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Modeling, Motion Study, and Computer Simulation of Thomas Earnshaw's Chronometer Detent Escapement Mechanism

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Additional information is available at the end of the chapter

Abstract

The escapement is a very important horological invention and it is commonly used in theory of clocks and chronometers. It transfers energy to the timekeeping element and allows the number of its oscillations to be counted. The chronometer detent escapement used in marine chronometers was modified and simplified by Thomas Earnshaw, English renowned watchmaker, in order to make it available to the public. This chapter deals with 3D modeling and assembling of all escapement parts in SolidWorks, as well as constructive geometry of mechanism and computer simulation. The whole process has been accomplished in program "SolidWorks 2016," where all parts are assembled by using standard mates since this approach is suitable for motion and dynamical analysis. Generated simulation results are very close to the real ones, thereby using computationally strong kinematic solvers.

Keywords: computer simulation, escapement mechanism, Thomas Earnshaw, detent chronometer, motion analysis

1. Introduction

Escapement is a mechanism in mechanical clocks or watches, and it is considered to be one of the most important horological inventions. It transfers energy to the timekeeping element and allows the number of its oscillations to be counted [1].

The detent or chronometer escapement is considered the most accurate of the balance wheel escapements and it was used in marine chronometers [1]. In 1748, Pierre Le Roy invented the early form of it. He created a pivoted detent type of escapement [2, 3]. Around 1775, John Arnold invented the first effective design of detent escapement. In 1780, Arnold's escapement was modified by Thomas Earnshaw [3, 4]. If watches or clocks had been equipped with free harmonic oscillators, they would have performed harmonic oscillations with constant frequency. But real watch balance wheels always perform dumped and driven oscillations. Thomas's modification to the chronometer escapement was very close to previously mentioned ideal [5].

Two different but equally important functions are accomplished by escapement:

1. Impulsive: It maintains the balance wheel oscillations and keeps its amplitude constant [5, 6].

2. Regulative: It regulates the speed of the watch main movement [5, 6].

Important characteristics of Thomas Earnshaw's chronometer detent escapement mechanism are:

1. Balance wheel (oscillator) is almost free from the escapement influence and thus independent from the interference by the main gear train. In accordance to this, Thomas Earnshaw's escapement belongs to the escapement group named as "detached." Balance wheel coupled with detached escapement performs almost free harmonic oscillations [5].

2. Escapement wheel is locked on a stone (jewel) carried in a detent. Impulse is given by the teeth of the escapement wheel (when a tooth is unlocked) to a pallet on the balance staff in every alternate swing of the balance wheel. Instead as a pivoted lever, the detent is designed and constructed as a blade spring and consequently does not require lubrication [1, 5].

3. Geometry and kinematics of the escapement teeth and impulse pallet are designed in such a way that they also do not need lubrication. This feature is of greatest importance for the stability of the balance wheel oscillations and uniform chronometer's going rate [5].

2. Constructive geometry and basic principles

Figure 1 shows all components of chronometer escapement mechanism. Escapement wheel (1) receives the energy from twisted mainspring and is mashed with the last gear of the chronometer main gear train [5]. Balance wheel (B) performs torsion oscillations with a rotational motion about the axis of the helical spring (S), while the rotation of escapement wheel is blocked by the locking pallet (10) until the discharging pallet (5) pushes the gold spring (9) supported by the horn of detent (11) [5, 7]. Discharging event occurs during the period of time in which balance wheel (B) rotates in positive (counterclockwise) direction. As the
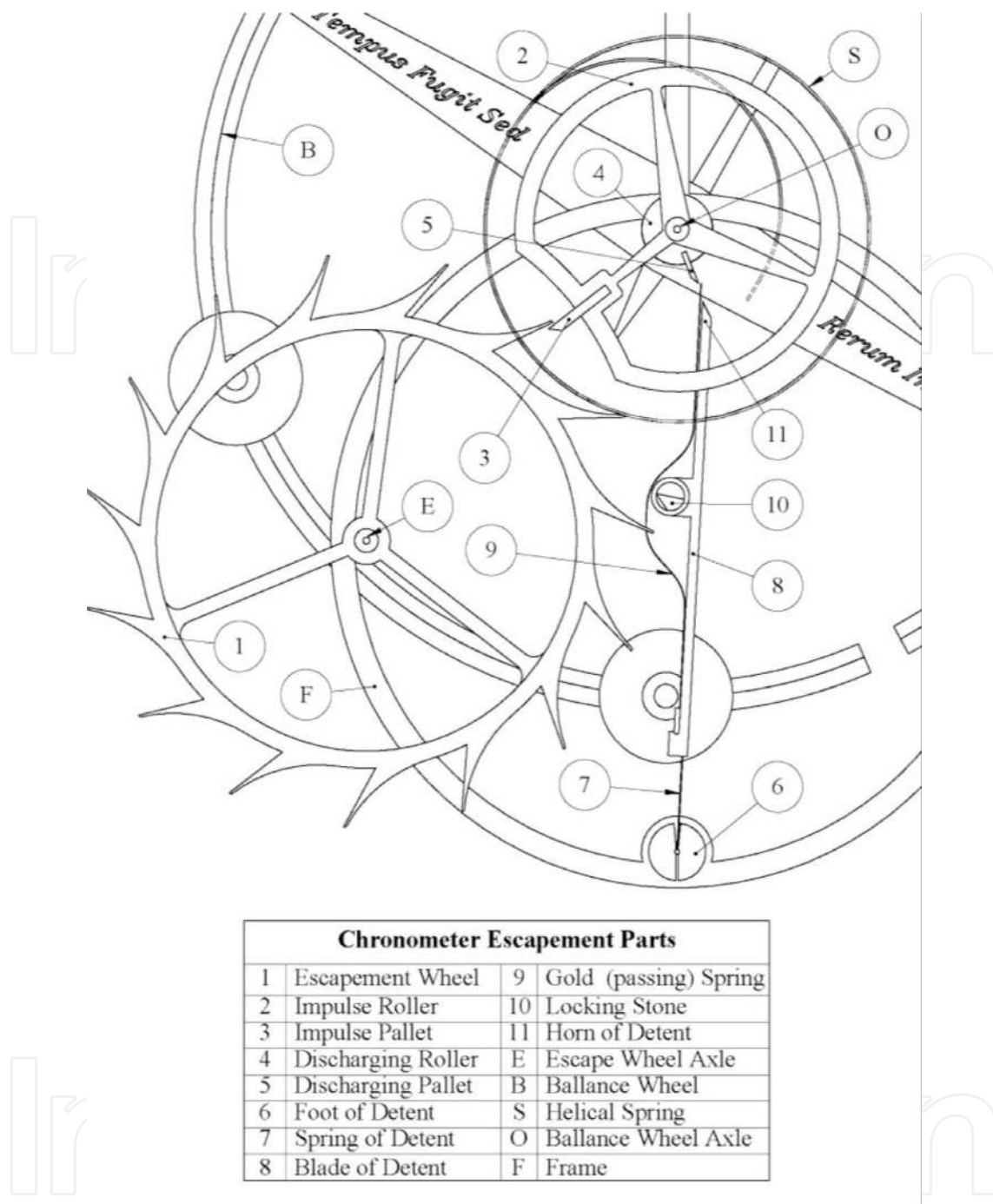
Chronometer Escapement Parts			
1	Escapement Wheel	9	Gold (passing) Spring
2	Impulse Roller	10	Locking Stone
3	Impulse Pallet	11	Horn of Detent
4	Discharging Roller	E	Escape Wheel Axle
5	Discharging Pallet	B	Ballance Wheel
6	Foot of Detent	S	Helical Spring
7	Spring of Detent	O	Ballance Wheel Axle
8	Blade of Detent	F	Frame

Figure 1. All parts of Thomas Earnshaw's chronometer detent escapement mechanism.

balance moves, the discharging pallet (5) on the balance staff engages the gold spring (9) and moves the detent blade (8) until the locking stone (10) releases the wheel tooth. At that precise moment, one tooth of the escapement wheel drops (escapes) and the next in advance engages the impulse pallet (3), which is a jewel fastened into the impulse roller [1, 5]. As the balance wheel proceeds, the wheel tooth continues to push the pallet (3), and after the short movement, the detent (8) is released and drops back to rest. Now, in the rest position, detent locking stone

(10) is ready to lock the nest tooth. The wheel tooth continues to push on the pallet (3) until the tooth drops off, and the appropriate tooth is locked on the detent locking stone (10) [5, 7]. On its return, the balance wheel (B) rotates clockwise and comes against the gold (passing) spring (9) through the discharging pallet (5) again but on the opposite site [2, 5]. However, as the balance wheel (B) proceeds, instead of lifting the detent (8), the passing spring (9) gives way, and as the balance continues rotation, the passing spring (9) is released. This is particularly important for the proper operation of the escapement since no push or impulse is given to the locking stone (10) and discharge roller (4) during the clockwise rotation of the balance wheel (B) [5]. Escapement working cycle can repeat endlessly long. This was the explanation of basic working principles of Thomas Earnshaw's chronometer detent escapement mechanism.

Some of the parameters of escapement constructive geometry (**Figure 2**) are known, some of them can be acquired willingly, and the rest must be rigidly established [5, 7].

Commonly, the escapement wheel has 15 teeth that are at mutual angular distance out of 24°, even though the wheels of 12, 14, and 16 teeth can be found often. The angle between *EO* and detent line is 45°, the diameter of escapement wheel is assumed to be d_E = 120 mm, and the
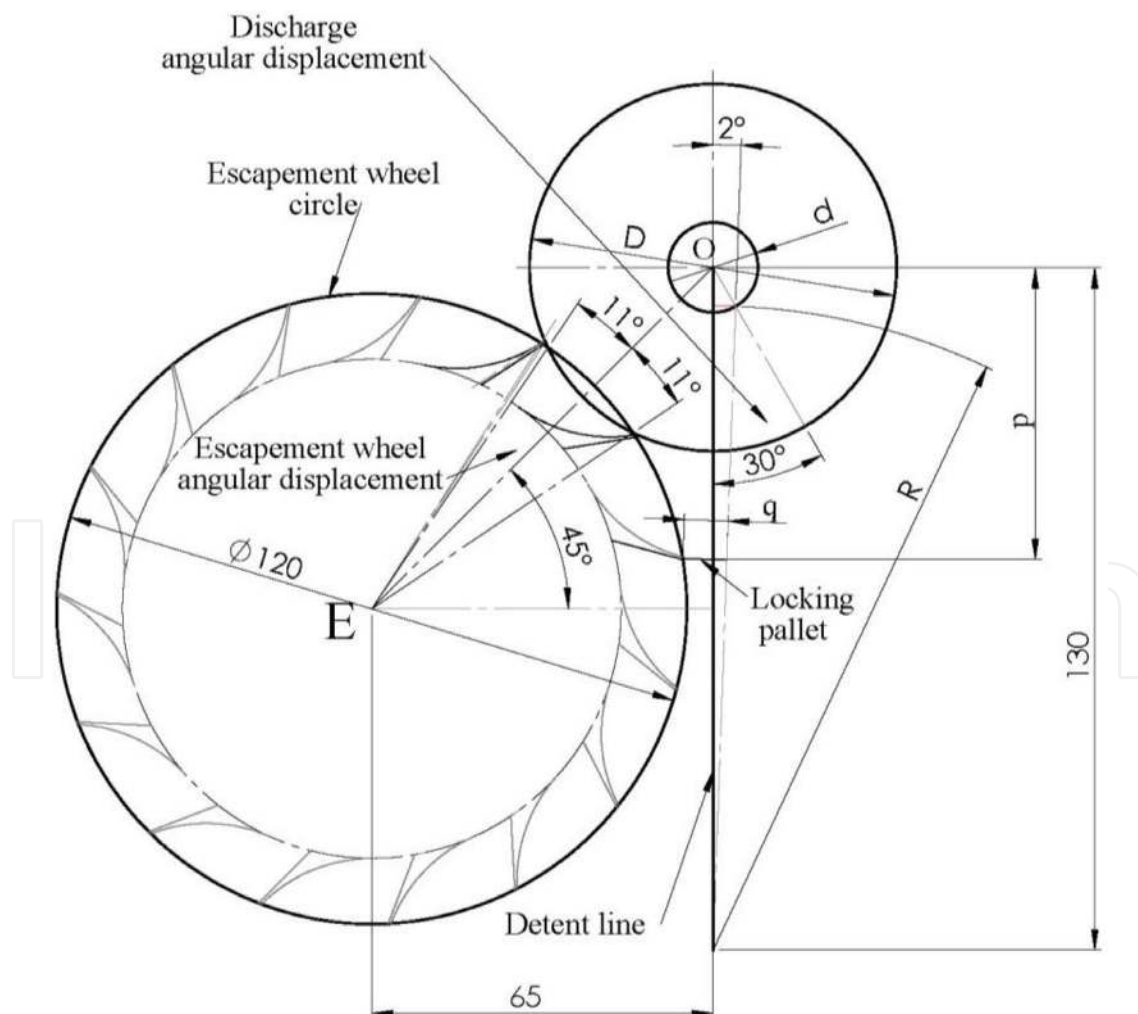

Figure 2. Constructive geometry of Thomas Earnshaw's chronometer detent escapement mechanism.

length of detent line is assumed to be l_d = 130 mm. The distance between the point E (center of escapement wheel) and detent line should be a bit longer than the radius of escapement wheel and it is presumed to be l = 65 mm. For the reason of safe mashing between impulse pallet and escapement teeth, the impulse pallet drop of at least 1° on each side of the pallet must be defined, and as a result, the escapement wheel rotates by 22° [5]. The diameter of the impulse pallet circle D_i is determined by geometrical construction in SolidWorks sketch, as well as D_d (diameter of the discharge pallet's circle—the assumption is that it rotates by 30° during discharge) and R (length of the detent—the assumption is that it rotates by 2° during discharge). The position p and length q of the locking pallet can be found from the disposition of the escapement tooth and detent angular displacement [1, 5].

There is no need for lubrication of the escapement wheel of Thomas Earnshaw's chronometer escapement and that is its biggest advantage over all other watch escapements. Balance's impulse pallet and the escape tooth roll together, so there is less friction (they not slide across one another) [2, 5]. Lubricant viscosity changes due to the temperature changes (it can even dry up), and the ability of chronometer escapement to run dry can result in more consistent timekeeper [5, 7]. The constructive geometry of this mechanism can be modified and adapted by dynamical analysis [5].

3. Making of 3D model and assembly

Since the constructive geometry and basic principles have been explained so far, now, 3D modeling can be easily conducted. Making of 3D model and assembly was completed in "SolidWorks 2016" and the procedure will be explained in continuance.

As it is known, when using some of the programs for 3D modeling, all parts of one assembly must be modeled separately. In this case, all parts of chronometer detent escapement mechanism were created according to the constructive geometry that is previously explained and applied in sketches definition. The set of SolidWorks commands named "Features" was used for part modeling. Commands such as "Extruded Boss/Base," "Revolved Boss/Base," "Lofted Boss/Base," and "Swept Boss/Base" were used for material adding, while commands such as "Extruded Cut," "Revolved Cut," "Lofted Cut," and "Swept Cut" were used to remove the material in various ways. Part modeling includes the specification of materials and physical properties that are principally important for dynamical analysis and appropriate motion study of a mechanism as a whole. **Figure 3** [5] shows the modeling of escapement wheel. All other components are modeled in the same way; they are shown in **Figure 4** and their list is given beneath:

1. Escapement wheel

2. Impulse roller

3. Balance wheel and discharge roller

4. Balance wheel thermal compensation

5. Helical spring

6. Gold (Passing) spring

7. Detent

8. Locking pallet (Jewel stone)

9. Discharging pallet (Jewel stone)

10. Impulse pallet (Jewel stone)

11. Chronometer mechanism frame [5, 8].

All parts named above have been assembled in one functional mechanism in accordance with kinematical principles and constructive geometry that has been previously explained.

Complex assemblies contain many different parts, which can be the components of some other assemblies, so-called sub-assemblies [5]. When adding a part to an assembly, the bond between them is made and when user opens the assembly in SolidWorks, one can identify the
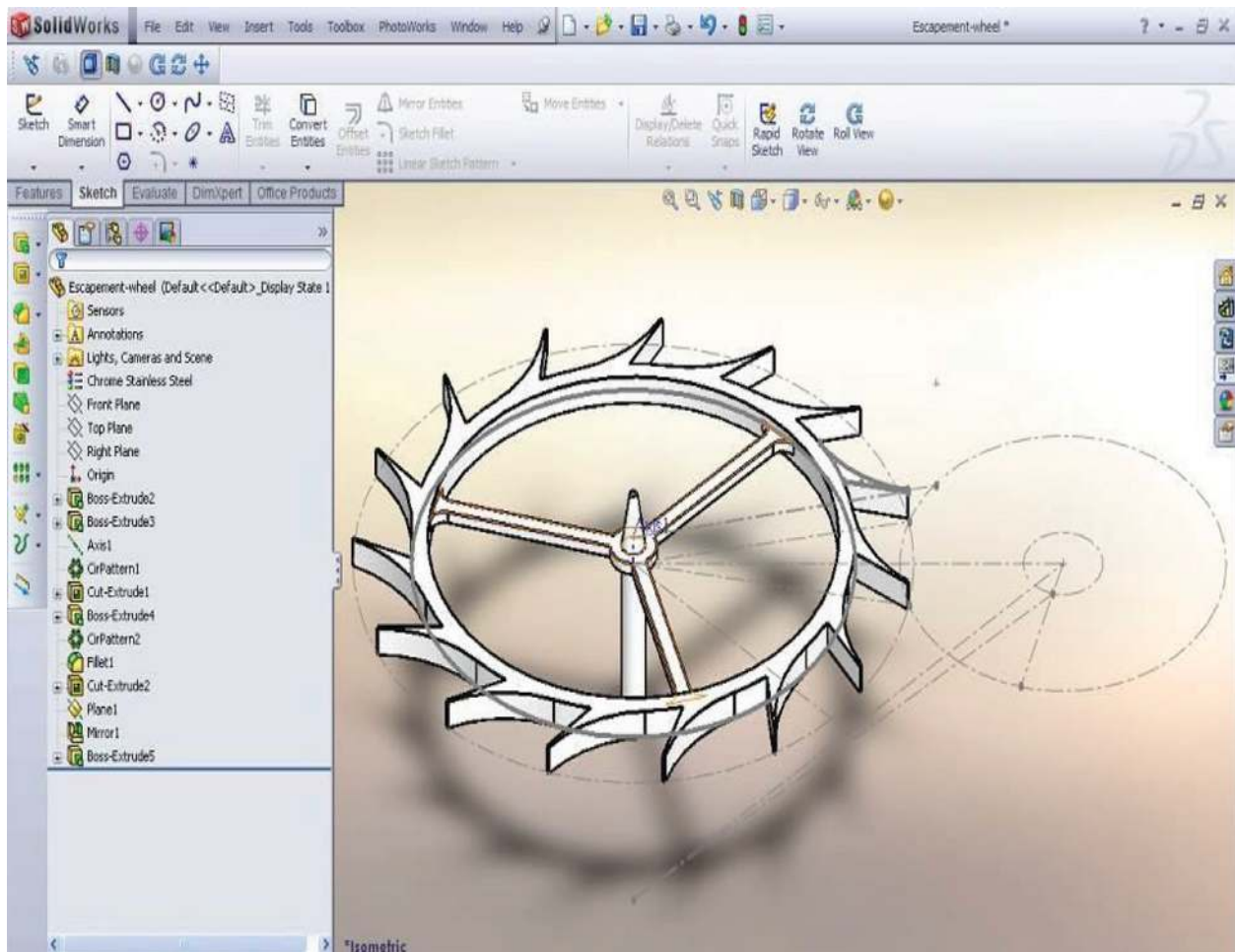

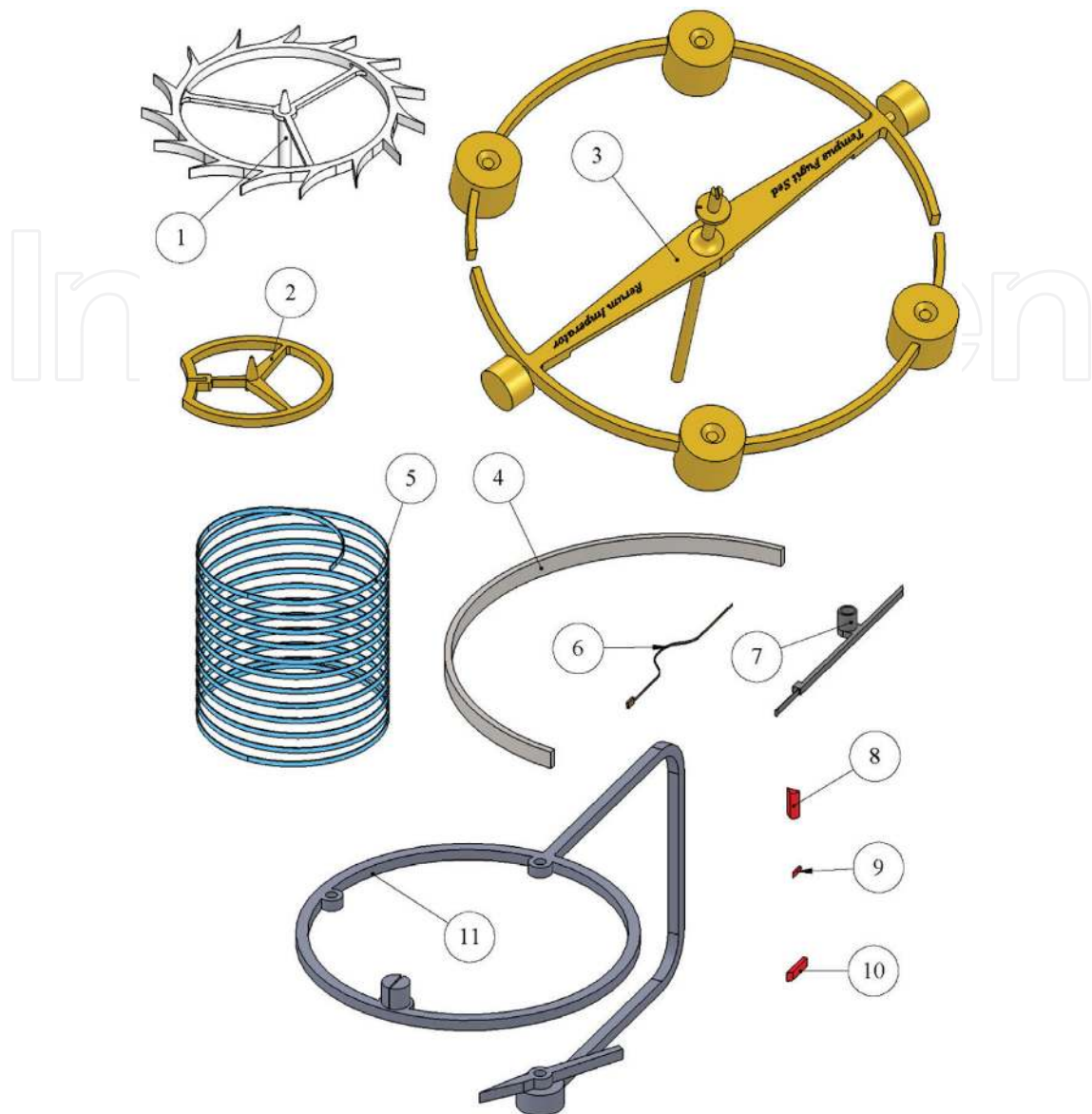**Figure 3.** Escapement wheel modeled in SolidWorks 2016.

Figure 4. Components of chronometer detent escapement mechanism.

component file as a part of assembly. Changes in components manifest in the very assembly and parts are linked by command "Mate" that creates geometric tie between components. Mates define the allowable directions of linear or rotational motion of the components. They can be moved within its degrees of freedom, visualizing the assembly's behavior [8, 9]. Complete chronometer detent escapement modeled in "SolidWorks 2016" is shown on **Figure 5** [5].

There are three categories of mates—standard, advanced, and mechanical.

1. Standard mates define geometrical links between components (parallel, tangent, concentric, coincident, perpendicular, distance, or angle). For example, a concentric mate forces two cylindrical mates to become concentric, while a coincident mate forces two planar faces to become coplanar [8].

2. Advanced mates include limit, symmetry, width, path, profile center, and linear/linear coupler. For instance, profile center mate automatically center-aligns geometric profiles to each other and fully defines the components. A path mate constrains a selected point on a component to a path that has been defined by selecting one or more entities in the assembly [8].

3. Mechanical mates contain gear, screw, hinge, slot, rack and pinion, cam-follower, and universal joint mates. For example, a hinge mate limits the movement between two components to one rotational degree of freedom. Gear mates force two components to rotate relative to one another about selected axes. A cam-follower mate is a type of tangent or coincident mate and it allows the user to mate a cylinder, plane, or point to a series of tangent extruded faces [8, 9].

The assembling of Thomas Earnshaw's chronometer detent escapement was done only by using standard mates. This access describes the real process of the mechanism assemblage [5]. Firstly, chronometer frame is set as an immovable part of mechanism. Then, balance and escapement wheels are linked to the frame (axles of balance and escapement wheel are concentric with related bearings). On the inner surface of the balance wheel are thoroughly adhered two thermal compensation pieces. Helical spring is attached to the balance wheel and the frame (coincident mate is used), so its axis and axis of balance wheel are collinear. Detent assembly is made by linking detent blade to the detent foot so it can rotate about
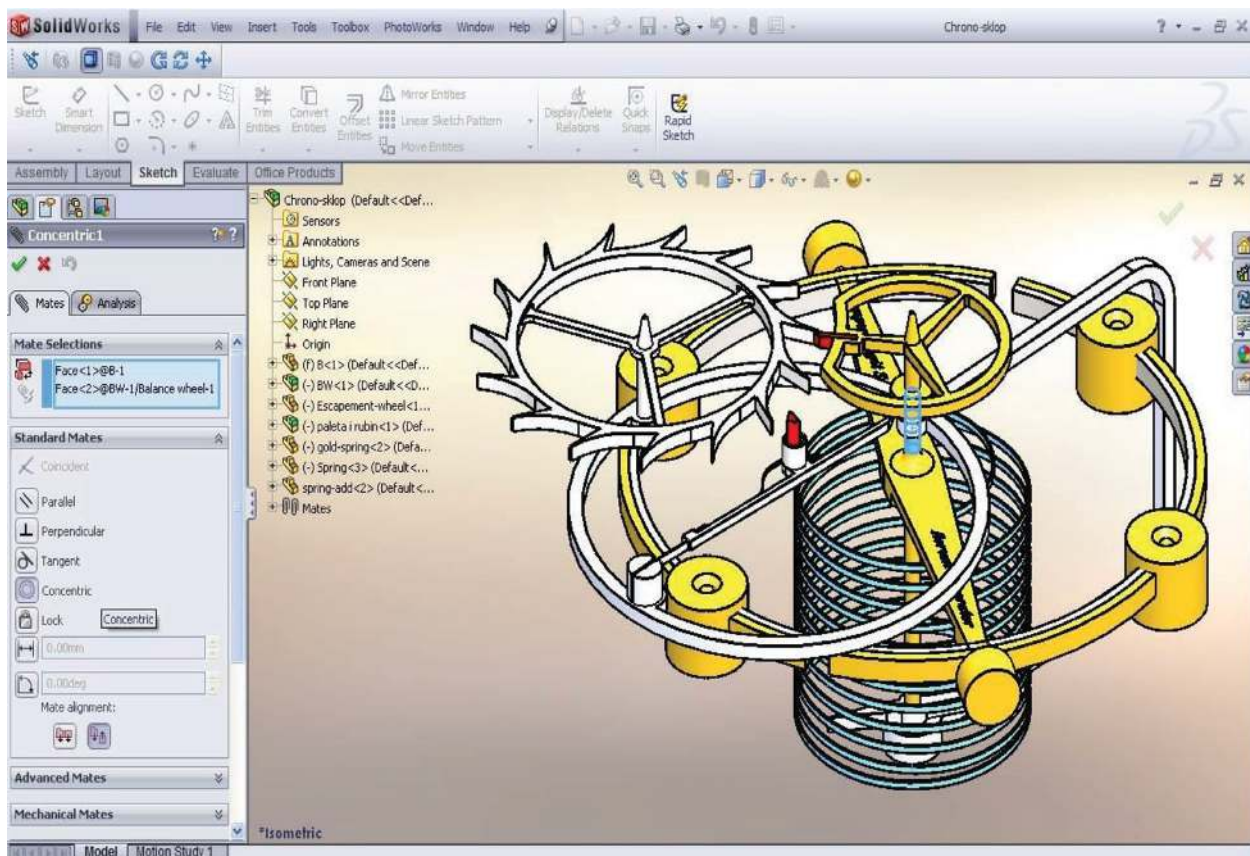

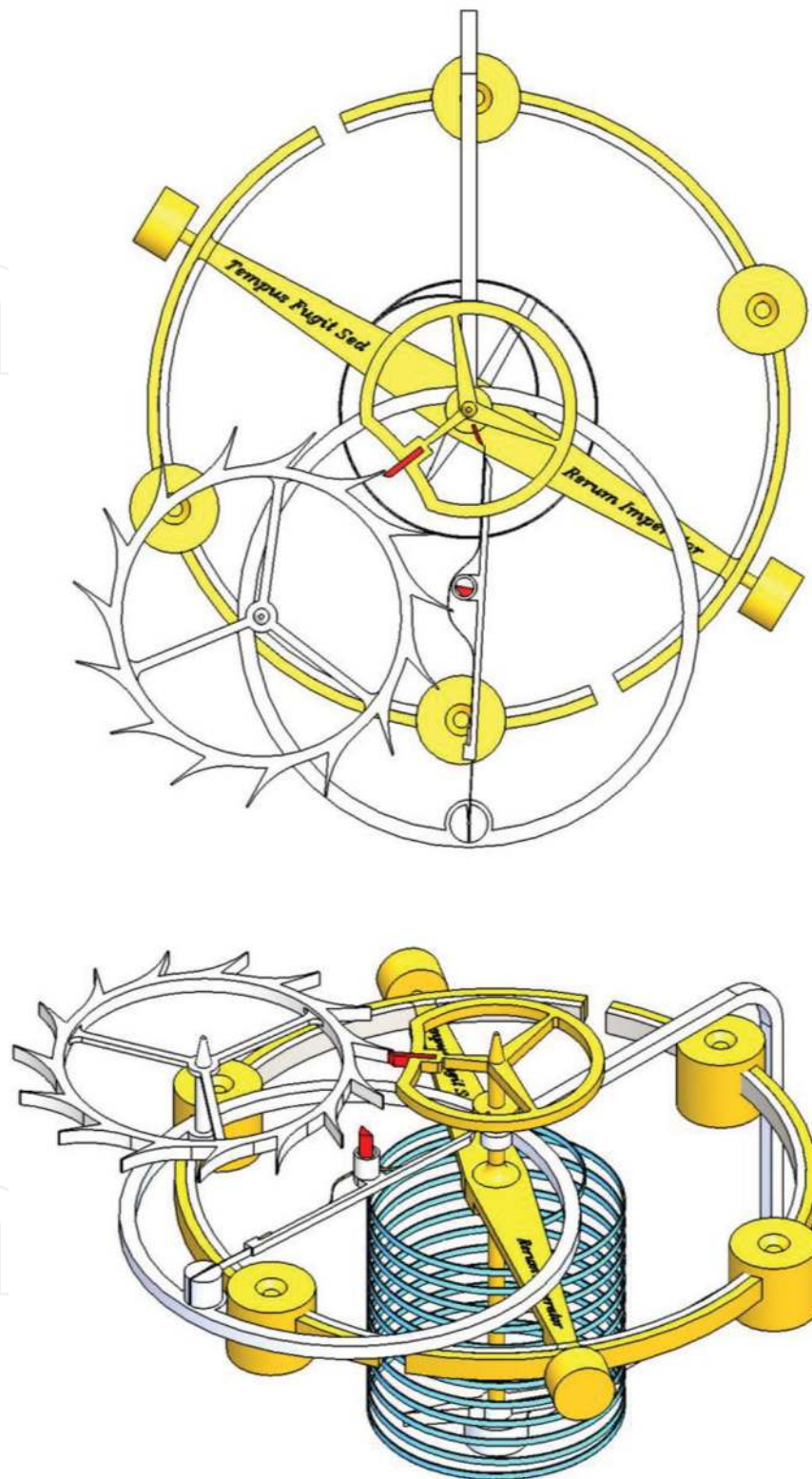**Figure 5.** The assembly of Thomas Earnshaw's chronometer detent escapement mechanism.

Figure 6. Horizontal and isometric projection of Thomas Earnshaw's chronometer detent escapement mechanism.

detent foot axle. Eventually, mechanism is completed by adding three pallets–the locking, the impulse, and the discharging jewel stones [1, 5, 8]. Chronometer detent escapement mechanism is shown in **Figure 6** in horizontal and isometric projection [5].

4. Motion study

SolidWorks motion studies are graphical simulations of motion for assembly models. Motion studies do not change an assembly model or its properties, but they simulate and animate the motion that is prescribed for a model. Motion study has a timeline-based interface named "Motion Manager" that includes animation, basic motion, and motion analysis [8, 9].

Animation is available in core of SolidWorks, and it can be used to animate the simple motion of assemblies by adding motors to drive the motion of one or more parts of an assembly or by prescribing the positions of assembly components at various times using set key points. Animation uses interpolation to define the motion of assembly components between key points [8].

Basic motion is available in the core of SolidWorks and it can be used for the approximation of the effects of motors, springs, contact, and gravity. Even though the mass is taken into consideration, computation is relatively fast [8, 9].

Motion analysis is available with the SolidWorks application "Motion TM" add-in to SolidWorks Premium. It is used accurately for simulations and analyses of the effects of motion elements (dampers, forces, springs, and friction) on an assembly. Motion analysis uses computationally strong kinematic solvers and accounts for material properties as well as mass and inertia in the computations [9].

The graphics section for SolidWorks motion study of Thomas Earnshaw's chronometer detent mechanism is split horizontally into upper and lower area and it is shown on **Figure 7** [5]. Assembly of the mechanism as a whole is in the upper area and the lower area is divided into three segments: timeline with key points and time bar on the right, the motion manager toolbar across the top, and the motion manager design tree on the left [5, 8, 9].

The motion manager toolbar contains some of the following property managers:

1. Gravity (property manager) is a simulation element that moves components around an assembly by inserting a simulated gravitational force. Gravity parameters are direction reference and numeric gravity value, but only one of these definitions can be used in any simulation [8, 9]. Gravity has been eliminated from dynamical analysis of escapement mechanism, since it does not affect the performance of the mechanism [8].

2. Damper (property manager) is consisted of linear and torsional damper and it simulates the effects of energy dissipation [8]. This motion study does not deal with dumpers separately, since the dumping characteristics have already been included into the spring simulation [5].

3. Motors are motion study elements that move components in an assembly by simulating the effects of various types of motors. Motors can be rotary and linear [8]. This function was not used in the motion study of Thomas Earnshaw's chronometer detent escapement mechanism [5].

4. Springs are simulation elements that move components around an assembly by simulating the effects of various types of springs. They can be linear and torsional springs [8]. Parameters are spring constant (k), damping constant (c), free length (angle ϕ), exponent

of spring force expression (*e*), and exponent of damper force expression (*d*) [8, 10]. Spring property manager was used for the simulation of helical spring (**Figures 4** and **5**), gold (passing) spring (**Figures 4–6**), and detent blade (**Figures 4–7**), and parameters settings for the simulation are shown in **Table 1** [5].

5. Contact must be defined in a motion study to prevent parts from penetrating each other during motion [8]. Forces can be generated between contacting components, or components can be constrained to touch continually [5]. In the motion study of this mechanism are shown four different contacts: between discharging pallet and gold spring, escapement wheel teeth and impulse pallet, detent, and gold spring and between escapement wheel teeth and locking pallet [5, 8]. Static and kinetic friction coefficients simulate dry friction, since the lubrication of escapement wheel teeth is not needed. The escapement wheel is made of steel and all pallets are made of ruby (corundum) [8, 9].

6. Force/Torque property manager applies forces, moments, or torques with uniform distribution to faces, edges, reference points, vertices, and beams in any direction for use in structural studies [8]. Forces can be defined by type, parameter values, and mathematical expressions [9]. The escapement wheel receives the energy from the twisted chronometer's mainspring and the constant torque out of $M = 25$ N acts on it [5].

The motion manager tree (on the left) is divided involves used simulation elements (forces, motors, and springs), components entities that appear in SolidWorks Feature Manager design tree, orientation, and camera views settings [9]. The timeline is located to the right of the motion manager design tree. It displays the times and types of animation events in the motion study and it is divided by vertical grid lines corresponding to numerical markers showing the time [8, 9].

Key points represent a beginning or end of a change in animation position or other attributes at a given time. In other words, a key point is the entity that corresponds to define assembly component positions, visual properties, or simulation element states. Key frame defines the portion of the timeline that separates key points (it can be any length of time). Change bars are horizontal bars connecting key points and they indicate a change between key points (component motion, animation duration, and simulation element property changes) [5, 8, 9].

As it was previously mentioned, standard mates were used for the assemblage of chronometer escapement components since these mates do not change physical properties of assembly in dynamical analysis.

The working cycle of Thomas Earnshaw's chronometer detent escapement mechanism is divided into six steps that are shown in **Figure 8** [5]:

1. Rotation of the escapement wheel is blocked by the detent locking pallet. Balance wheel rotates counter clockwise [5, 7].

2. Discharging event is taking place. Discharging pallet engages the gold spring and moves the detent blade until the moment when locking stone releases the wheel tooth [5].

3. Impulse event is starting to occur. Tooth of the escapement wheel drops (escapes) and engages the impulse pallet. The balance wheel proceeds counter clockwise, and the wheel tooth continues to push the pallet [5, 7].

4. The detent is released by the discharging pallet and drops back to rest. The escapement wheel tooth continues to push on the pallet until the tooth drops off, and the appropriate tooth is locked on the detent locking stone. Impulse event is finished. The balance wheel reaches its amplitude position and begins to rotate clockwise [5].

5. The balance wheel rotates clockwise and comes against the passing spring through the discharging pallet again, but on the opposite site. However, instead of lifting the detent, the passing spring gives way. As the balance wheel continues rotation the passing spring is released [5, 7].

6. The balance wheel reaches its amplitude position and begins to rotate counter clockwise. Mechanism has just finished the complete working cycle and is ready to repeat the new cycle, which is effectively equivalent to the previous one [7].
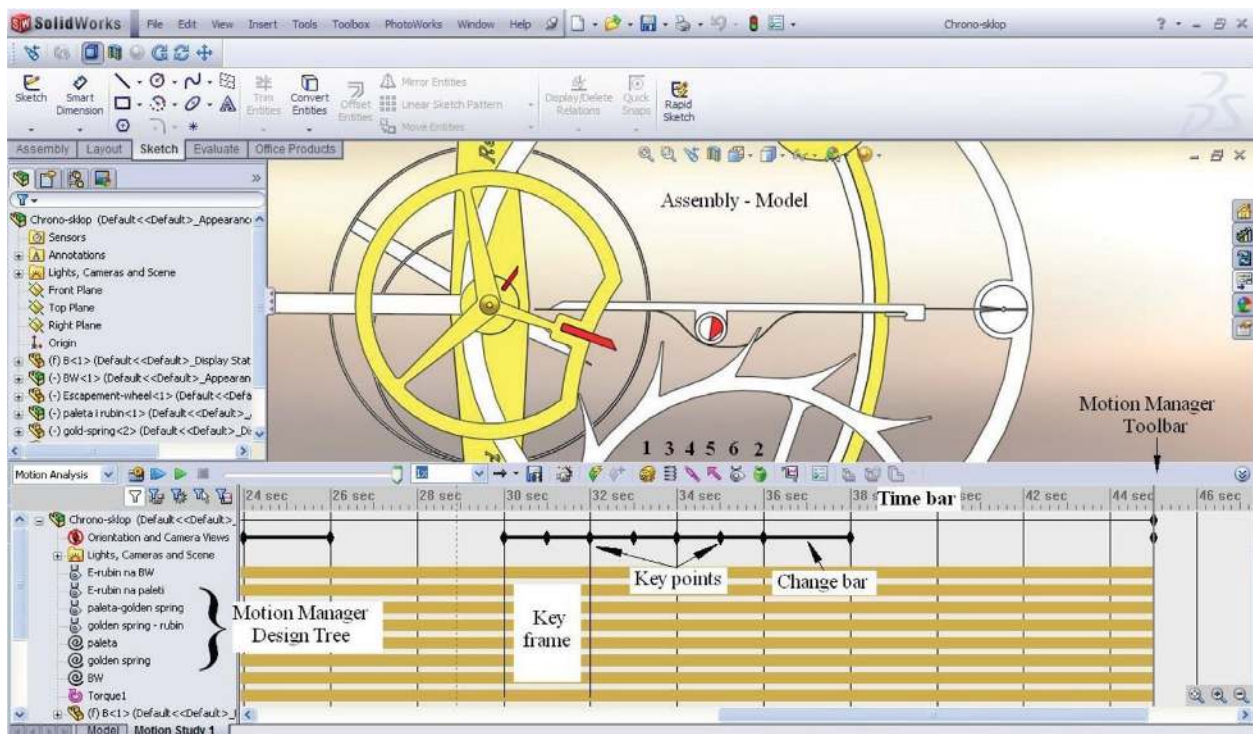

Figure 7. Motion study of Thomas Earnshaw's chronometer detent escapement mechanism.

	φ [deg]	k [mm/deg]	c [N mm/(deg/s)]	e	d
Helical spring	180	0.1	0.02	1	1
Gold spring	0	15.0	0.05	1	1
Detent blade	0	0.05	0.0001	1	1

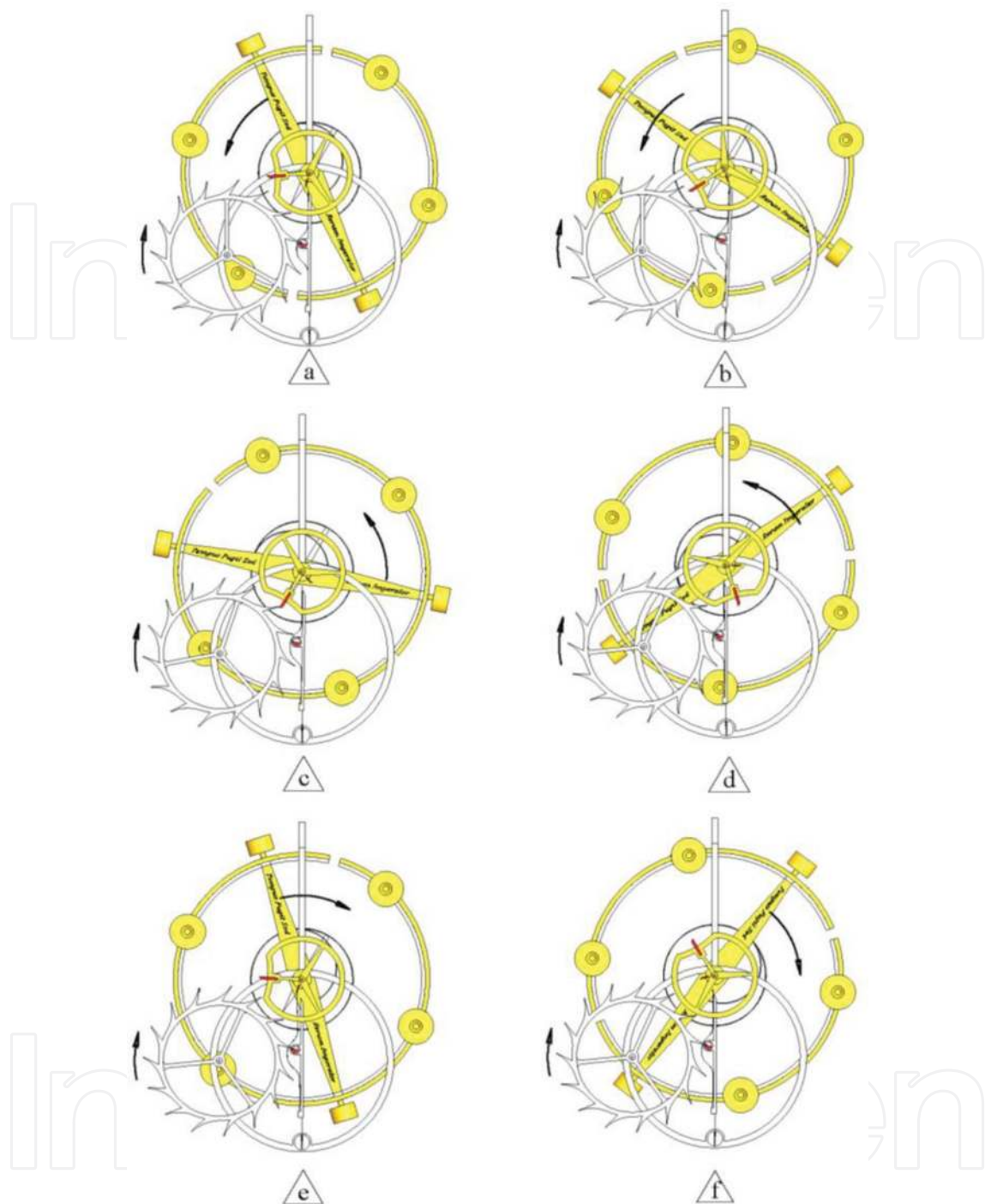**Table 1.** Parameters settings for the motion manager spring function.

Figure 8. Six steps (a–f) of working cycle of Thomas Earnshaw's chronometer detent escapement mechanism.

The amplitude of the balance wheel oscillation must achieve the value of nearly 270° to each side of its center equilibrium position. This amplitude can be achieved by choosing the proper value of the escapement wheel torque [5]. The center equilibrium position should be chosen in such a way to deliver impulses to the impulse pallet symmetrically and that can be achieved by the adjustment of the helical spring free angle [1, 5].

5. Conclusion

This chapter deals with constructive geometry and basic principles of Thomas Earnshaw's chronometer detent escapement mechanism. Moreover, it deals with 3D modeling and assembling of previously mentioned chronometer, thus showing the whole process of making a mechanism and its motion analysis. Solid modeling, motion analysis, and simulation are done in "SolidWorks 2016" and they are based on constructive geometry that is explained at the very beginning. Even though the chronometer escapements are invented in the past times, these mechanisms present the basis of today timekeepers' industry.

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