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Experimental tribological analysis of the Swiss lever escapement

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ABSTRACT

95% of existing mechanical watch movements use the Swiss lever escapement. Little is known about the contact between the anchor and the escape wheel, which combines impact and sliding and occurs roughly 500,000 times within only 24 h. It can be considered as a mechanical exploit and a result of the behaviour of the third body, which plays a decisive role in the operation's success and, ultimately, in the precision of a mechanical watch.

To obtain better understanding of this contact, an analysis based on high-speed camera observations on "new" and "aged" mechanical watch movements, coupled with observations of components at various stages of wear is proposed. The influence of the power reserve on the dynamics of the escapement and the difference of speed profiles between the input and the output pallet are shown, and the reconstruction of the contact's life through the evaluation of 1st and 3rd body flows by electron microscopy observations is proposed.

1. Introduction

Despite the massive marketing of quartz watches in the world due to their good performance and affordable prices, mechanical watches are distinguished by their mechanical beauty and Swiss knowhow.

A mechanical watch movement is a remarkable technical system on account of its functioning and its relative accuracy to within less than 0.01%, ensured exclusively by the movement of mechanical parts in interaction with each other. It must accommodate mechanical, magnetic, thermal and chemical constraints and operate for years. Energy is delivered by a spring that progressively releases energy to rotate the different wheels and, finally, the hands.

The escapement [1–5], one of the most important elements of a horological mechanism, is located at the end of the gear train and allows moderating the movement and regulating the flow of the driving force, which is released at the necessary speed and uniformity.

Three and a half centuries of scientific work and watchmaking devoted to the measurement of time have led to the invention of dozens of escapements with different operating principles and forms [2]. These include the Swiss lever escapement (Fig. 1) whose intrinsic properties (robustness, reliability and ease of use), make it the most commonly used mechanism, functioning in approximately 95% of current mechanical watch movements. It consists of a wheel, an anchor and a double plate connected to a balance wheel. The anchor is formed of a body linked to a stinger and two ruby pallets that mesh with the teeth of the wheel. A tooth of the escape wheel first rubs on the entry pallet and another tooth rubs on the output pallet during the alternating second.

The contact [6–9] between the anchor and the escape wheel combines impact and sliding, and occurs roughly 500,000 times within only 24 h. This mechanical feat is the result of the behaviour of the third body [10], situated at the interface between the teeth of the escape wheel and the pallets, and it plays a decisive role in ensuring correct functioning.

The power reserve [1], which is the energy reserve located in the hairspring of a mechanical watch movement, is nonetheless severely limited by losses due to friction and shocks, mainly localized at the escapement. Limiting friction in order to minimize energy losses would reduce the energy required to maintain the oscillations of the balance wheel and significantly increase the power reserve of the mechanism. This requires better understanding of the contact between the anchor and the escape wheel through tribological analysis.

In order to predict the behaviour of the tribological triplet [10] (a third body between two first bodies), the reconstruction of the contact life scenario through the tribological system [11] (Fig. 2) is paramount. This involves evaluating the rates of the first and third bodies that depend on multi-scale and multiphysical coupling [12,13].

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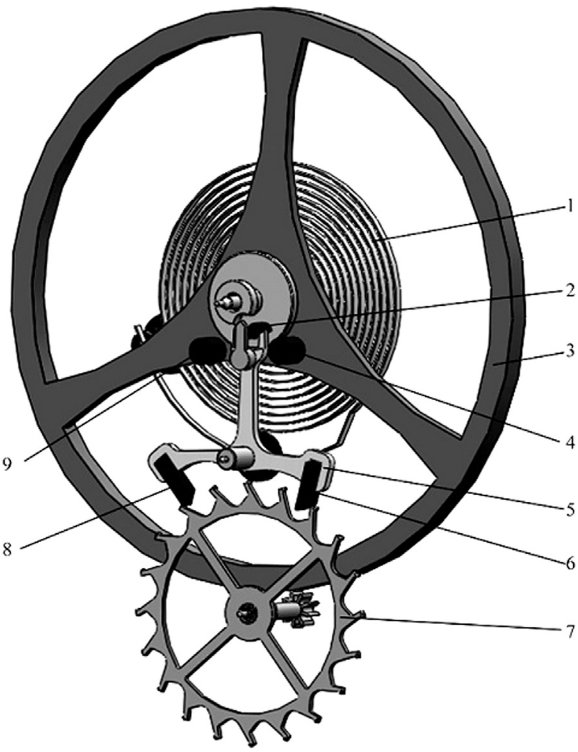

Fig. 1. Swiss lever escapement and balance wheel: 1-hairspring, 2-dowel, 3-balance wheel, 4-output banking pin, 5-anchor, 6-output pallet, 7-escape wheel, 8-input pallet and 9-input banking pin.

A tribological investigation approach based on high speed camera observations was conducted to better understand the contact and observations with scanning electron microscopy were used to evaluate the first and third body flows.

2. Experimental details

2.1. Conceptual analysis tools

Developed by Godet in the 70 s [10,14], the concept of the 3rd body defines a contact as two bodies (both the tooth of the escape wheel and the pallet) and a third body between them. The addition of the mechanisms applying the contact conditions of the concept defines the Tribological Triplet [11]. The 3rd body transmits load and accommodates relative velocities between these two 1st bodies.

The tribological circuit describes the life of the third body through several particle flows (solid and fluid) (Fig. 2). The flows describe the formation of 3rd body particles inside the contact, their circulation inside the contact (Qi), and their ejection outside the contact (Qe). The latter flow is divided into two sub-flows: the recirculation flow (Qr) corresponding to ejected 3rd body particles re-entering the contact, and the wear flow (Qw) corresponding to the third body particles definitively ejected outside the contact. Two other flows are also defined: the plastic flow (Qp) describing the plastic deformation of the 1st and 3rd bodies, and the external source flow (Qse) corresponding to the external supply of elements from outside the contact. The description based on flows allows visualizing and formalizing the contact studied from the dynamic viewpoint [12].

Table 1
Mechanical properties of the parts constituting the escapement mechanism.

	Pallets (1st body 1)	Escape wheel (1st body 2)	Anchor
Young's modulus (MPa)	440,000	210,000	195,000
Poisson's ratio	0.3	0.3	0.3
Density (kg/m^3)	4000	7860	8100

The 1st body 1 (Fig. 2) is made of ruby while the 1st body 2 (Fig. 2) is made of steel (Table 1).

To study the behaviour of this tribological triplet, scale experimental models can be used to simulate the system-wide interface, but this is difficult in our case for several reasons:

- The geometry of the contact is very small and placing instruments inside it to perform measurements is difficult if not impossible;
- The influence of various parameters on the behaviour of bodies in contact is difficult to determine.

Thus a study combining real time observations by high-speed camera and post-operation observations by Scanning Electron Microscopy and Optical Microscopy was implemented.

2.2. Global kinematics of the contact

An observation bench equipped with a high-speed camera (Phantom V710 from Vision Research) has been developed (Fig. 3) to obtain the real kinematics of the contact between the anchor and the escape wheel. A comprehensive study of the material needs was conducted since the movement of the escape wheel is very fast (around 500,000 alternations in less than 24 h), very small (0.4 mm^2) and provides a restricted viewing area (0.5 mm^2) in the mechanical watch movement.

The analysis of the global kinematics of the escapement mechanism was performed on commercial mechanical watch movements without any modifications (for example, laser contact opening) so as not to modify the kinematic chain.

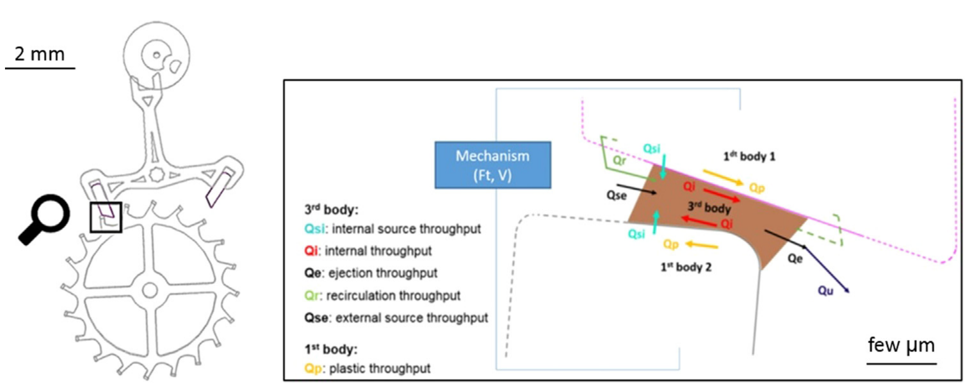

Fig. 2. Tribological triplet and circuit adapted to the contact between a tooth of the escapement wheel and a pallet.