell balances linked together so that they perform opposite rotations of equal amplitudes. This oscillator has a spring-based restoring force provided by 4 helical springs connecting the 4 moving masses to the frame (Figure 3a). This mechanism has a fixed center of mass, two identical balances rotating in opposite directions and a total inertia tensor varying along axes within its plane of oscillation[1]. H1's oscillator is hence theoretically insensitive to linear and angular accelerations, but sensitive to angular velocities. Indeed, one can find in [11, p. 105] a mention saying that – « While testing H-2 [Har-

1 The inertia tensor of this generic oscillator architecture has been computed in [1, Sec. 2.6.8].

Table 1: Balancing conditions required for a mechanism to be insensitive to the motions of its chassis.

Type of motion of the chassis	Translation	Rotation around a fixed axis	Rotation around any axis
Constant speed	None	**I**	**F**
Acceleration at low speed	**F**	**M**	**FM**
Acceleration at high speed	**F**	**MI**	**FMI**

rison's second marine chronometer having the same oscillator kinematic as H1] Harrison discovered that if the timekeeper was subjected to a sudden forward-backward motion, the period of oscillation of its bar balances could be affected by centrifugal force». Within the balancing taxonomy (Figure 6) the H1 oscillator is located in the **FM** area, *i.e.*, it is force and moment balanced, but it is not inertially balanced.

H3: Harrison's third marine chronometer

H3 is Harrison's third chronometer, designed to alleviate the problems encountered in the previous versions H1 and H2. We mentioned earlier that the angular velocity sensitivity of the H1 and H2 clocks was due to the varying inertia of their oscillating dumbbells. H3's oscillator was designed with 2 circular balances rotating in opposite directions (Figure 3b). As H1 and H2, this new oscillator is dynamically balanced, but additionally has a configuration invariant inertia tensor. As a result, it is inertially balanced. Unfortunately, this theoretically perfectly decoupled clock was never put to trial at sea. Within balancing taxonomy (Figure 6), H3 is located in the **FMI** area.

(a)

(b)

(c)

Figure 3: (a) H1 marine chronometer with its double dumbbell oscillator [3], (b) H3 marine chronometer with its double balance oscillator [4], and (c) H4's balance and hairspring oscillator [5].

H4: Harrison's fourth marine chronometer

H4 is Harrison's fourth marine chronometer that eventually won him the Longitude Prize. As illustrated in Figure 3c, it's oscillator kinematic is that of a balance spring, composed of a balance wheel and a hairspring, and is the most common oscillator used in nowadays mechanical watches. This mechanism has a fixed center of mass and a single cylindrical rotating body whose inertia tensor does not change during motion. As a result, H4's oscillator is force balanced and inertially invariant: it is insensitive to linear accelerations as well as angular velocities. However, this oscillator is sensitive to angular accelerations around its axis of rotation: rotation of the wrist about the axis of rotation perturbates the oscillator. Within the balancing taxonomy (Figure 6), the H4 oscillator is located in the **FI** area.

Quadrivot

Quadrivot is a 1-DoF rotational flexure-based oscillator [7]. A titanium implementation is shown in Figure 4a. The kinematic arrangement theoretically leads to zero parasitic shift and high radial stiffness. Its design is force balanced, inertially invariant, and particularly robust to linear shocks. However, as a balance spring, the Quadrivot remains sensitive to angular accelerations parallel to its axis of rotation. Within balancing taxonomy (Figure 6), Quadrivot is located in the **FI** area.

Wattone

Wattone is a 1-DoF flexure base oscillator whose kinematic is based on a Watt linkage. The Watt kinematic allows for the opposite rotation of two balance wheels using a connecting rod (Figure 5b). It then becomes possible to distribute the mass and inertia over the rigid segments to fix the CoM of the oscillator, cancel its angular momentum, and make constant its inertia tensor. Experimental tests have already shown its gravity and angular acceleration insensitivity in its plane of oscillation. Wattone is theoretically inertially invariant and is located in the **FMI** area within the taxonomy (Figure 6).

Wattwins

Wattwins is a planar 2-DoF flexure base oscillator derived from the IsoSpring® concept. Its kinematic is based on two Watt linkages arranged perpendicularly and connected to a 2-DoF end effector by a 3-arm coupling mechanism. Its flexure embodiment is shown in Figure 5c. An IsoSpring oscillator is designed to have two identical eigenfrequencies so its end effector follows elliptical orbiting trajectories with isochronous periods. The oscillatory motion can be maintained by a crank driving a pin attached to the end effector, eliminating the need of an escapement, see Figure 4. As the aim of Wattwins is to be integrated within future generation of wristwatches without escapement, its design is inertially balanced in order to prevent any inertial perturbation. Within balancing taxonomy, Wattwins is located in the **FMI** area.

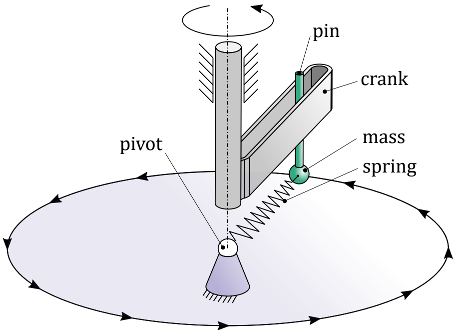
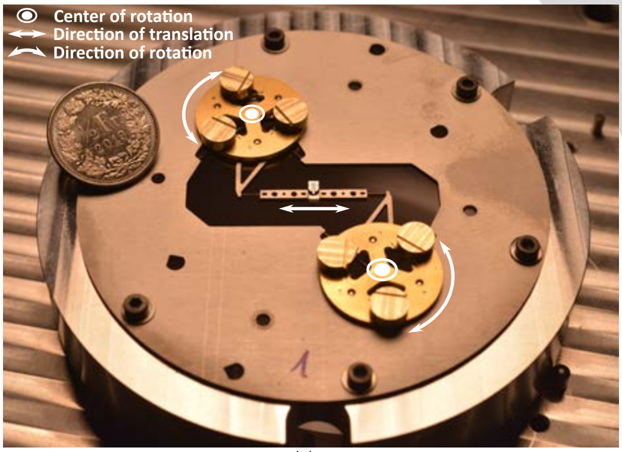
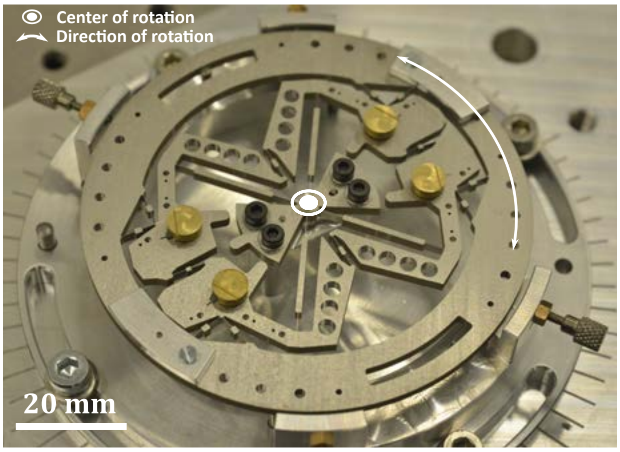


Figure 4 : Crank used to drive the 2-DoF IsoSpring® oscillator.



(a)



(b)

(c)

Figure 5 : Titanium time-base oscillators developed at Instant-Lab: (a) Quadrivot [7] (scale 10:1); (b) Titanium Wattone (scale 2:1); (c) Titanium Wattwins [10] (scale 2:1). (Coin diameter 18.2mm)

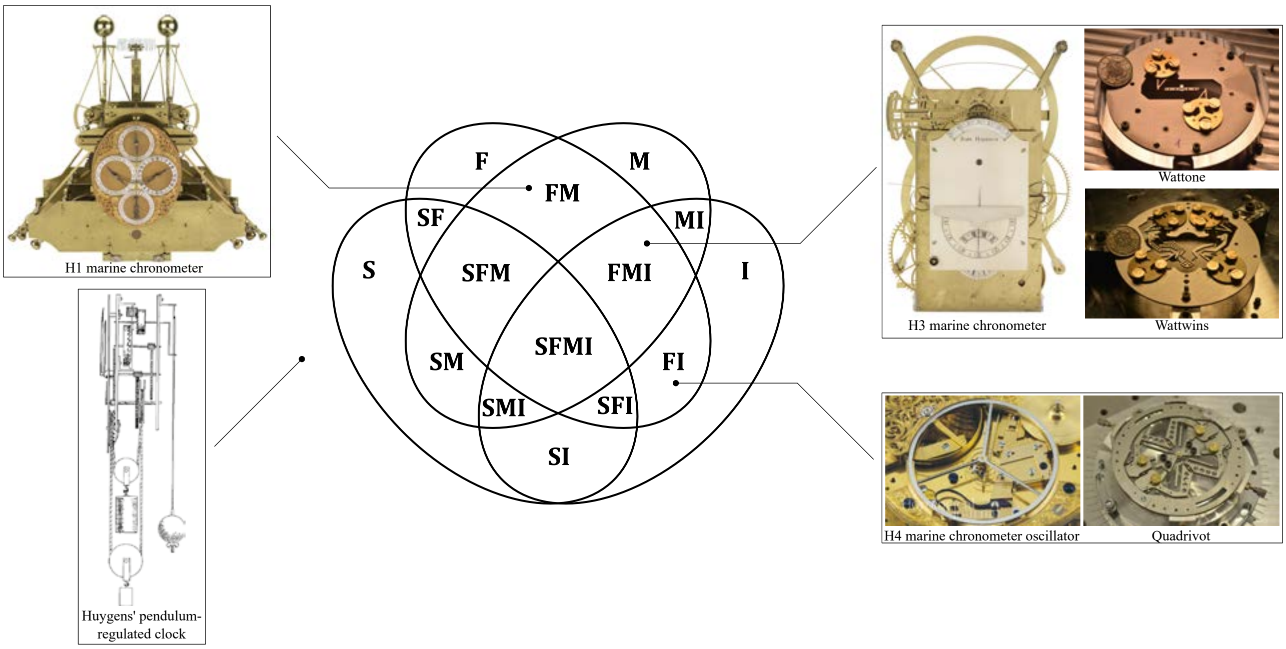


Figure 6 : Mechanism balancing taxonomy applied to selected horological oscillators [2]–[5], [7], [10].

Discussion

In this article, we have distinguished three types of inertial perturbation that mechanisms may be subject to, as a result of the motion of their chassis: linear accelerations, angular accelerations and angular velocities. In order to make the mechanisms insensitive to these perturbations, three respective balancing types have been introduced: force balancing, moment balancing, and inertial invariance. These three balancing types have been systematically classified within the newly introduced taxonomy.

Locating a selection of well-known time-base oscillators within the balancing taxonomy highlights their strengths and weaknesses with respect to external perturbations. Force balancing (**F**) is essential for ensuring a mechanical oscillator to be insensitive to change of orientation with respect to gravity and linear accelerations. Dynamic balancing (**FM**) extends this insensitivity to angular accelerations. Inertial balancing (**FMI**) achieves complete decoupling of the mechanism from all disturbances coming from the chassis movements, including angular velocities.

It is obvious that decoupling a wristwatch oscillator from its chassis motions is a desirable feature in order to enhance timekeeping accuracy. However, the introduction of dynamic and inertial balancing entails difficult technical challenges: indeed, they come at the cost of an increase in mechanical complexity and volume, since oscillators are often designed by symmetrizing a preliminary force balanced mechanism. The additional moving parts, complicate the assembly process and increase the likelihood of malfunctions due to the accumulation of geometrical tolerance errors. Fortunately, flexure based monolithic designs such as the Quadrivot, Wattone and Wattwins mechanisms pave the way for future miniaturized balanced time-bases which will benefit from the rapid progress in 3D advanced manufacturing technologies.■

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