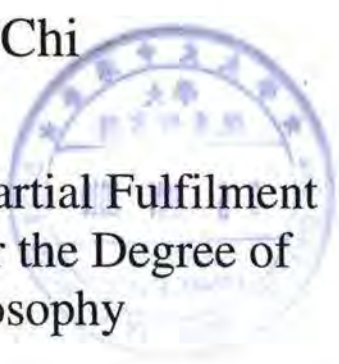


Geometry-Based Simulation of Mechanical Movements and Virtual Library

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A Thesis Submitted in Partial Fulfilment
of the Requirements for the Degree of
Master of Philosophy
in
Automation and Computer-Aided Engineering



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Abstract

Mechanical timepiece is an intricate precision engineering device. Invented some four hundred years ago, mechanical timepieces, including watches and clocks, are fascinating gadgets that still attract millions of people around the world today. Though, few understand the working of these engineering marvels.

This thesis presents a Virtual Library of Mechanical Timepieces. The Virtual Library is an online database containing different kinds of mechanisms used in mechanical watches / clocks. It uses 3-dimension (3D) Computer-Aided Design (CAD) models to demonstrate the working of these mechanisms. The Virtual Library provides an educational tool for various people who are interested to mechanical timepieces, including engineering students (university students and vocational school students), watchmakers, designers, and collectors. In addition, the CAD models are drawn to exact dimension. As a result, it can be used by watchmakers to validate their designs.

The Virtual Library is divided into three sections. They are the Mechanical Clock Escapements, the Mechanical Watch Escapements and the Accessory Mechanisms. Currently, the Virtual Library consists of nine records organized as follows:

- The Mechanical Clock Escapements
 1. The Graham Escapement;
- The Mechanical Watch Escapements

2. The English Lever Escapement;
 3. The Swiss Lever Escapement;
 4. The Daniels Co-Axial Double-Wheel Escapement;
 5. The Spring Detent Escapement;
 6. The Cylinder Escapement; and
 7. The Verge Escapement;
- The Accessory Mechanisms
8. The Automatic Winding System; and
 9. The Moon Phase Mechanism.

For each record in the Virtual Library, detailed background information, 3D CAD models, and computer animation video clips are offered. The Virtual Library is accessible on the internet at: http://www.ipe.cuhk.edu.hk/projects10_library.html.

This thesis describes the design and the implement of the Virtual Library in details.

摘要

機械鐘錶是複雜精確的工程設備。它於大約四百多年前被發明，機械時計，不論是手錶或時鐘，至今仍然讓成千上萬人著迷，是引人入勝的小配件。可是，只有少數人瞭解它背後的工程學奇蹟。

這份論文提出以機械錶芯庫為題的研究項目。機械錶芯庫包含不同種類的機械手錶和時鐘的機械運動，是一個網上的機械鐘錶資料庫。它使用三維(3D)計算機輔助設計(CAD)模型展示這些機制的機械運動。機械錶芯庫提供一種教育工具給對機械鐘錶感興趣的人士，包括工程學院的學生(大學生和職業學校的學生)、鐘錶製造師、設計師和收藏家。此外，各計算機輔助設計模型均以真實尺寸為標準而畫成。因此，這機械錶芯庫可幫助錶製造師驗證他們的設計。

機械錶芯庫由三個部分組成，分別為機械時鐘擒縱機構、機械手錶擒縱機構和配件。當前，機械錶芯庫存有九個紀錄，結構如下：

- 機械時鐘擒縱機構
 1. 格雷厄姆擒縱機構;
- 機械手錶擒縱機構
 2. 英國叉瓦式擒縱機構;

3. 瑞士叉瓦式擒縱機構;
4. 丹尼爾斯同軸雙輪擒縱機構;
5. 鎖簧式天文鐘擒縱機構;
6. 圓柱形擒縱機構; 和
7. 立軸擒縱機構;

- 配件

8. 自動上發條系統; 和
9. 月相機構。

每一個在機械錶芯庫裡的紀錄，都載有詳細的背景資料、三維計算機輔助設計模型和時計的機械運動電腦模仿錄像。機械錶芯庫的互聯網網址在：

http://www.ipe.cuhk.edu.hk/projects10_library.html。

這份論文描述機械錶芯庫從意念到實踐的詳細過程。

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Jennifer Tam

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Table of Contents

- 1. Introduction.....1**
 - 1.1. Background 1
 - 1.2. Objectives..... 5
- 2. Literature Survey 7**
 - 2.1. Existing Virtual Libraries..... 7
 - 2.2. Challenges 13
- 3. Virtual Library of Mechanical Timepieces 15**
 - 3.1. Structure of the Virtual Library 16
 - 3.2. Mechanical Clock Escapements 19
 - 3.2.1. Graham Escapement 19
 - 3.3. Mechanical Watch Escapements..... 21
 - 3.3.1. English Lever Escapement..... 21
 - 3.3.2. Swiss Lever Escapement..... 24
 - 3.3.3. Daniels Co-Axial Double-Wheel Escapement..... 26
 - 3.3.4. Spring Detent Escapement 31
 - 3.3.5. Cylinder Escapement 35
 - 3.3.6. Verge Escapement 41
 - 3.4. Accessories..... 46
 - 3.4.1. Automatic Winding System..... 46
 - 3.4.2. Moon Phase Mechanism 65
 - 3.5. Chapter Summary 71
- 4. Implementations.....73**
 - 4.1. CAD Modeling of the Escapement Structure 73
 - 4.2. Website Design 78
 - 4.3. An Application 79
- 5. Conclusions 82**
- References.....85**

Appendix A.....89

Appendix B.....101

Table of Figures

Figure 1: The evolutionary history of escapement design	2
Figure 2: The five parts of a mechanical watch movement	3
Figure 3: Barrel with mainspring	4
Figure 4: Official website of the WWW Virtual Library	8
Figure 5: The Swiss Lever Escapement on Clock-Watch: History and Technique of Clocks and Watches	10
Figure 6: Swiss Lever Escapement diagram	11
Figure 7: Mark Headrick's Horology Page showing a Swiss Lever Escapement.	12
Figure 8: Structure of the Virtual Library of Mechanical Timepieces.	17
Figure 9: Types of escapements in the Virtual Library.	18
Figure 10: The model of Graham Escapement	20
Figure 11: The five shocks of Graham Escapement	21
Figure 12: The model of English Lever Escapement.....	22
Figure 13: The two levels of pallet fork.....	23
Figure 14: The five shocks of English Lever Escapement	24
Figure 15: The assembly model of English Lever Escapement.....	25
Figure 16: The five shocks of the Swiss Lever Escapement in a cycle.	26
Figure 17: Daniels Co-Axial Double-Wheel Escapement with 2mm thickness.....	27
Figure 18: The wire-frame model of the Daniels Co-Axial Double-Wheel Escapement.	28
Figure 19: The model of Daniels Co-Axial Double-Wheel Escapement	28
Figure 20: Relationship of the balance wheel, the pallet fork and the escape wheel in three levels	29
Figure 21: The five shocks of Daniels Co-Axial Double-Wheel Escapement.	30
Figure 22: The model of the Spring Detent Escapement.....	32
Figure 23: The model of the Spring Detent Escapement is rendered by SolidWorks® ...	33
Figure 24: The five shocks of the Spring Detent Escapement.....	35
Figure 25: Edward Ellicott with a Cylinder Escapement, London, 1780.	36
Figure 26: Video of the Cylinder Escapement.....	36
Figure 27: The hollow tube inside the axis of the balance wheel.	37
Figure 28: The movement cycle of the Cylinder Escapement.....	41
Figure 29: Verge Escapement in 13 th century.....	42
Figure 30: Structure of the Verge Escapement in mechanism watches (Top view).....	43
Figure 31: Structure of the Verge Escapement in mechanism watches (Bottom view). ..	43
Figure 32: Video of the Verge Escapement.....	44
Figure 33: Locking of the escape wheel's front tooth.	45
Figure 34: Unlocking of the escape wheel's front tooth.....	45
Figure 35: Locking of the escape wheel's back tooth.....	46
Figure 36: A typical design of a self-winding system invented in the 17 th century.....	47
Figure 37: Automatic winding system of Rolex	50
Figure 38: Automatic winding system of Rolex – rotor rotates clockwise	51

Figure 39: Automatic winding system of Rolex – rotor rotates anti-clockwisely. 52

Figure 40: Structure of Seiko’s “Magic Lever System”. 53

Figure 41: Working mechanism of Seiko’s “Magic Lever System”. 54

Figure 42: “Double Wheels and Pinions System” of ETA mechanical watches 55

Figure 43: SolidWorks model of “Double Wheels and Pinions System” – Front side..... 56

Figure 44: SolidWorks model of “Double Wheels and Pinions System” – Back side. 56

Figure 45: Transparent mode of the “Double Wheels and Pinions System” model. 57

Figure 46: Reversing coupling wheel and the auxiliary reversing coupling wheel with
pawls. 58

Figure 47: Reversing wheel and auxiliary reversing wheel with specially designed
patterns. 58

Figure 48: Assembly of ball bearings and the “Double Wheels and Pinions System” 59

Figure 49: “Double Wheels and Pinions System” when rotor turns in clockwise direction.
..... 62

Figure 50: “Double Wheels and Pinions System” when rotor turns in anti-clockwise
direction. 64

Figure 51: Phases of the Moon, as seen from the Northern Hemisphere. 66

Figure 52: The Patek Philippe Calibre 89 with moon phase mechanism 67

Figure 53: A mechanical pocket watch with moon phase mechanism 67

Figure 54: Moon phase mechanism with 59 teeth moon phase disc simulation..... 69

Figure 55: Moon phase mechanism components with 135 teeth moon phase disc 70

Figure 56: Coordinate Measuring Machine (CMM).....74

Figure 57: Depth Gauge.....74

Figure 58: Cycloidal gear.....75

Figure 59: Assembly diagram of Graham Escapement in SolidWorks® 76

Figure 60: The animation setting interface in SolidWorks® 77

Figure 61: Website of the Virtual Library of Mechanical Timepieces. 78

Figure 62: Converting the construction blueprint into a CAD animation 80

Figure 63: A clock with the Graham Escapement. 81

1. Introduction

1.1. Background

According to literatures, the first mechanical watch appeared in the middle of the sixteen century. Since then, it has been studied by many people, including such geniuses as Galileo, Huygens and Hooke. Today, it still fascinates millions of people around the world. With the growth of the world economy, the watch industry continues to grow in recent years. For example, Swiss watch exports grow at a steady rate of 12% in 2005 [1]. Hong Kong's watch manufacturing industry is the second largest in the world. It is also the 4th largest industry sector in the region. Therefore, studying the mechanical watches has a global and local significance.

Among various parts of a mechanical watch, escapement is the most important. The escapement is so-called because it allows the stored energy being “escaped” in equal amount to assure the timekeeping accuracy. As shown in Figure 1, escapement design has a long evolutionary history. [2][3][4] The first generation of escapement uses a pendulum for timekeeping. The Graham Escapement invented in 1715 by an English watchmaker George Graham is a typical example of this design. This escapement is also called the deadbeat escapement. It is modified from the anchor escapement by eliminating recoil. Graham Escapement is mainly used in pendulum clocks. This escapement is still used today.

First generation
Pendulum
1710s



Second generation
Hairspring and balance
wheel
1850s



Third generation
More complicated
structure
1990s



Figure 1: The evolutionary history of escapement design.

The second generation of escapement replaces the pendulum with a balance wheel and a hairspring, which greatly reduces its dependence on stationary positions and its size. Typical examples include the English Lever Escapement, the Spring Detent Escapement and the Swiss Lever Escapement.

In the past century, more complex escapements are being designed. One of the prominent examples is the Daniels Co-Axial Double-Wheel Escapement design by the master watchmaker Dr. George Daniels. This escapement has been used by Omega Co. in 1999. [5] Moreover, various aesthetic and exotic features are considered, such as moon phase, chronograph, tourbillon and etc.

Generally speaking, a mechanical watch is made of five parts as shown in Figure 2. These are: the winding mechanism, the power reserves (mainspring), the gear train, the display and the escapement.

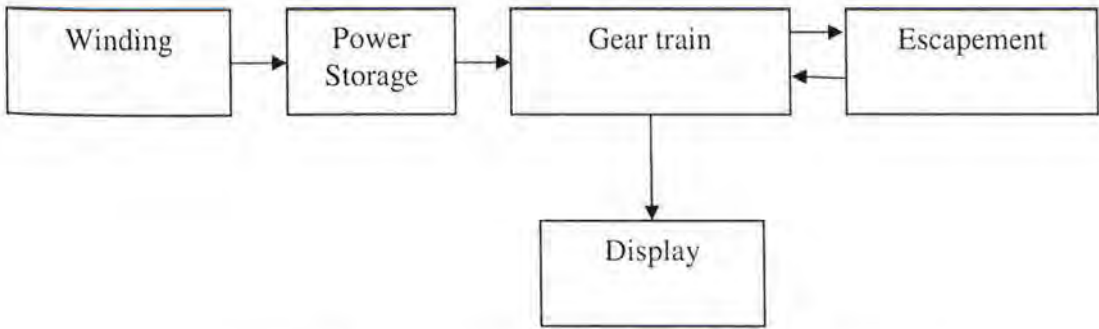


Figure 2: The five parts of a mechanical watch movement.

A mechanical watch receives energy from the winding system. There are two kinds of winding systems: manually winding and automatic winding. Through an automatic winding system, movement of the wearer’s arm is transmitted to the semi-circular shaped oscillating weight. This kinetic energy is then stored by means of

recoiling of the mainspring. The mainspring is located in a circular box called barrel as shown in Figure 3. For automatic winding systems, the barrel has a special mechanism to prevent over-winding.

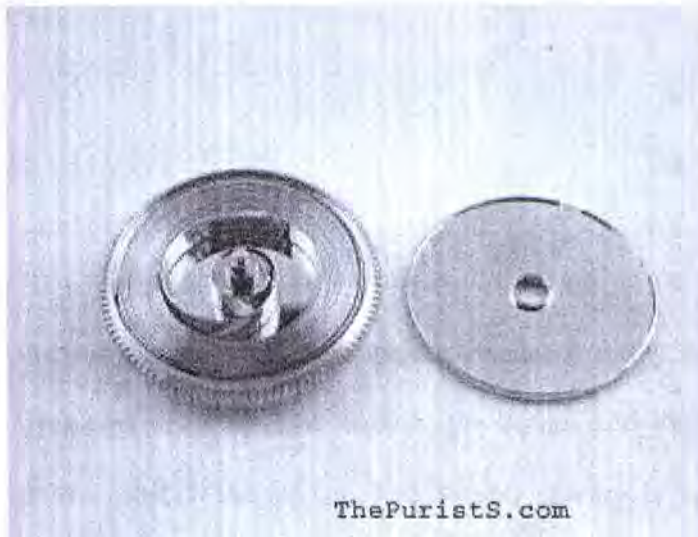


Figure 3: Barrel with mainspring. [6]

The stored energy is transmitted to the escapement through a gear train, which usually consists of three sets of gears: the second pinion and wheel, the third pinion and wheel, and the escape pinion and gear. The escapement is a self-regulating system that gives a rhythm for timekeeping. Time is finally shown on the display of the watch.

Escapement is the most important and most distinctive in a mechanical watch. [7] It is said that there are over one hundred different types of escapements. Though, they share the same function: to provide a stable oscillation feedback to regulate the timekeeping accuracy.

Although mechanical watches / clocks are fascinated by many people, engineers or non-engineers alike, few really understand their working. This is due mainly to the fact

that a mechanical watch is a moving mechanism, stationary views and wordy descriptions are hard to understanding. [8] Searching through websites and literatures, most records and books [9][10] could not show how a mechanical watch works. This motivates the presented research.

1.2. Objectives

The objective of the presented research is to provide an educational tool for engineers or anyone who are interested to understand the working of the mechanical watch / clock movements. This is done through the design and implementation of a Virtual Library of Mechanical Timepieces. The Virtual Library is made of 3D CAD models of various mechanical timepieces. It provides 3D animations demonstrating the working of various mechanical timepieces. In addition, the CAD models are drawn to exact dimension and hence, can be used by watchmakers to validate their design and manufacturing.

This thesis presents the details of the design and the implementation of the Virtual Library. It consists of five chapters. Chapter 2 is the literature survey presenting the related research around the world. The major challenges of the research are also discussed. Chapter 3 is the main body of the thesis. The structure of the Virtual Library is first presented, followed by nine kinds of mechanical clock / watch mechanisms. Detailed working principles of each entry are explained. Chapter 4 presents the implantations of the Virtual Library. Issues from CAD models building procedures to website design are

discussed. An application of the Virtual Library is also included. Finally, Chapter 5 contains the conclusions.

2. Literature Survey

This chapter presents a literature survey and some background information regarding to this research project as well as technical details on the Virtual Library of Mechanical Timepieces preparing the readers for the rest of the thesis. The idea of visualizing the two-dimensional information from books, magazines, journals to digital form has been exploited recently by some researchers and this chapter presents the works of these researchers.

Virtual libraries are a library that consists only of resources available in the digital format, which can be accessed on a hard disk or through computer networks and released to public or for private use. Virtual libraries often follow certain guidelines upon the selection of content in order to maintain a consistent collection of data. The selection, categorization and management of information resources of a virtual library are generally handled by one or a group of experts.

2.1. Existing Virtual Libraries

Presently, dozens of virtual libraries are available on the Internet. Followings are some of the popular ones.

1. WWW Virtual Library [11]

The idea of building a virtual library on the Internet has been exploited by researchers in recent years. The first online virtual library, WWW Virtual Library, appeared and became publicly available in 1991 with the first webpage written on 13th November, 1990. The WWW Virtual Library is one of the earliest examples of virtual library, started by Tim Berners-Lee and maintained by volunteers. This virtual library can be reach online at <http://vlib.org/>. Information resources of the library are divided by different categories, including Agriculture, Arts, Law, Recreation, etc. Figure 4 shows the webpage of the WWW Virtual Library.

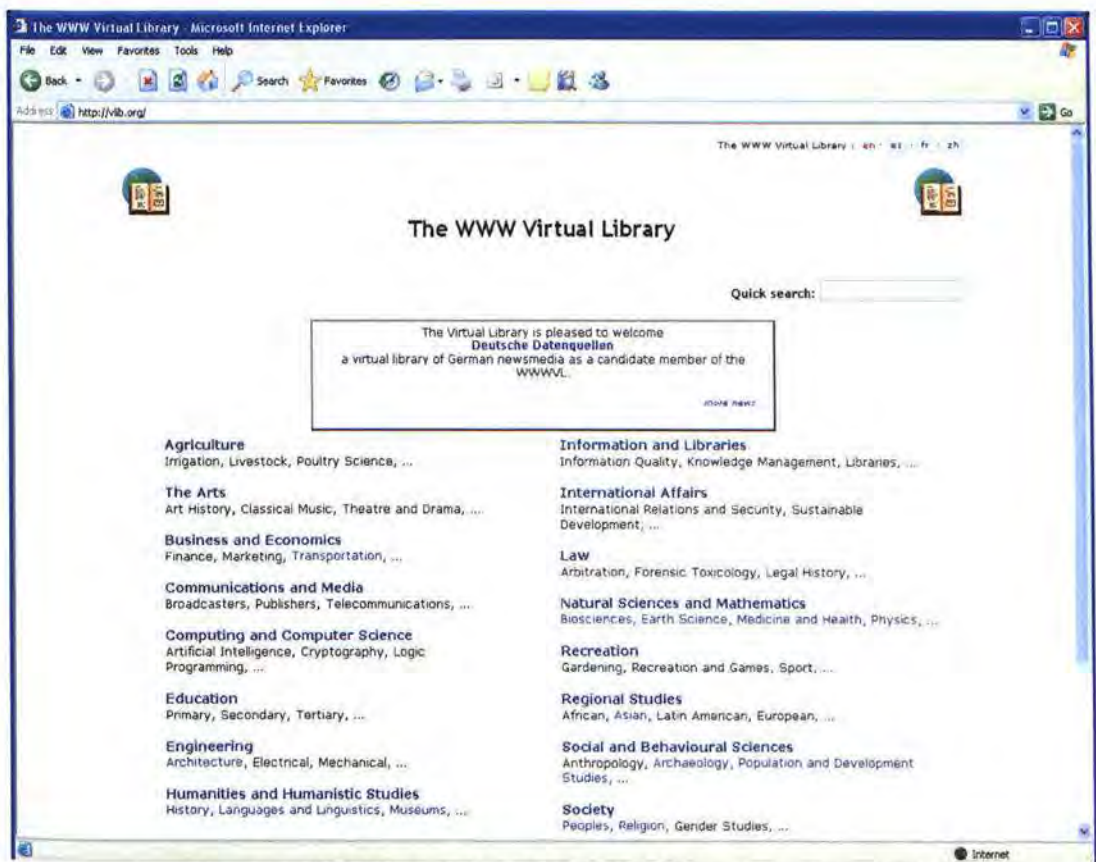


Figure 4: Official website of the WWW Virtual Library. [11]

The WWW Virtual Library is not a commercial catalogue, so its maintenance can only rely on a confederation of volunteers. In this situation, the library shows the data management problems due to the limited human resources and budget. It is obvious that the layout and interface of pages under each category are not consistent. This ruins the structural integrity of the whole virtual library as one. Besides, the reliability of information recourses is questioned as information is provided by individuals such as volunteers and experts in certain area, without a monitoring system to check the consistency and trustworthiness of the information sources.

2. Clock and Watch: A Brief History [12]

The website of Clock-Watch: History and Technique of Clocks and Watches at <http://www.clockwatch.de/> contains a number of two-dimensional animations about different types of escapements with the help of Microsoft Flash. It allows users to interact with some of the animations to change the model parameters, such as the oscillating angles and the size of the components.

Figure 5 is the Swiss Lever Escapement found on the Clock-Watch: History and Technique of Clocks and Watches. It is convenient that the speed of movements can be controlled by the icons at the top (indicated by the red box in Figure 5). The balance wheel, pallet fork and escape wheel would rotate little by little to show the movement clearly. However, this simulation fails to show the detailed mechanism of mechanical watch movements. It shows only the movement of the escapements but it can not tell how the escapement is connected with the gears train and other components, such as hairspring, barrel, rotor etc. Besides, this model also fails to explain where the moments

of force coming from. Readers are always interested in how the movement is triggered and where the components gain the force.

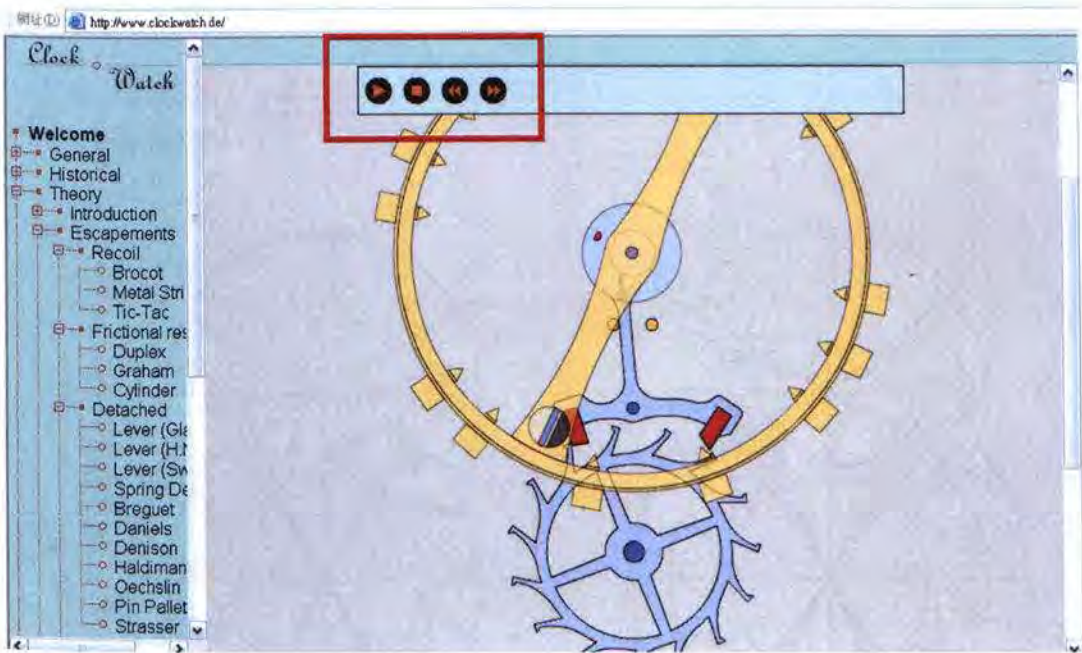


Figure 5: The Swiss Lever Escapement on Clock-Watch [12]: History and Technique of Clocks and Watches. The speed of movements can be controlled by the icons at the top (indicated by a red box).

3. Mark Headrick’s Horology Page [13]

Mark Headrick’s Horology Page at <http://www.geocities.com/mvhw/> is a homepage for the book “Clock and Watch Escapement Mechanics” authored by Headrick in 1997. The book shows the way to draw an escapement step by step. Figure 6 shows the method of designing and drawing the Swiss Lever Escapement as stated in the book. Angles and lines are labelled for easy understanding. Both escapements of mechanical clocks and watches are covered. Its descriptions are so detailed that one can learn the

geometry and the drawing techniques. Although it gives detailed information of escapements, animations on the website are far too simple. It shows only a wireframe model but with all the details missing. Hence, it is impractical to learn the details through these animations.

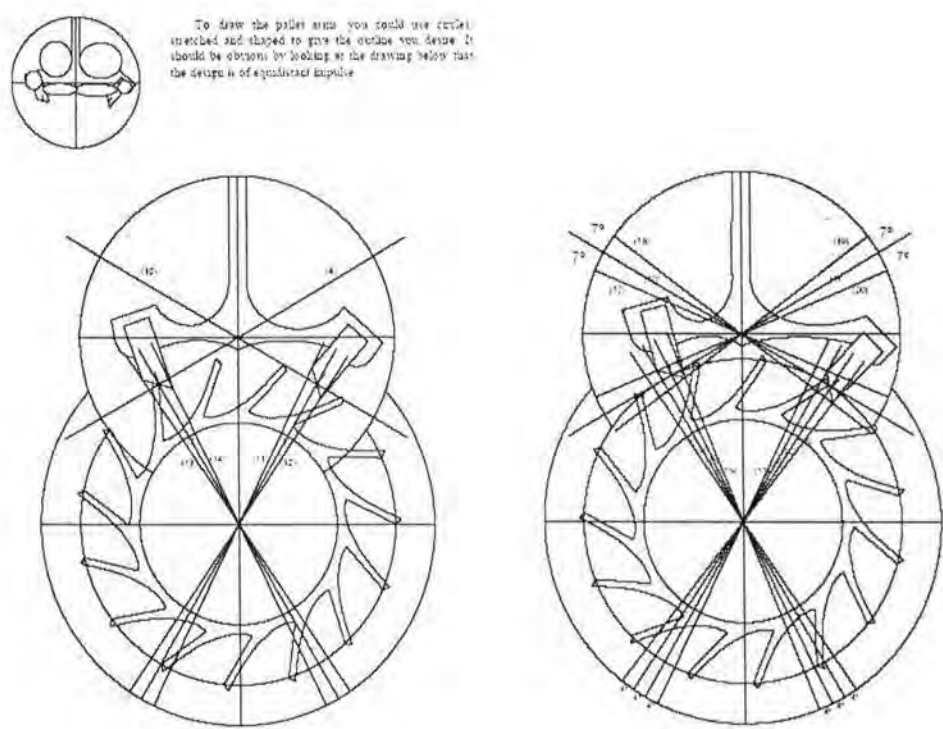


Figure 6: Swiss Lever Escapement diagram [14]

All records of escapements in the book “Clock and Watch Escapement Mechanics” can be found on the website Mark Headrick’s Horology Page. However, as seen in Figure 7, the animation is so simple and crude. It shows only the outlook of the structure. Details of the movements are missing. It is too rudimentary for watch making students to use this website as a learning material.

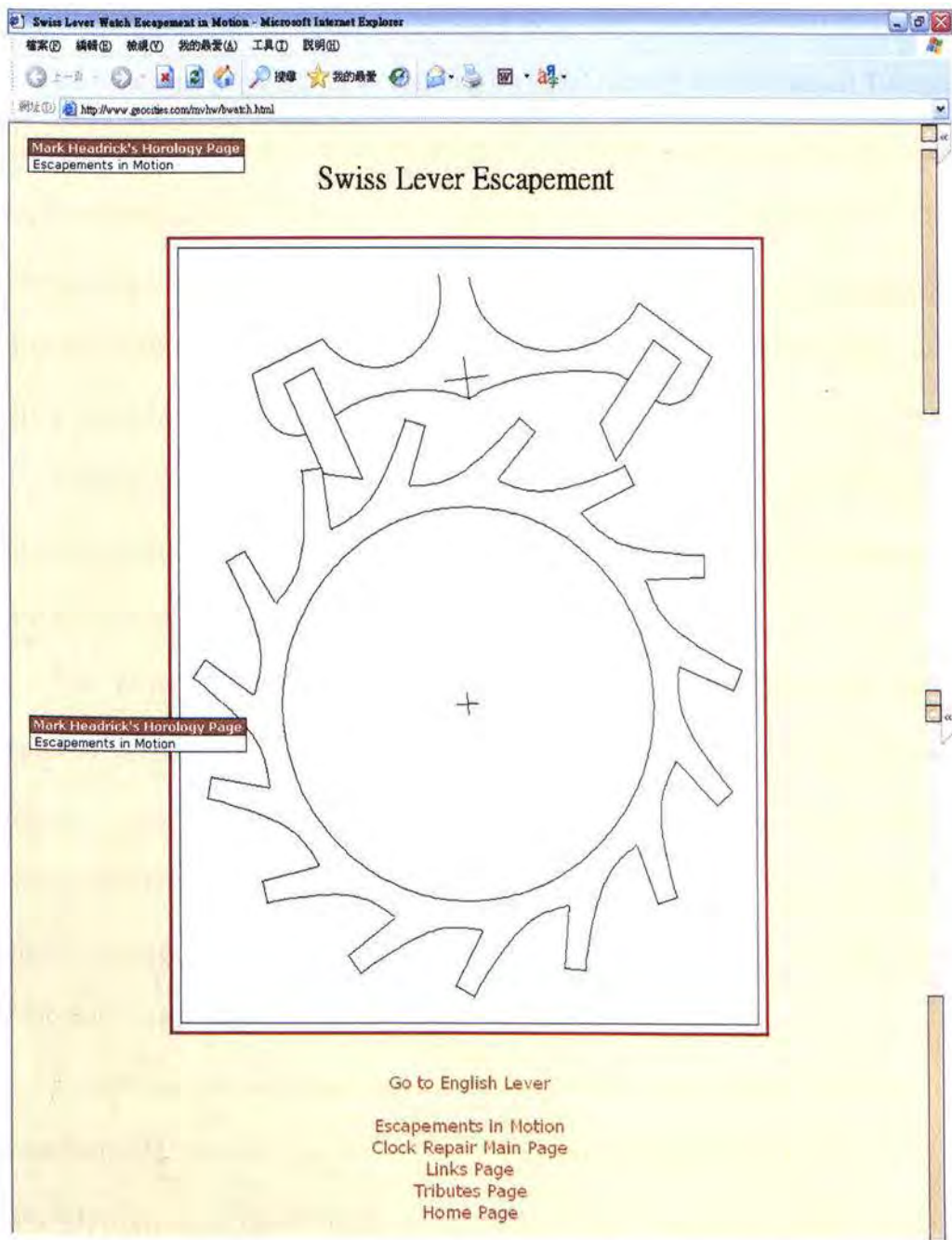


Figure 7: Mark Headrick’s Horology Page showing a Swiss Lever Escapement. [13]

2.2. Challenges

This research project aims at building a Virtual Library of Mechanical Timepieces to provide a convenient and reliable source of information to demonstrate the working principles of mechanical watch and clock designs. It is predicted that the Virtual Library will have a big contributions on the educational purpose. To visualize the structure and mechanism of mechanical watch/ clock movements, it would help watch-making students to gain a better understanding on the teaching materials.

After reviewing several existing virtual libraries and mechanical timepiece related information source and teaching materials, it is believed that the major challenges of the Virtual Library of Mechanical Timepieces are as follows:

- a) The Virtual Library has to be able to provide reliable information, including background information, history, inventor and products in the mechanical timepiece market of the records. It would be a big challenge as nowadays it lacks a complete and systematic database for these kinds of information. That means if such a database has to be built, it would just like writing a dictionary from nothing. From this example, how hard the task is can be predicted.
- b) Converting the structure of mechanical clock/ watch mechanism into three-dimensional CAD models is a crucial part of this research project. It is planned to build the models with an advanced engineering product design software, SolidWorks®. [15] From the engineering point of view, by what means to present the working mechanisms precisely, on both the components dimensions and the movements, is one of the main

concerns. It would be a challenge to produce movement-based simulations with a consideration on precision engineering. One more point to note is that the models would be most desirable if materials used could be reflected on the simulations.

c) Clear and systematic structure is a must for the Virtual Library to present its mechanical clock/ watch mechanisms records. This is extremely important for the ease of readers to find their required information. Being a successful database, good organization of records is a prerequisite.

3. Virtual Library of Mechanical Timepieces

Mechanical watch is one of the most intricate mechanical devices that men have ever invented. Throughout the history, it has been studied by many such geniuses as Galileo and Huygens. It still attracts many people today. In general, a mechanical watch movement may consist of some 100 components. Among these components, escapement is the most important. It determines the timekeeping accuracy, and is often regarded to as the brain of movements.

According to literatures, there are over 100 different types of escapements. [16] In this thesis, a Virtual Library of Mechanical Timepieces is presented. Objective of this project is to provide an educational tool for mechanical engineers or anyone who are interested to understand the working principle of the mechanical timepiece movements. Currently, it consists of nine different mechanical timepiece mechanisms. For each record, background information, CAD models and movement simulation video clips are available in the Virtual Library of Mechanical Timepieces which becomes one of the most instructive online encyclopaedias. The Virtual Library is accessible on the Internet at: http://www.ipe.cuhk.edu.hk/projects10_library.html.

3.1. Structure of the Virtual Library

The Virtual Library of Mechanical Timepieces was divided into three sections. Structure of the Virtual Library is shown in Figure 8. They are the Mechanical Clock Escapements, the Mechanical Watch Escapements and the Accessories. Currently, the Virtual Library of Mechanical Timepieces consists of nine records.

The Mechanical Clock Escapements section has a record of the Graham Escapement, which is the oldest and the most common escapement for clocks. While the Mechanical Watch Escapements section has six records, including the English Lever Escapement, the Swiss Lever Escapement, the Daniels Co-Axial Double-Wheel Escapement, the Spring Detent Escapement, the Cylinder Escapement and the Verge Escapement. At this moment, there are two records in the Accessories section within the Virtual Library of Mechanical Timepieces. They are the Automatic Winding System and the Moon Phase Mechanism.

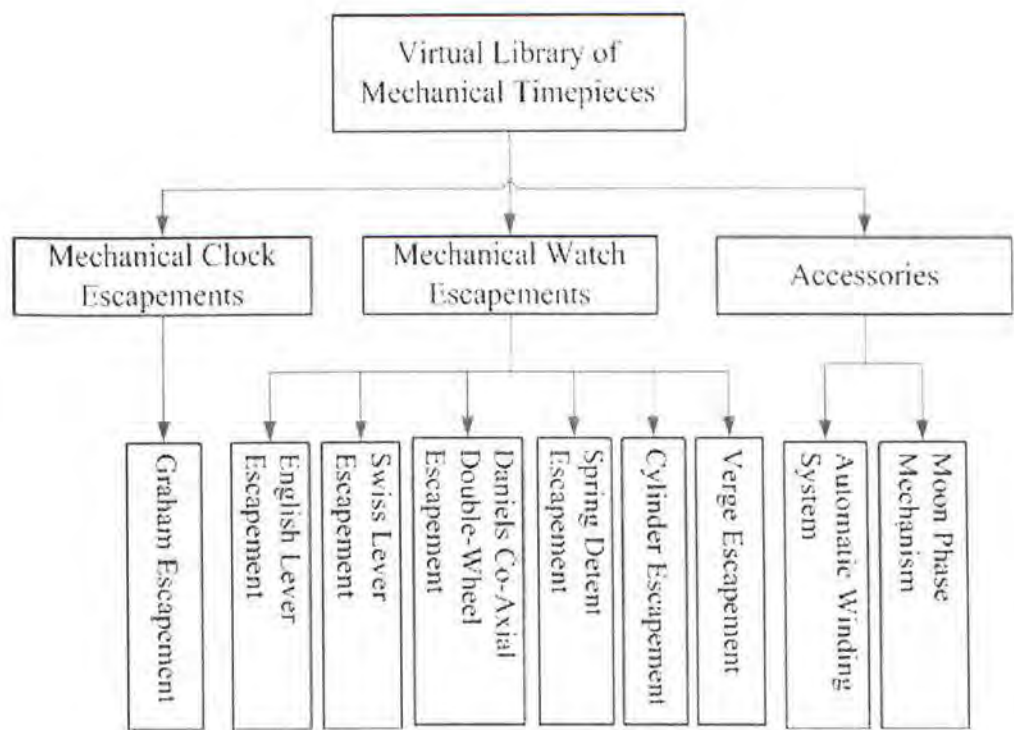


Figure 8: Structure of the Virtual Library of Mechanical Timepieces.

Escapements can be further divided into two categories as shown in Figure 9. They are the anchor escapements and the detached lever escapements.

Anchor escapement means its mechanism in a clock that maintains the swinging of a pendulum for accurate timekeeping. The Graham Escapement which has a pendulum belongs to this category.

Another group is the detached escapement which means the time-keeping element runs entirely free of interference from the escapement during a portion of the operating cycle. As stated in the previous section, energy stored in the barrel goes through the gear train and reach the escape wheel. This provides a torque on the escape wheel, however, the rotation of the wheel is regulated by the balance wheel and the hairspring and

controlled by the oscillation of the pallet fork. Finally, the escapement gives a rhythm to the gear train. This is how a detached escapement provides stable oscillation feedback to adjust the timekeeping accuracy. The English Lever Escapement, the Swiss Lever Escapement, the Daniels Co-Axial Double-Wheel Escapement and the Spring Detent Escapement belong to this group.

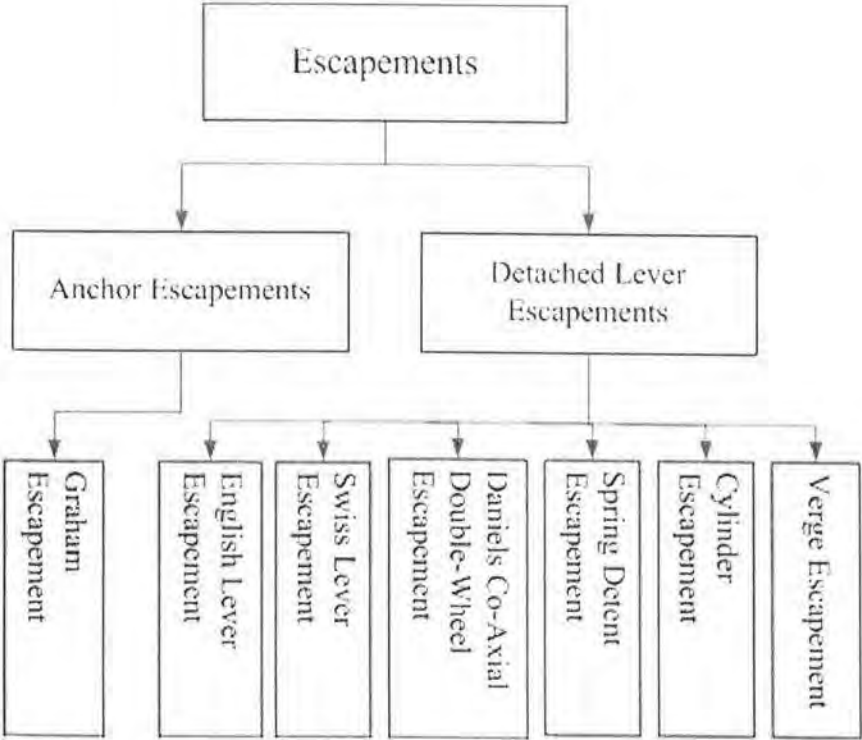


Figure 9: Types of escapements in the Virtual Library.

3.2. Mechanical Clock Escapements

The following describes the records inside the Mechanical Clock Escapements section of the Virtual Library of Mechanical Timepieces.

3.2.1. Graham Escapement

In 1715, English watchmaker George Graham (1673-1751) invented the Graham Escapement. Born in Hethersgill, England, Graham was one of the most well-known horologists of the eighteenth century. In 1688, he became an apprentice to Henry Aske who was a clockmaker in London. Seven years later, he worked with another renowned horologist Thomas Tompion. Besides the Graham Escapement, he is also the inventor of the mercury compensation pendulum, the Cylinder Escapement for watches and the first chronograph. The mercury pendulum can achieve accuracy within a few seconds per day. Graham refused to patent these inventions because he felt that they should be used by other watchmakers. He is a very talented and generous inventor.

The Graham Escapement is also called the deadbeat escapement. [17] It is modified from the anchor escapement by eliminating recoil [18]. Graham Escapement is mainly used in pendulum clocks but not wrist watches. This is because it requires the use of a pendulum and could only work well in the upright position. [19] This escapement is still widely used today.

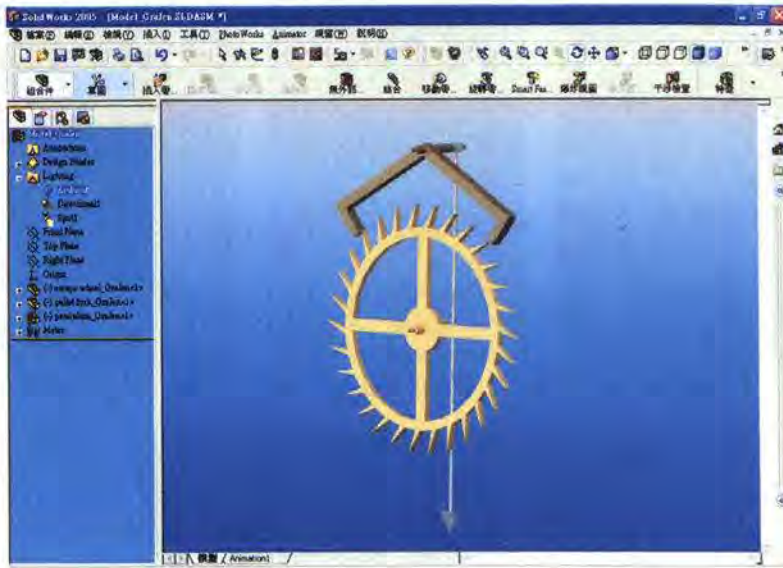


Figure 10: The model of Graham Escapement

Figure 10 shows the assembly of the Graham Escapement. It consists of the escape wheel, the pallet fork, and the pendulum.

The working principle of the Graham Escapement is straightforward. [20] Figure 11 shows the steps that the escapement goes through in a complete cycle. Note that in the figure the circle indicates the points to be noticed and the arrow shows the rotation direction of the escape wheel. Figure 11(a) shows the 1st shock, which is the contact of a tooth on the escape wheel onto the entry pallet of the pallet fork. Figure 11(b) shows the 2nd shock, at which the pendulum reaches the farthest point and begins to move to the opposite direction. Figure 11(c) shows the 3rd shock, another tooth on escape wheel touches the exit pallet of the pallet fork. Figure 11(d) shows the 4th shock, the pendulum reaches the other farthest point. Finally, Figure 11(e) shows the 5th shock, the pallet fork and pendulum return to their original position completing a cycle.

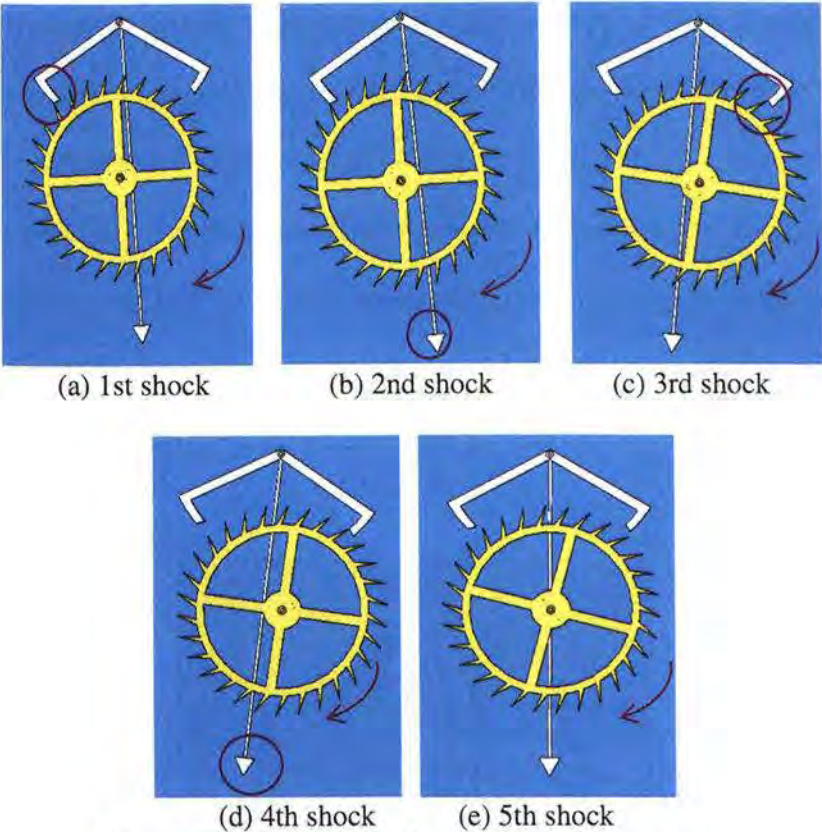


Figure 11: The five shocks of Graham Escapement

3.3. Mechanical Watch Escapements

The following describes the records inside the Mechanical Watch Escapements section of the Virtual Library of Mechanical Timepieces.

3.3.1. English Lever Escapement

This is one of the first lever escapements invented by an English clockmaker Thomas Mudge (1715 - 1794) in 1754. Mudge was apprenticed to George Graham. His

work was treated as a mark of quality at that time. Since he is an Englishman, this escapement design is referred to as the English Lever Escapement. It is one of the earliest detached level mechanisms that do not require a pendulum. [21]

The English Lever Escapement is composed of four parts: the escape wheel, the anchor, the pallet fork, and the balance wheel (with the hairspring). It is assembled in the right-angled triangle form. The axis of balance wheel, pallet fork and the escape wheel forms a right-angled triangle as shown in Figure 12. [22]

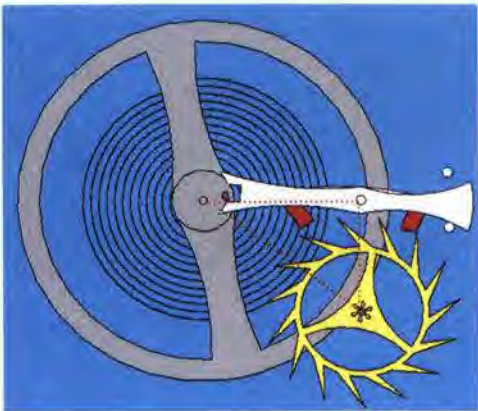


Figure 12: The model of English Lever Escapement. The dotted lines indicated the right-angled relationship of the balance wheel, the pallet fork and the escape wheel.

Figure 13 shows the two levels of pallet fork. Level One works with the balance wheel and it has a slot to hold the ruby on the balance wheel. Level Two works with the escape wheel and there are two rubies on the pallet fork.

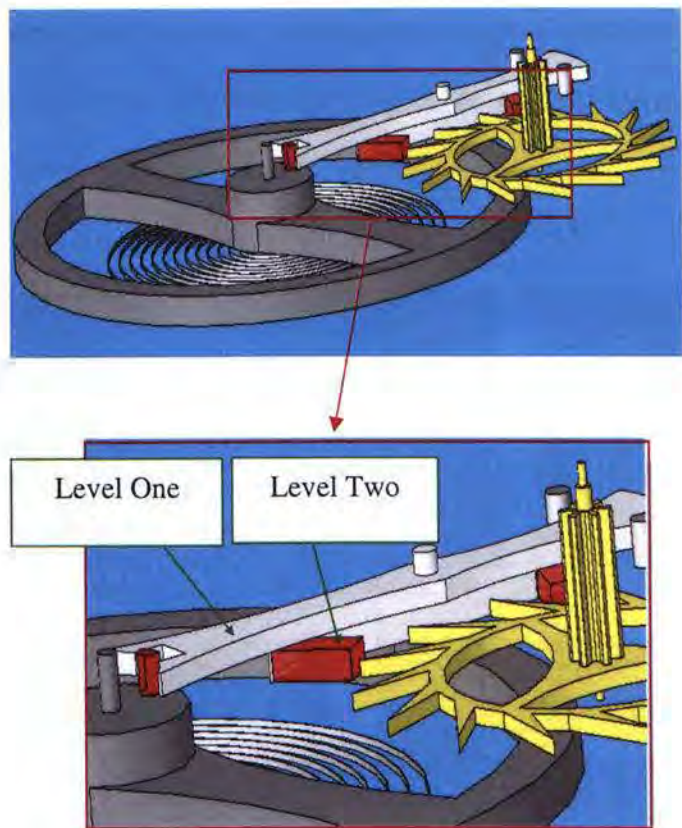


Figure 13: The two levels of pallet fork

Figure 14 shows the movements of the English Lever Escapement in a complete cycle. The 1st shock is the contact of the impulse pin (the half-circle shaped ruby on the balance wheel) with the entry of the pallet fork. At the meantime, the tail of the pallet fork touches one of the banking pins as shown in Figure 14(a). Then, the escape wheel is stopped by one of the rubies on the pallet fork causing the locking of the escape wheel. This is the 2nd shock as shown in Figure 14(b). Figure 14(c) shows the 3rd shock. At this time, the tooth of escape wheel contacts the exit pallet of the pallet fork. The escape wheel is stopped until the impulse pin on the balance wheel collides with the entry of the pallet fork again. As shown in Figure 14(d), the 4th shock is the situation that another side of the tail of the pallet fork touches another banking pin. At the same time, the

balance wheel pauses and then starts rotating to the opposite direction. The 5th shock is the last one, the impulse pin hits the other side of the entry of the pallet fork. This is shown in Figure 7(e).

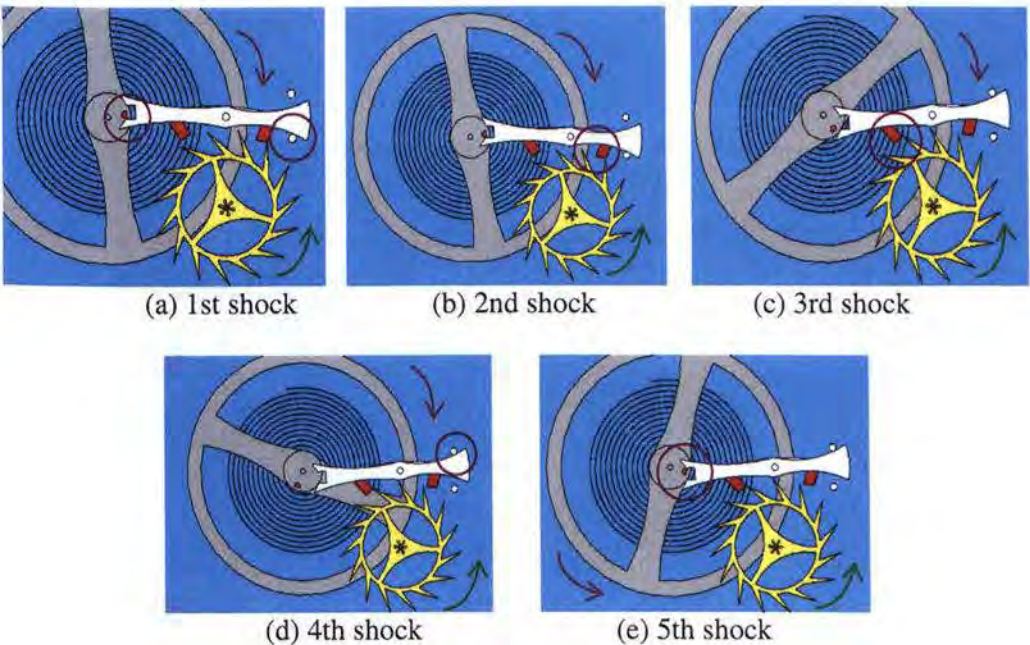


Figure 14: The five shocks of English Lever Escapement

3.3.2. Swiss Lever Escapement

Appeared in the middle of the nineteenth century in Switzerland, the Swiss Lever Escapement is a modification of the English Lever Escapement. It is the most common escapement in the world. In fact, at least 95% of the existing mechanical movements use this escapement because of its high accuracy and reliability.

The model of the Swiss Lever Escapement is shown in Figure 15. It consists of the balance wheel, the hairspring, the pallet fork, and the escape wheel. [23] Swiss Lever Escapement may have many different versions. [24] For this model in Figure 15, there are 15 club teeth on the escape wheel, therefore: $360 / (2 \times 15) = 12$; that is, the angle for each impulsive movement is 12.



Figure 15: The assembly model of English Lever Escapement

Similar to the English Lever Escapement, during a complete cycle, five shocks occur. [25] The 1st shock (Figure 16(a)) corresponds to the contact of the impulse pin (the ruby on the balance wheel) with the entry of the pallet fork. The 2nd shock is shown in Figure 16(b). It is caused by the contact of the escape wheel tooth with the impulse plane of the entry pallet of the pallet fork. As shown in Figure 16(c), the 3rd shock is the situation when the other side of the entry of the pallet fork contacts the impulse-pin. Figure 16(d) shows the 4th shock. It happens when the escape wheel tooth touch the

locking-plane of the exit pallet of the pallet fork. The last stage is the 5th shock (Figure 16(e)). It is the situation that the pallet fork contacts the banking pin. The whole cycle is completed by then.

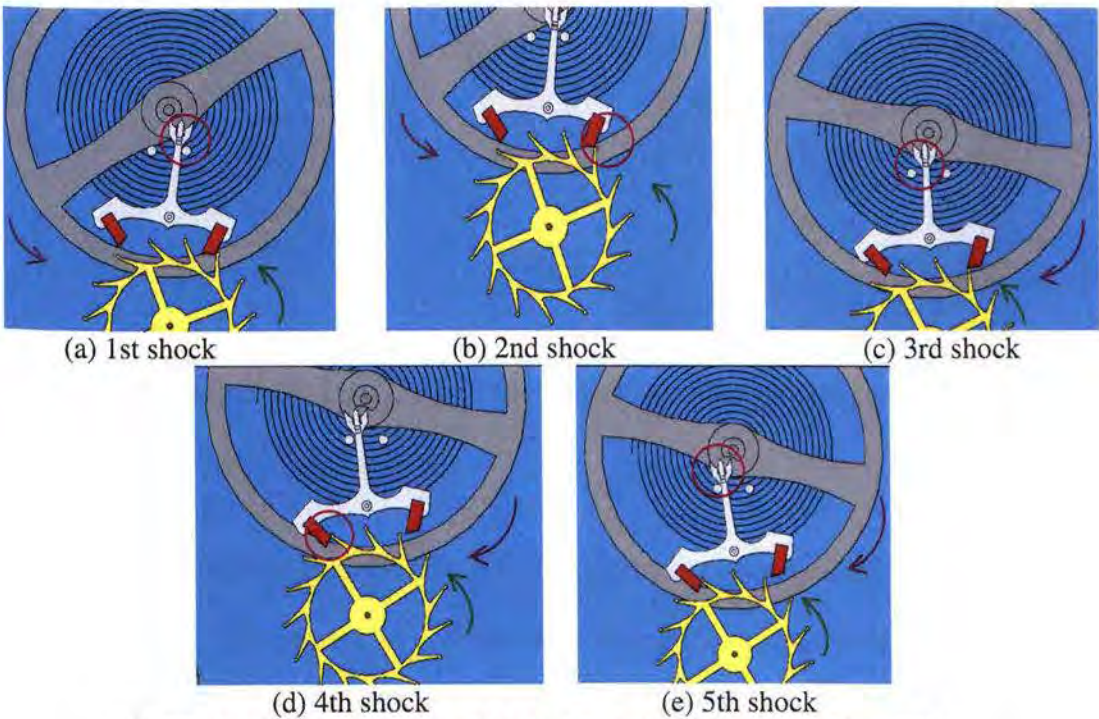


Figure 16: The five shocks of the Swiss Lever Escapement in a cycle.

3.3.3. Daniels Co-Axial Double-Wheel Escapement

The Daniels Co-Axial Double-Wheel Escapement is the masterpiece of Dr. George Daniels (1926 – Now). Dr. Daniels is a professional horologist with rich experiences. Besides inventing the co-axial escapement, he is also a famous author on

mechanical watch movements and the past President of the Horological Institute. He has received a number of prestigious international awards [26].



Figure 17: Daniels Co-Axial Double-Wheel Escapement in a mechanical watch with 2mm thickness. [27]

The Daniels Co-Axial Double-Wheel Escapement is much more complicated than the Swiss Lever Escapement. In order to show the structure and movements in a clear way, a wire-frame view of this escapement is shown in Figure 18. With the wire-frame mode, all the three rubies on the pallet fork could be seen at the same time. It helps to gain better understanding of the whole structure and its movements.



Figure 18: The wire-frame model of the Daniels Co-Axial Double-Wheel Escapement.

The escapement (Figure 19) consists of two escape wheels, a pallet fork, and a balance wheel (with hairspring).

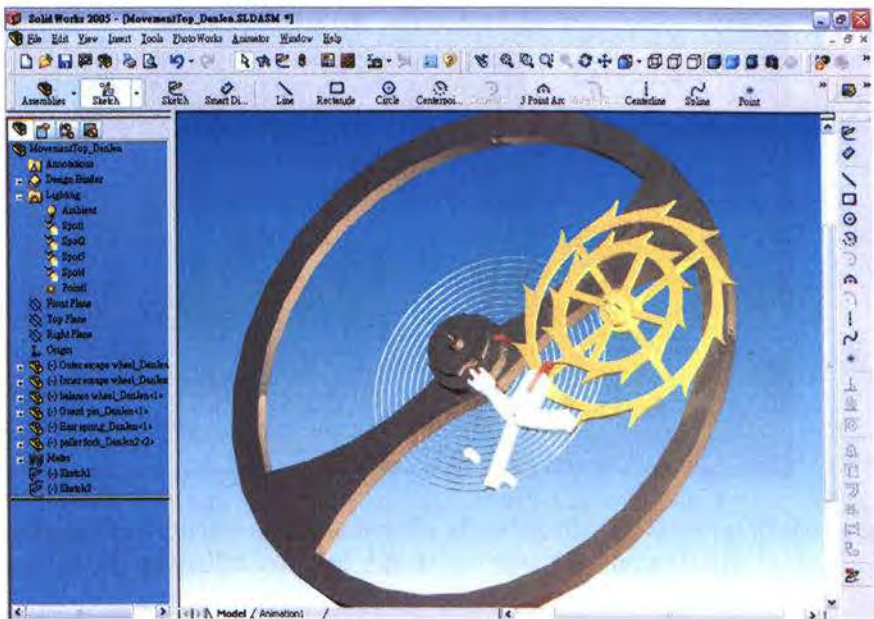


Figure 19: The model of Daniels Co-Axial Double-Wheel Escapement.

Figure 20 shows the details of the escapement. From the figure, it is seen that the escapement has three levels. In Level One, the balance wheel contacts the pallet fork. The banking pins are also at this level. The escape wheel has two levels, called the inner escape wheel and the outer escape wheel, with 12 teeth in each level. In Level Two and Level Three, the pallet fork contacts the inner and outer parts of the escape wheel. [28]

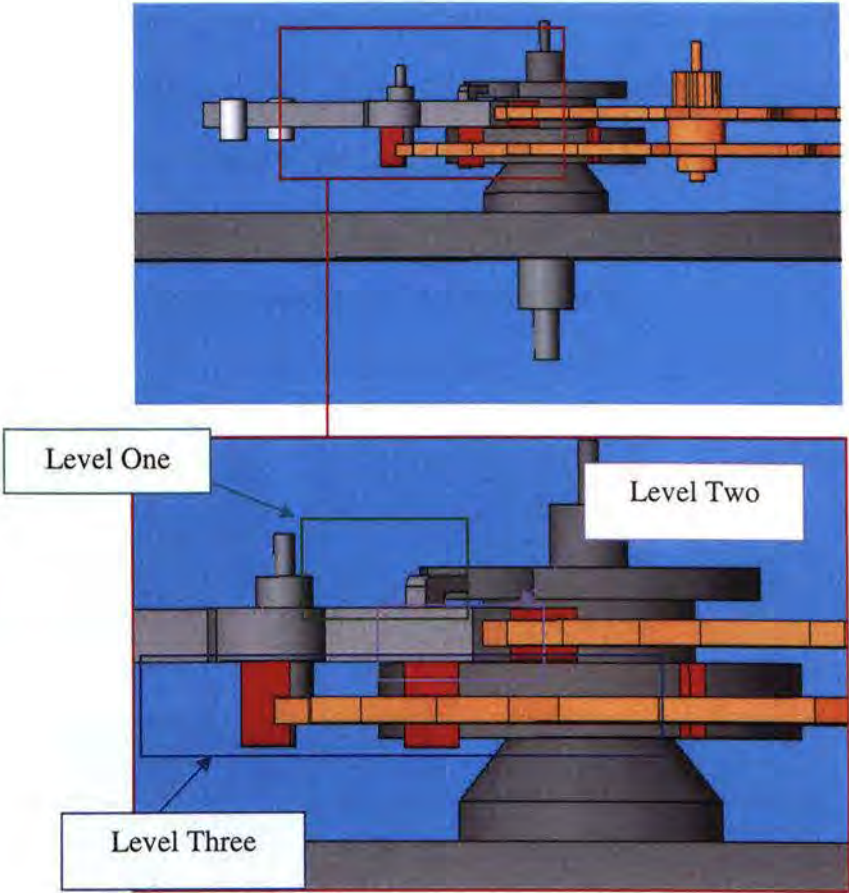


Figure 20: This is the top view of the assembly showing the relationship of the balance wheel, the pallet fork and the escape wheel in three levels.

As shown in Figure 21, the Daniels Co-Axial Double-Wheel Escapement has five shocks in a complete cycle. The cycle of movement start from the 1st shock as shown in

Figure 21(a). It is the contact of the semi-circular impulse-pin with the entry pallet of the pallet fork. In the meantime, the trapezium shape ruby on the balance wheel pushes the outer escape wheel to move in the clockwise direction. Figure 21(b) shows the 2nd shock. It happens when the outer escape wheel stopped by the impulse stone at the head of the pallet fork. The inner escape wheel touches the trapezium shape impulse stone of the pallet fork. The next stage is the 3rd shock, shown in Figure 21(c). It is the situation when the other side of the entry pallet of the pallet fork contacts the semi-circle shaped impulse-pin on the balance wheel. Figure 21(d) shows the 4th shock. It occurs when the outer escape wheel is stopped by the locking-stone on the right arm of the pallet fork. The 5th shock (Figure 21(e)) is the situation that the pallet fork contacts one of the banking pins. Movement cycle of the escapement is then completed.

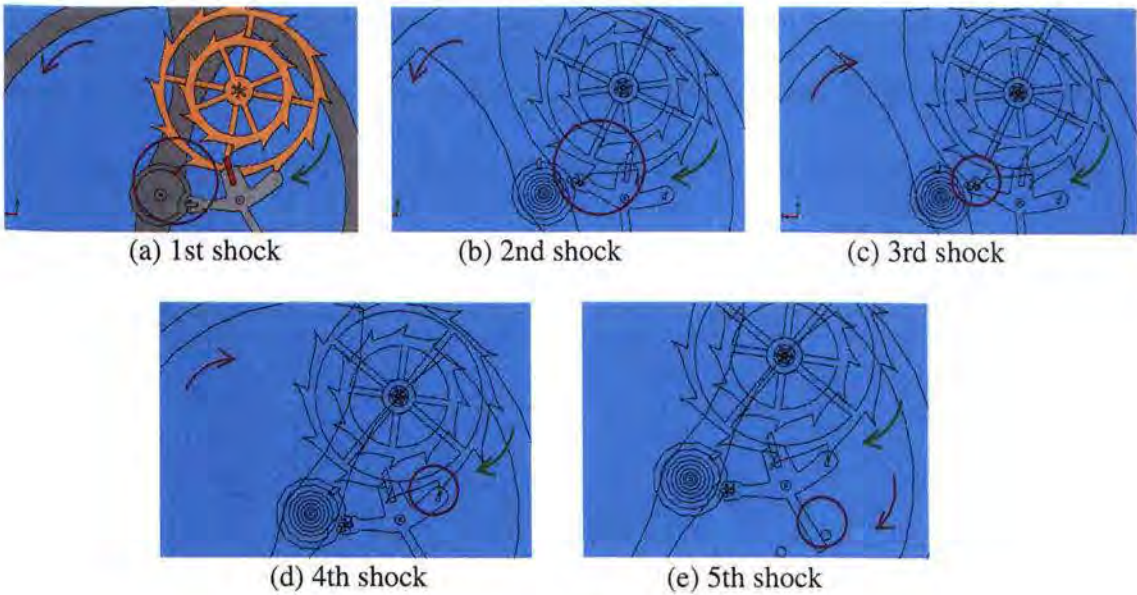
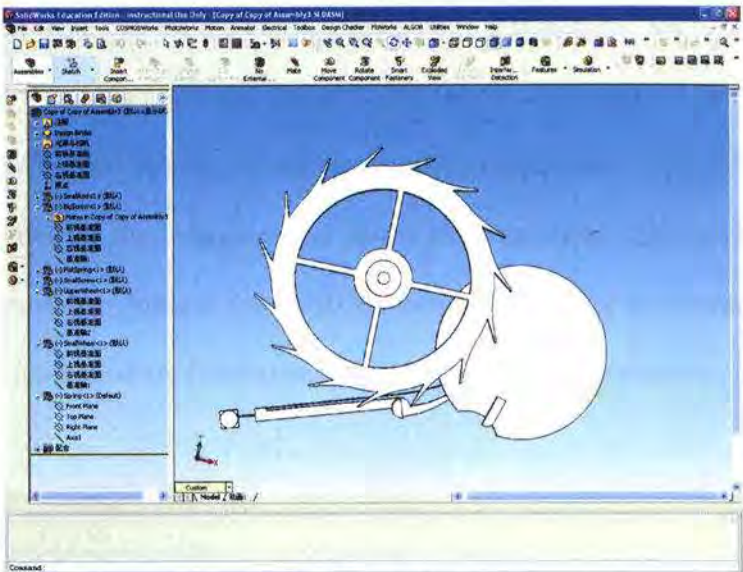


Figure 21: The five shocks of Daniels Co-Axial Double-Wheel Escapement.

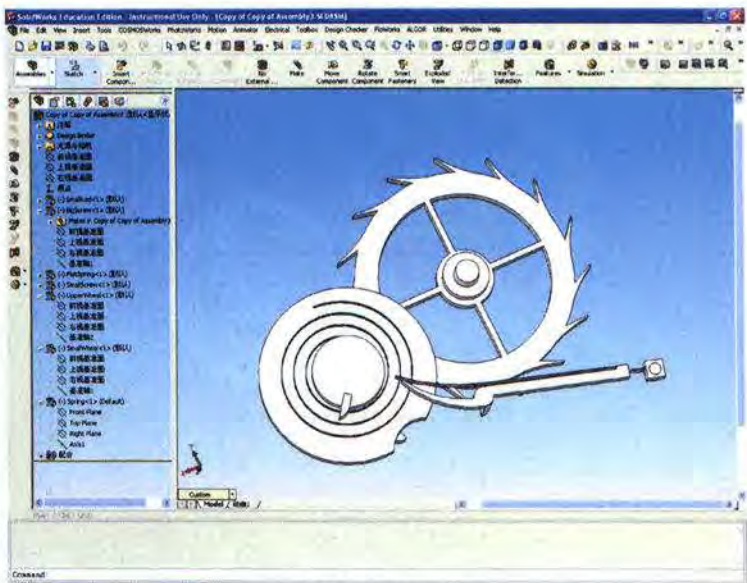
Although the cost of Daniels Co-Axial Double-Wheel Escapement is much higher owing to its high level precision requirement during manufacturing and assembly process, this special design of escapement can effectively minimize the loss of energy due to friction and reduce wear on components. It is claimed that the Daniels Co-Axial Double-Wheel Escapement design has a higher efficiency and greater stability than the traditional lever escapement design. [29][30]

3.3.4. Spring Detent Escapement

The Spring Detent Escapement, a kind of simplified chronometer, developed by John Arnold and Thomas Earnshaw [31] in the late eighteen century. Earnshaw and Arnold were awarded by the Board of Longitude for their contributions to chronometers with £3000. Thomas Earnshaw (1749 - 1829) was an English watchmaker who contributed to the simplification of chronometer. He was also well known for temperature-compensated balance used in the marine chronometer. John Arnold (1736 - 1799) was a watchmaker who developed the pivoted detent escapement in the eighteenth century. He simplified the complicated structure of chronometer by applying a helical balance spring on pivoted detent escapement. This design could achieve a very high accuracy.



(a) Front view



(b) Back view

Figure 22: The model of the Spring Detent Escapement.

An assembly model of the Spring Detent Escapement is shown in the Figure 22. The Spring Detent Escapement contains five main parts in its structure. They are the escape wheel, the balance wheel, the hairspring, the flat spring and the horizontal rod with one end fixed with a pin. In Figure 22 (a) showing the front view of the escapement,

two rubies are found, one on the balance wheel with a trapezium shape while the other one on the rod with a semi-circular shape. At the back view of the escapement (Figure 22 (b)), one more ruby can be found at the back of the balance wheel. This ruby locates near the center position on the balance wheel, above the hairspring. The hairspring is put on the balance wheel providing a torque to its movements. Also, it is notes that the flat spring and the horizontal are fixed at one end with a pin on the mainplate.

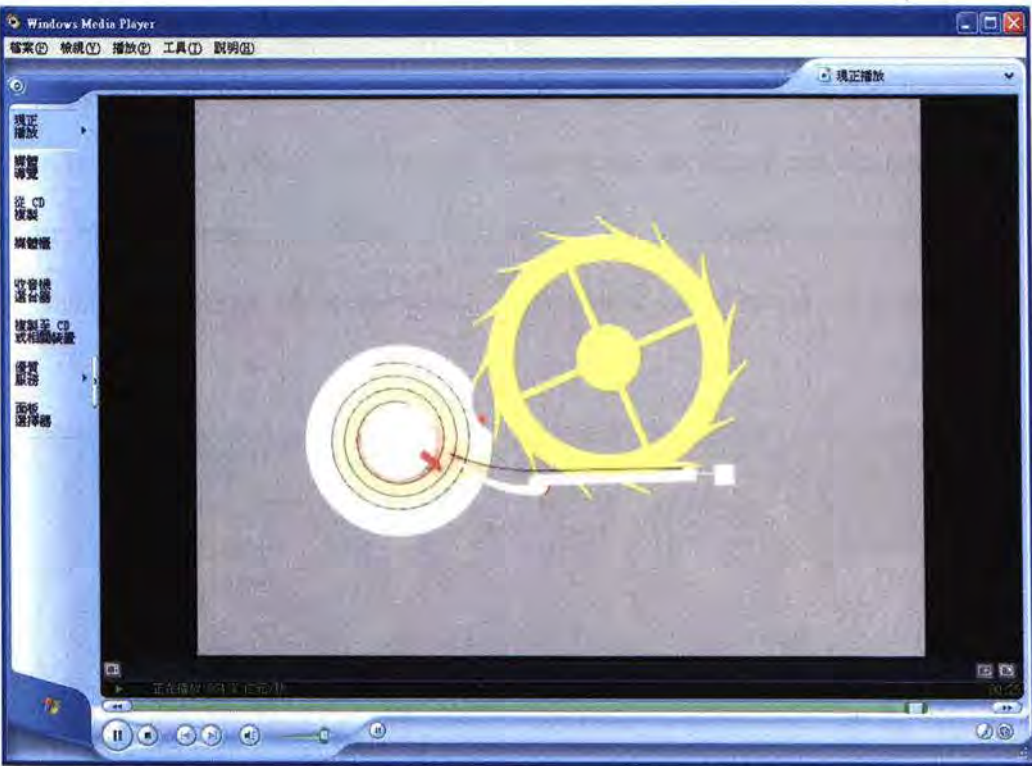
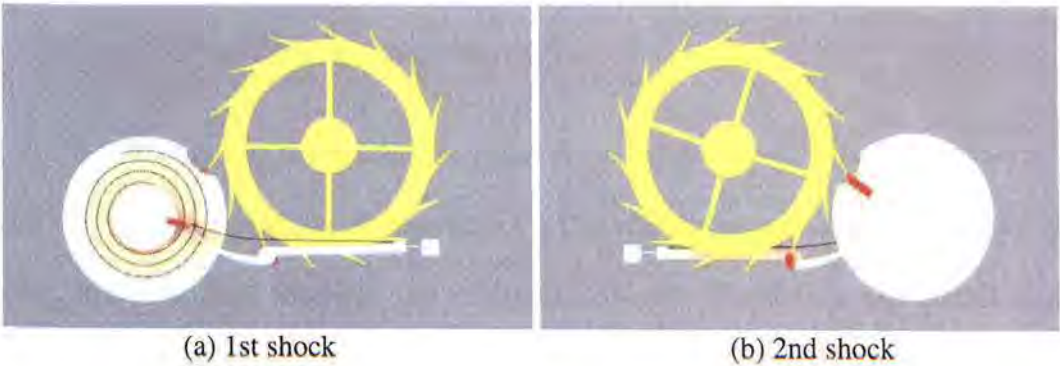


Figure 23: The model of the Spring Detent Escapement is rendered by SolidWorks® and then recoded as a video.

As shown in Figure 24, the Spring Detent Escapement has five steps in a complete cycle. The cycle of movement start from the 1st shock as shown in Figure 24(a). The cycle starts with a push from the ruby, on the back of the balance wheel moving anti-

clockwisely, to the flat spring. The flat spring then moves upward and makes no effect on any component. Figure 24(b) shows the 2nd shock. The balance wheel reaches the end of the rotation and returns back to another direction. At the time when the ruby at the front of the balance wheel collides with a tooth on the escape wheel, the 2nd shock occurs. The next stage is the 3rd shock, shown in Figure 24(c). The ruby at the back of the balance wheel move the flat spring downward, and at the same time bring the horizontal rod moving downward. This triggers the next step, the 4th shock (Figure 24(d)). As the horizontal rod is pull downward, the ruby on the horizontal rod is also moving at the same direction and so let the tooth on the escape wheel move forward .The 5th shock as shown in the Figure 24(e) is the situation that both the flat spring and the horizontal rod returns to their original position. The ruby on the horizontal rod then blocks the movement of a tooth on the escape wheel. A complete cycle of movement is finished.



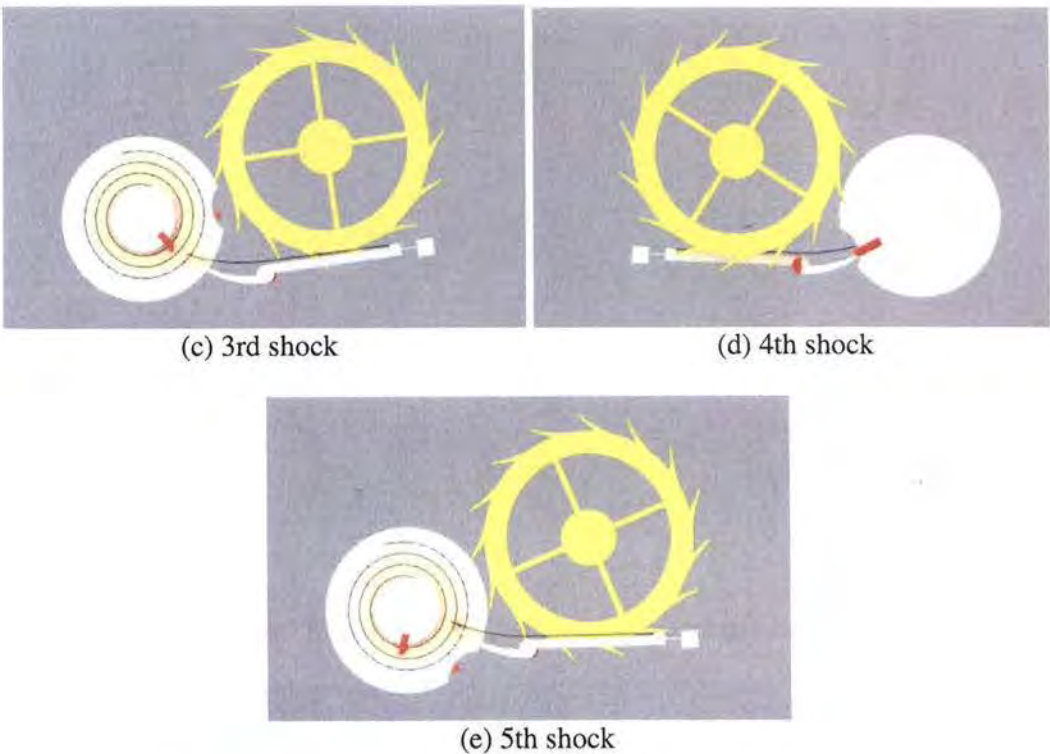


Figure 24: The five shocks of the Spring Detent Escapement.

3.3.5. Cylinder Escapement

The Cylinder Escapement consists of an escape wheel and a cylinder. It is different from the typical escapement that the Cylinder Escapement does not have a pallet fork. It is a kind of frictional rest escapement. Figure 25 shows a mechanical watch applying the Cylinder Escapement.



Figure 25: Edward Ellicott with a Cylinder Escapement, London, 1780. [32]

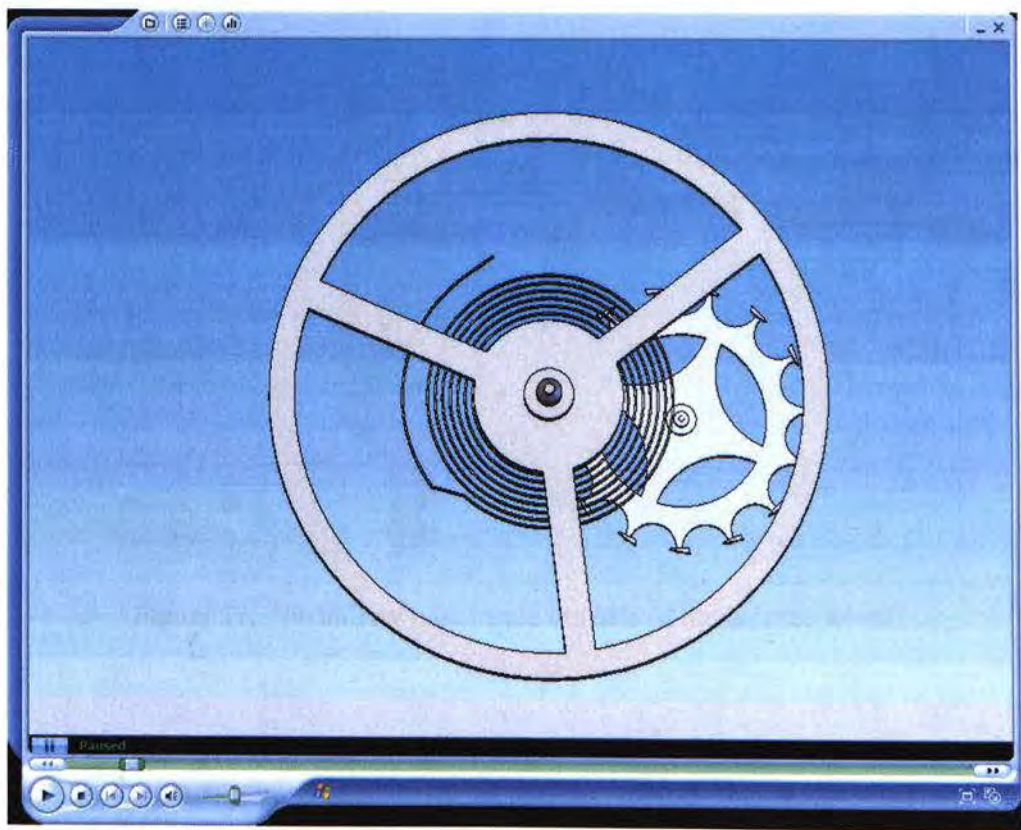


Figure 26: Video of the Cylinder Escapement.

A hollow tube [33] at the middle of the axis of the balance wheel has the same function as a pallet fork. The semi-circular shape hollow tube keeps guiding the escape wheel teeth coming in and getting out of it. [14] This special feature is actually a combination of balance wheel and pallet fork, making them as one part to simplify the structure.

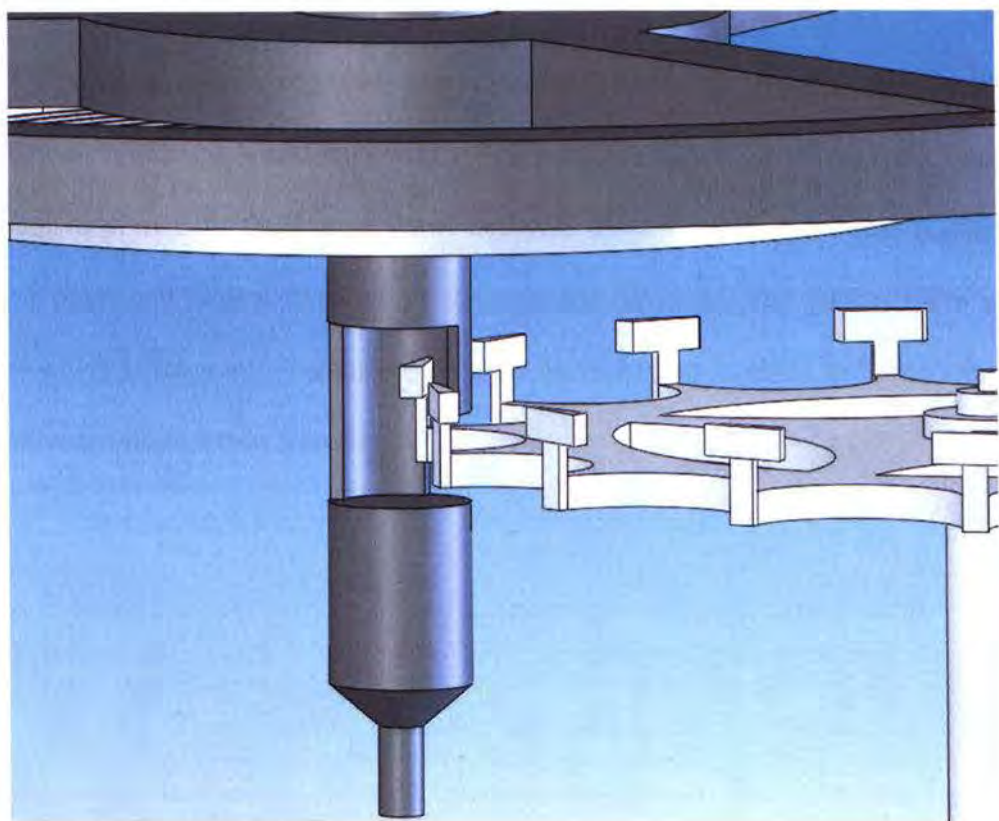
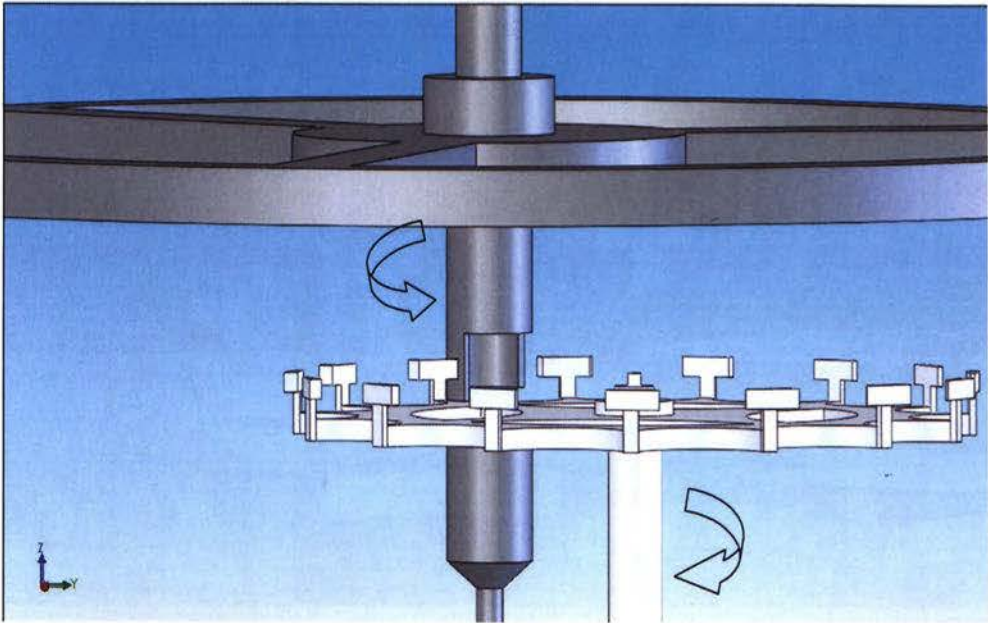


Figure 27: The hollow tube inside the axis of the balance wheel.

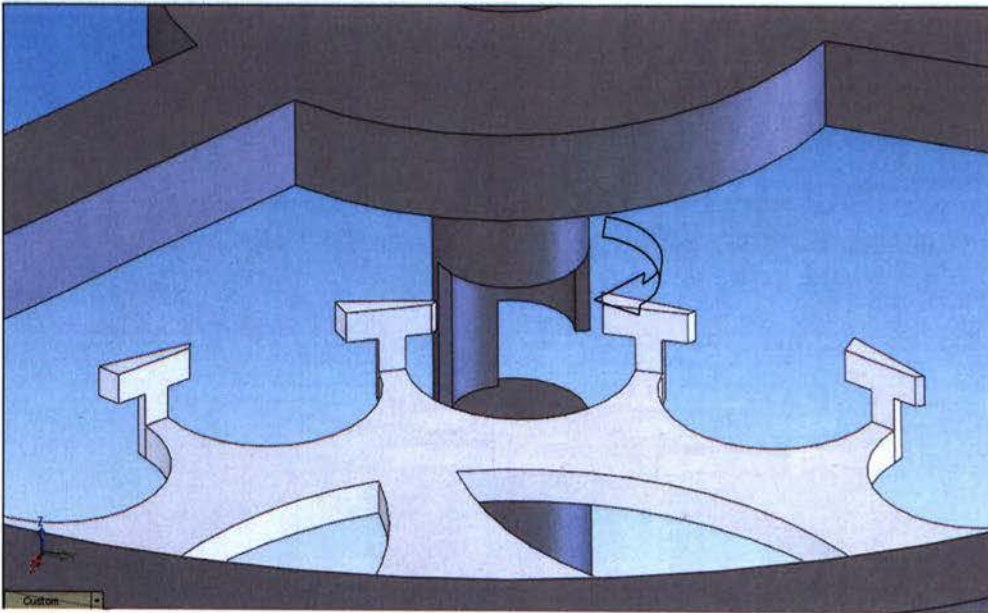
One more special design feature is that the teeth of the escape wheel are tailor-made in triangular shape for a better movement. The dimension and angle of the teeth has

to be a perfect combination with the dimension and geometry of the hollow tube. Otherwise, the escapement would fail to function well.

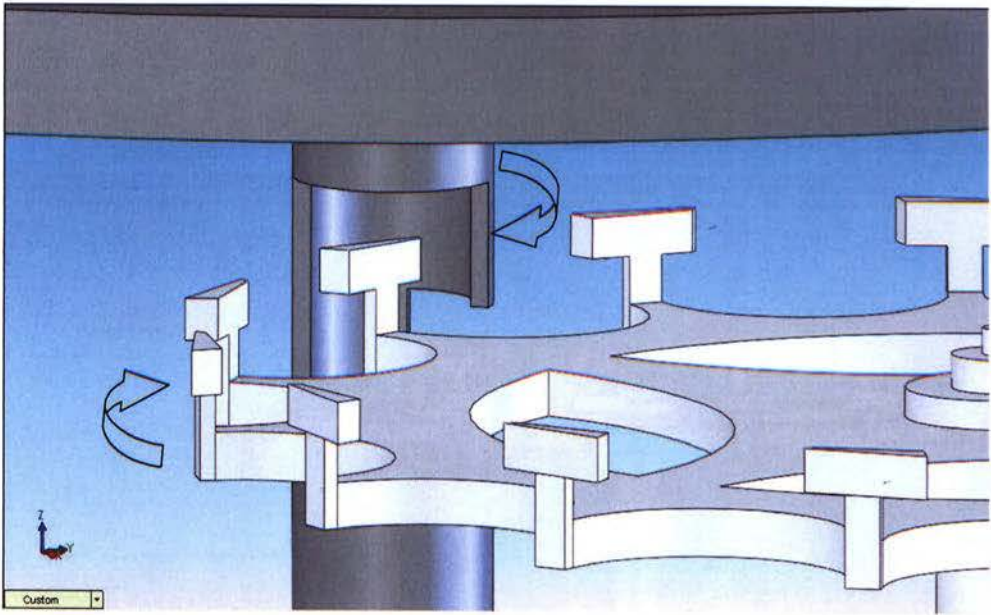
As shown in Figure 28, the Cylinder Escapement has five steps in a complete cycle. The cycle of movement starts from the 1st step as shown in Figure 28(a). The hollow tube rotates in anticlockwise direction and blocks the way of the escape wheel. The escape wheel stops. Figure 28(b) shows the 2nd step. The balance wheel reaches the end of the rotation and returns back to another direction. The escape wheel is released and rotates clockwise. Tooth of escape wheel goes inside the hollow tube (Figure 28(c)). The 4th step in Figure 16(d) shows the situation that the inner wall of the hollow tube blocks the escape wheel from rotating further. The escape wheel stops by then. The last step as shown in the Figure 28(e) happens when the balance wheel reaches the farthest point and begins to move to the opposite direction. The locked tooth of the escape wheel is released. A complete cycle of movement is repeated and repeated again to achieve the task of time keeping. [34]



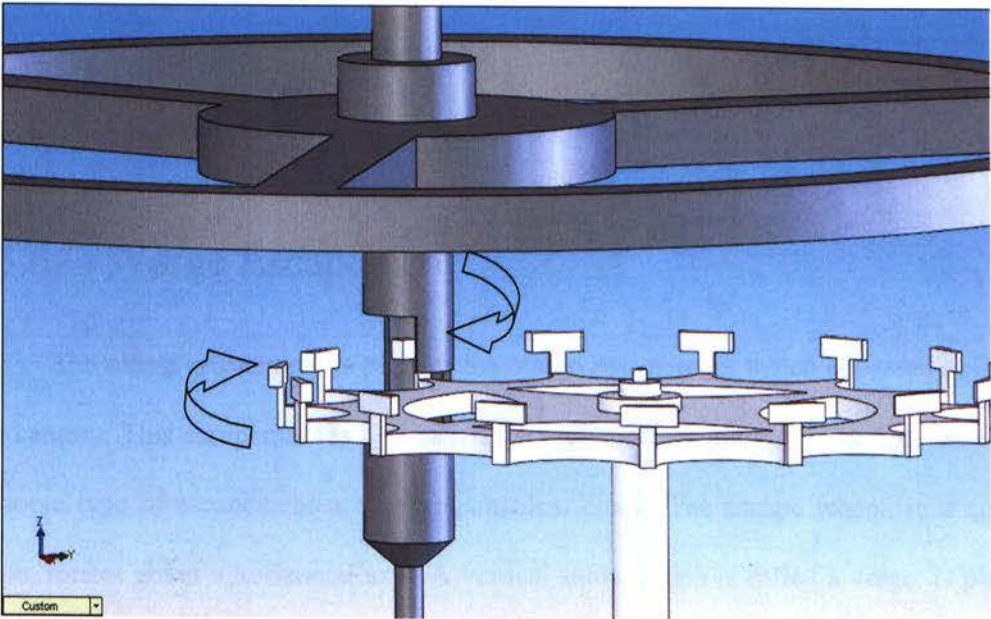
(a) 1st step



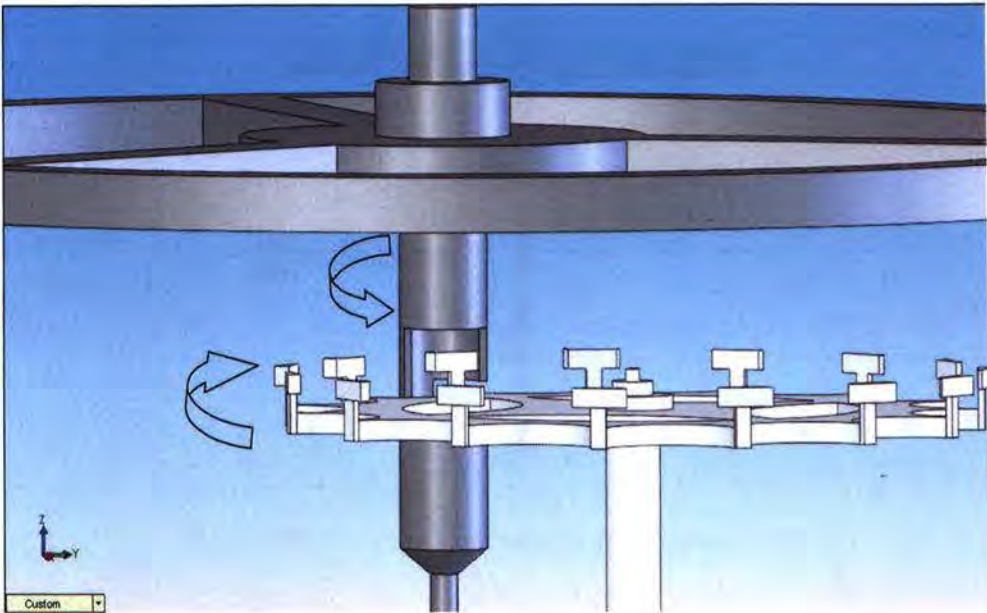
(b) 2nd step



(c) 3rd step



(d) 4th step



(e) 5th step

Figure 28: The movement cycle of the Cylinder Escapement.

3.3.6. Verge Escapement

The oldest escapement is perhaps the Verge Escapement which appeared at about 13th century. This escapement is also called the crown-wheel-and-verge escapement. It is a simple type of escapement used by mechanical clock. The escape wheel, in a crown shape, rotates about a horizontal axis. A vertical shaft, which is called a verge, is placed at the middle of another horizontal bar with two small weights one on each end.

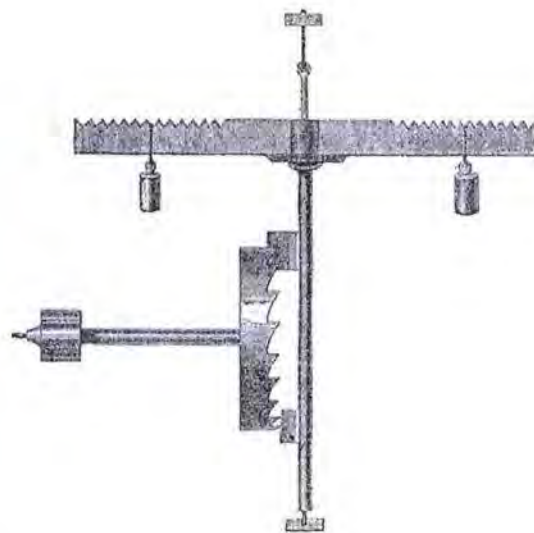


Figure 29: Verge Escapement in 13th century. [18]

The Verge Escapement is a kind of clock escapements and usually used as domestic clock with reasonable accuracy. [35] This escapement is not suitable for high precision time measurement. Clocks with the Verge Escapement have to be adjusted every day to keep the time.

Despite the fact that the Verge Escapement is well known as a clock escapement, the Verge Escapement had been modified and applied on mechanical watch. The main features of the crown-shaped escape wheel and the vertical shaft are retained in the new design except the two weights on the horizontal bar has been replaced by a hairspring. This innovative design is recorded in this virtual library.

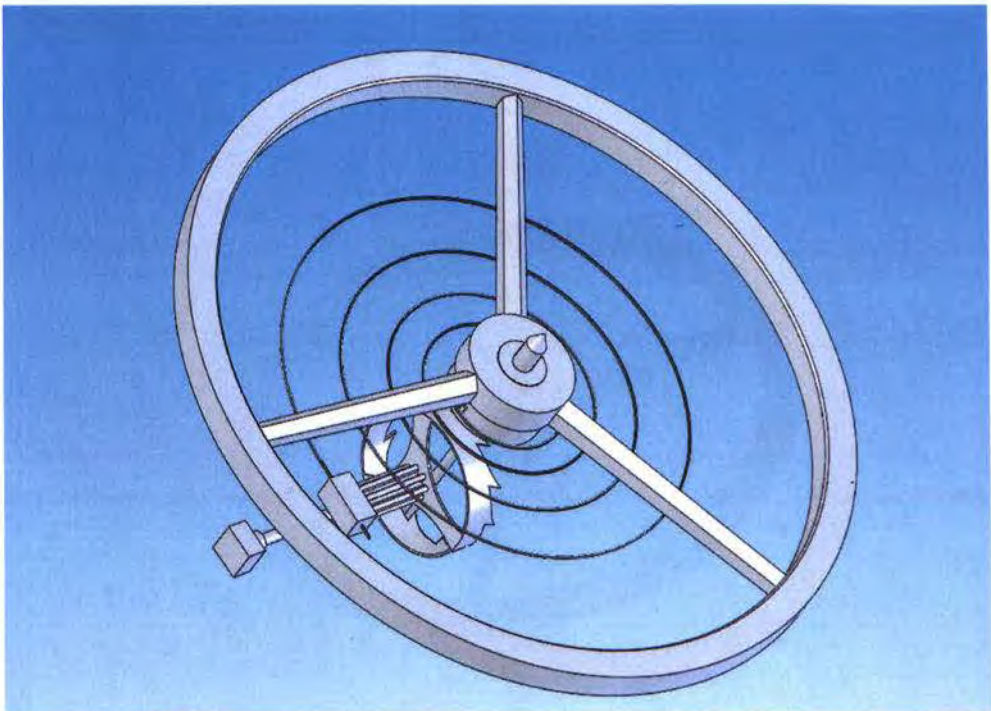


Figure 30: Structure of the Verge Escapement in mechanism watches (Top view).

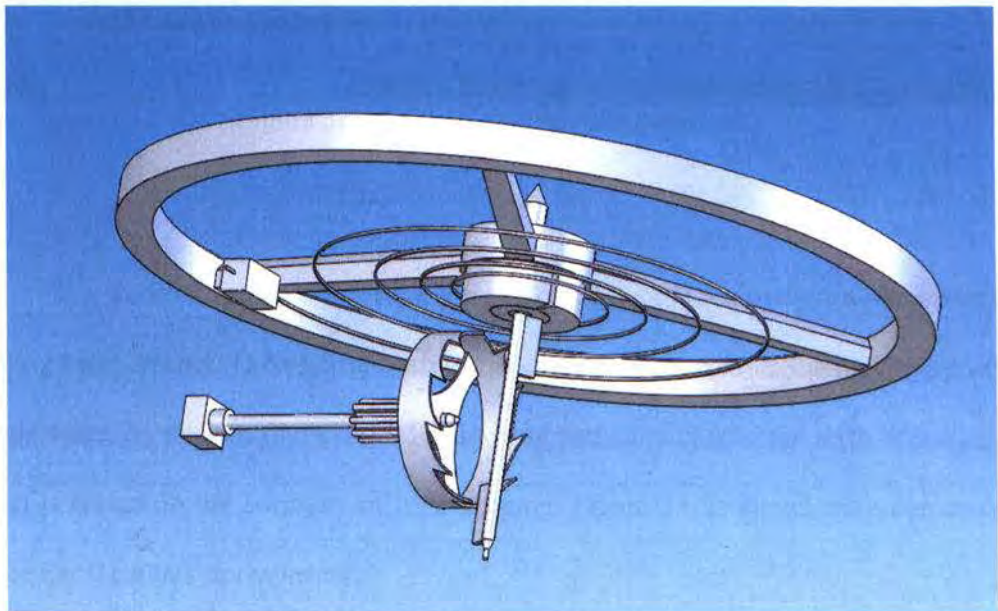


Figure 31: Structure of the Verge Escapement in mechanism watches (Bottom view).



Figure 32: Video of the Verge Escapement.

The working mechanism of the Verge Escapement is relatively simple among the existing escapements. The vertical shaft keeps oscillating to regulate the movement of the escape wheel by the two flat boards. The locking and unlocking of the teeth of the escape wheel is crucial to the accuracy of time keeping. Figure 33-35 shows the three steps of Verge Escapements’ movements.

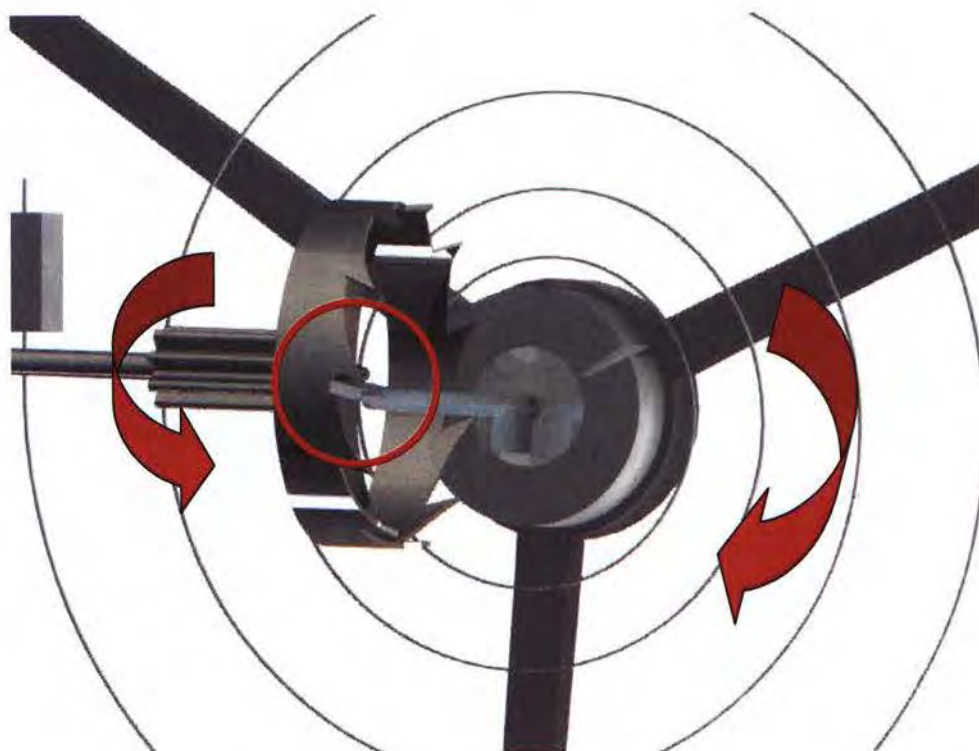


Figure 33: Locking of the escape wheel's front tooth.

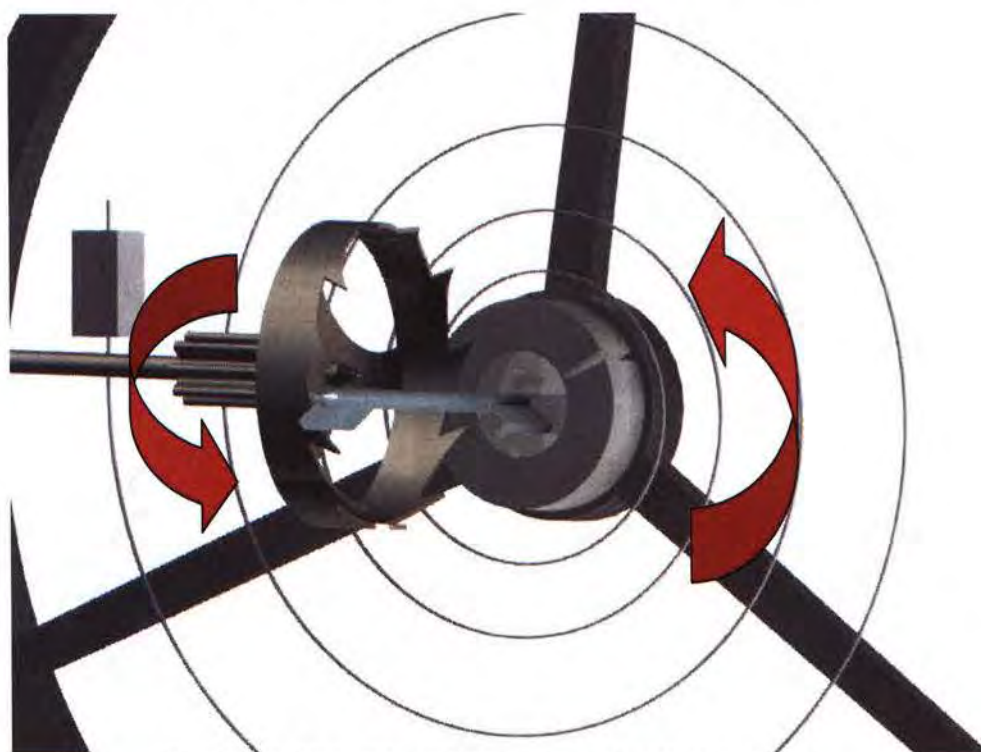


Figure 34: Unlocking of the escape wheel's front tooth.



Figure 35: Locking of the escape wheel's back tooth.

3.4. Accessories

The following describes the records inside the Accessories section of the Virtual Library of Mechanical Timepieces.

3.4.1. Automatic Winding System

Automatic winding system is not one of the main functional parts of a mechanical watch. A mechanical watch without the automatic winding system can still gain energy

from manual winding on the winding stem. The existence of the automatic winding system is to act as another source of energy to the mechanism. For this reason, automatic winding system is always called as an accessory of a mechanical watch.

Traditional Design

The function of automatic winding system is to gain energy through the natural movements of wearer’s arm. [36] Figure 36 shows the typical structure of a self-winding system applied in pocket watch in the seventeenth century. Despite the different designs on the structure of the winding system, the majority of winding systems are based on the same working principle.

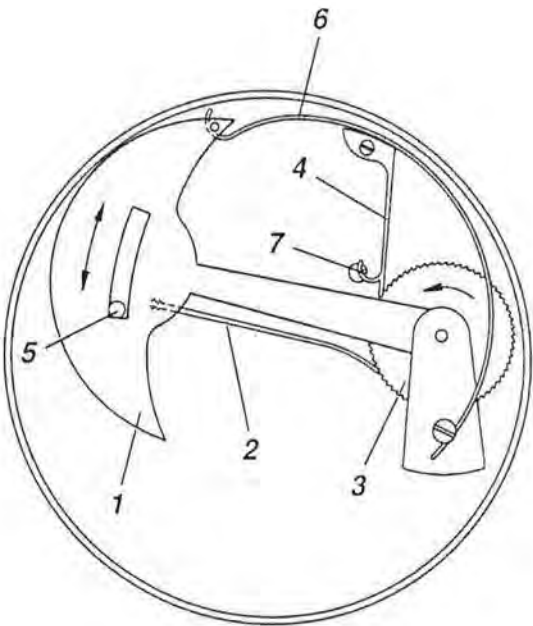


Figure 36: A typical design of a self-winding system invented in the 17th century. [37]

Usually, a typical automatic winding system includes the following parts:

- (1) **Rotor** – It is also called oscillating weight. Oscillating weight is usually in semi-circular shape and it is a key component to transmit the movements of the wearer's arm to the mainspring.
- (2) **Winding spring** – It is attached to the rotor to transmit movements to the winding wheel.
- (3) **Winding wheel** – Rotation of the winding wheel is transmitted to the barrel arbour through the gear train.
- (4) **Stop spring** – This feature only exists in one-way winding system. Stop spring helps preventing the winding wheel from turning backwards.
- (5) **Buffer pin** – It restricts the movement of the rotor.
- (6) **Spring** – It brings the rotor back to its original position.
- (7) **Pin** – The pin plays a crucial role in preventing the mainspring from over wound. When the mainspring is fully wound, the pin would lift the stop spring and prevent the mainspring from being wound further.

Two-way Automatic Winding System

Automatic winding system can be divided into two types: one-way winding system and two-way winding system. Traditional design usually indicated to one-way winding system. It means only energy produced by rotor moving in one particular direction would be stored in the barrel. This mechanism is relatively simple and has lower efficiency in energy storage. Contrary to the one-way automatic winding system, the two-way winding mechanical is more desirable.

The following section would introduce the two-way automatic winding systems which allow winding the mainspring in both directions according to the movements of the rotor. This mechanism is much more complicated than the previous one. No matter which direction the rotor rotating along, the gear train would only transmit the moment of force in one particular direction for the winding of mainspring. Some specially designed reversers are used to achieve this task. Three kinds of two-way automatic winding system from Rolex, Seiko and ETA were studied.

1. Rolex

Mechanical watches of Rolex achieve two-way winding of the mainspring by a set of specially designed gears. The Rolex 1570 movement made in 1972 would be discussed in this part. [38] Figure 37 shows a typical automatic winding system used in Rolex mechanical watches. The red circles and the blue rectangle indicate the special features that enable the rotor to wind the mainspring when rotating in either direction. Red circles highlights the locks to limit the rotation of the inner gears of wheels No. 2 and 3; while blue rectangle calls attention to the wheel No.4 that it connects to wheel No.3 only but not wheel No.2.

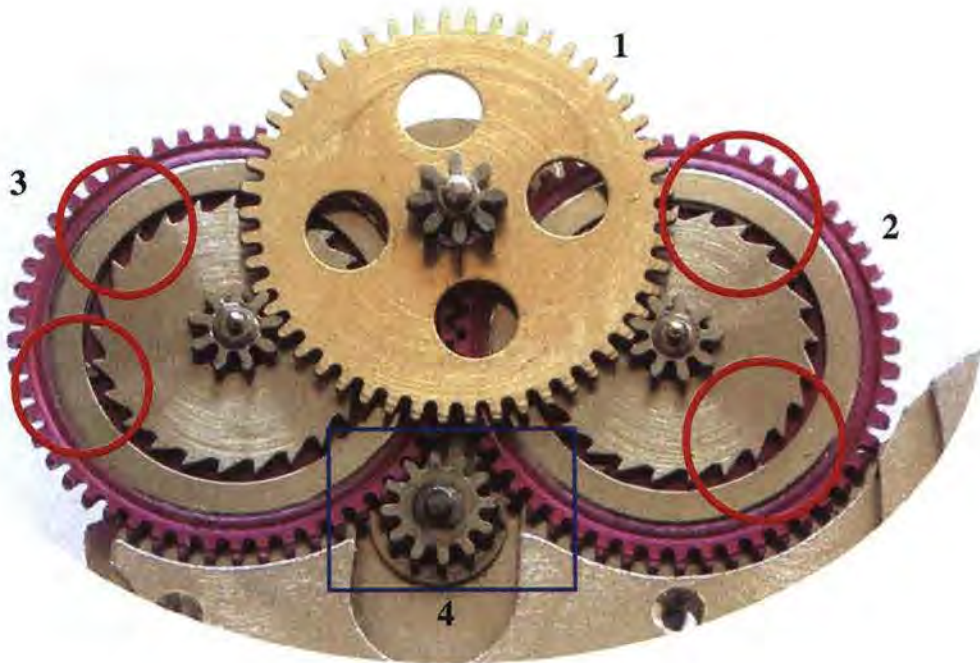


Figure 37: Automatic winding system of Rolex. [39]

After having a brief study on the structure, it is possible to predict its movements when the rotor rotates in either direction. Figure 38 tries to simulate the situation when the rotor rotates in clockwise direction; while Figure 39 simulates the case when rotor rotates in anti-clockwise direction. Comparing these two simulations, an interesting result is found. Although wheel No.1 in both cases rotates in different, wheels No.3 and 4 would rotate along the same direction finally. The inner and outer gear pairs of wheels No.2 and 3 make a big contribution on the result. In Figure 38, the inner and outer gear pairs of wheel No.3 move in opposite directions; in Figure 39, the inner and outer gear pairs of wheel No.4 also move in opposite directions. When the inner gear rotates along an undesirable direction, the outer gear would ignore the movements of the inner gear by

the locks (indicated by red circles in Figure 37). That is how the Rolex two-way automatic winding system works.



Figure 38: Automatic winding system of Rolex – rotor rotates clockwise. [39]



Figure 39: Automatic winding system of Rolex – rotor rotates anti-clockwisely. [39]

2. Seiko

Seiko has invented the “Magic Lever System” to be the winding system for their mechanical watches. The “Magic Lever System” accomplishes efficient transmission of rotor’s power to the mainspring. This winding system involves four crucial components: a rotor, a Magic Lever and two wheels. Structure of the “Magic Lever System” is shown in Figure 40. While maintaining a high level of functionality, this structure is robust and simple. The function of the Magic Lever is to act as a reverser so as to make the winding of mainspring by the rotor rotating in both directions possible. The “Magic Lever System” highly increases the efficiency of power transmission to the mainspring compared to the one-way winding system.

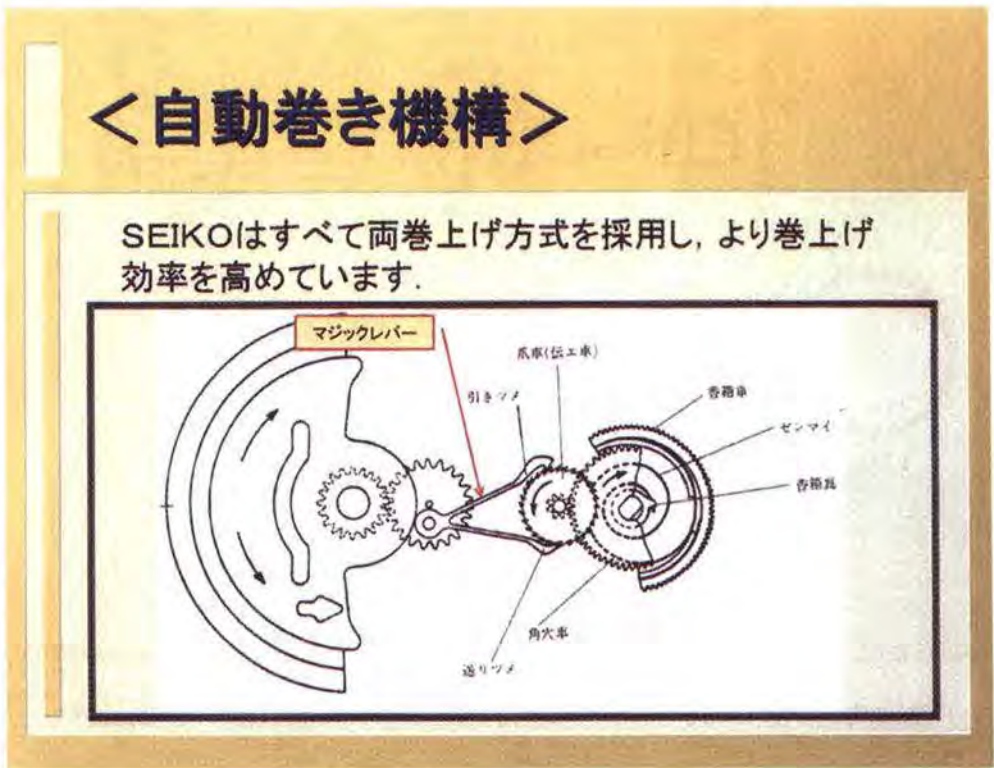


Figure 40: Structure of Seiko’s “Magic Lever System”. [40]

The idea of “Magic Lever System” was originally applied in trains (Figure 41). This idea has been modified and applied on the automatic winding system by Seiko. When the driving wheel rotates along clockwise and anti-clockwise direction, the two arms of the Magic Lever pull and push the driven wheel respectively. This keeps the driven wheel rotating along the desirable direction. This system achieves 30% more efficient than the traditional winding systems by allowing the mainspring to gain energy no matter which direction the rotor moving along.

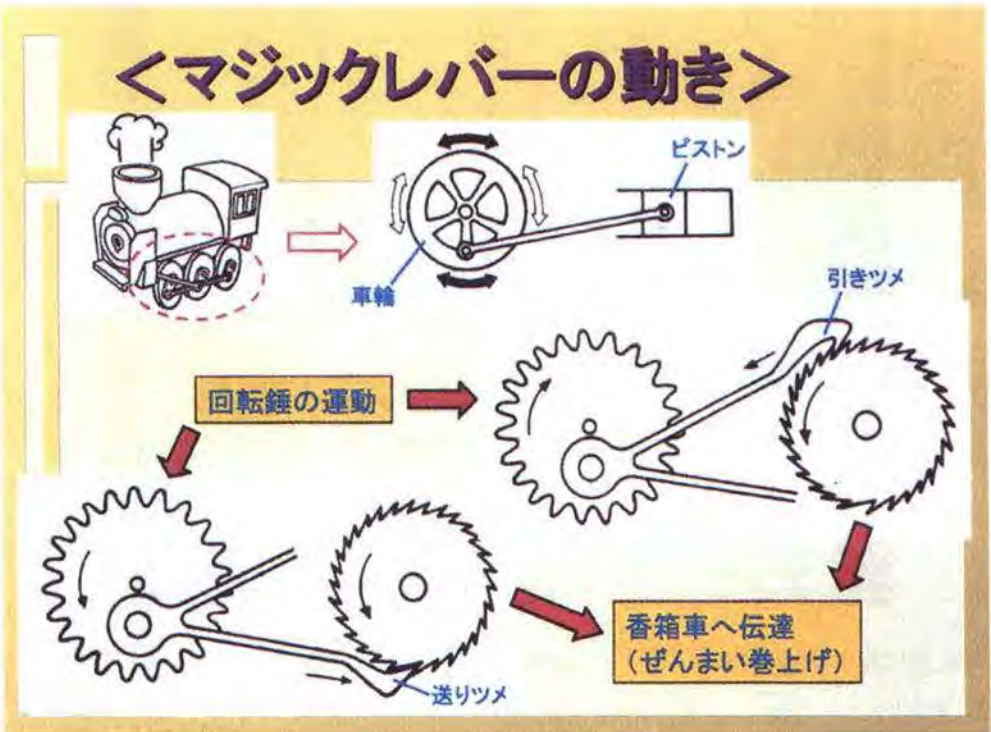


Figure 41: Working mechanism of Seiko’s “Magic Lever System”. [40]

3. ETA

The last automatic winding model to be studied is the ETA automatic winding system. ETA applies the “Double Wheels and Pinions System” on the automatic winding mechanism design. A real part of the automatic winding system being disassembled from ETA mechanical watch is shown in Figure 42. This model is one of the targets of our research and it is now one of the records of the Virtual Library.



Figure 42: “Double Wheels and Pinions System” of ETA mechanical watches. [41]

An ETA automatic winding system was disassembled and its SolidWorks model was built to be the first step of producing a record for the Virtual Library. Figures 43 and 44 show the front and back sides of the SolidWorks model respectively. It is observable from the figures that the whole structure is connected by two bridges: one connecting the rotator and the gear train through ball bearings, another bridge with three rubies on it holding the gear train with a screw.

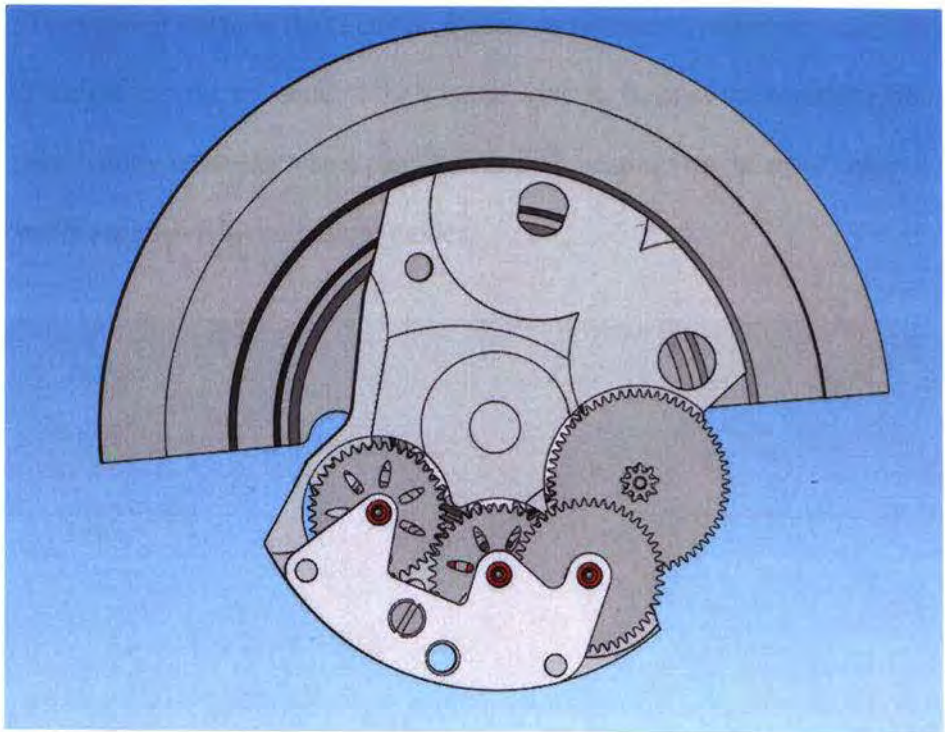


Figure 43: SolidWorks model of “Double Wheels and Pinions System” – Front side.

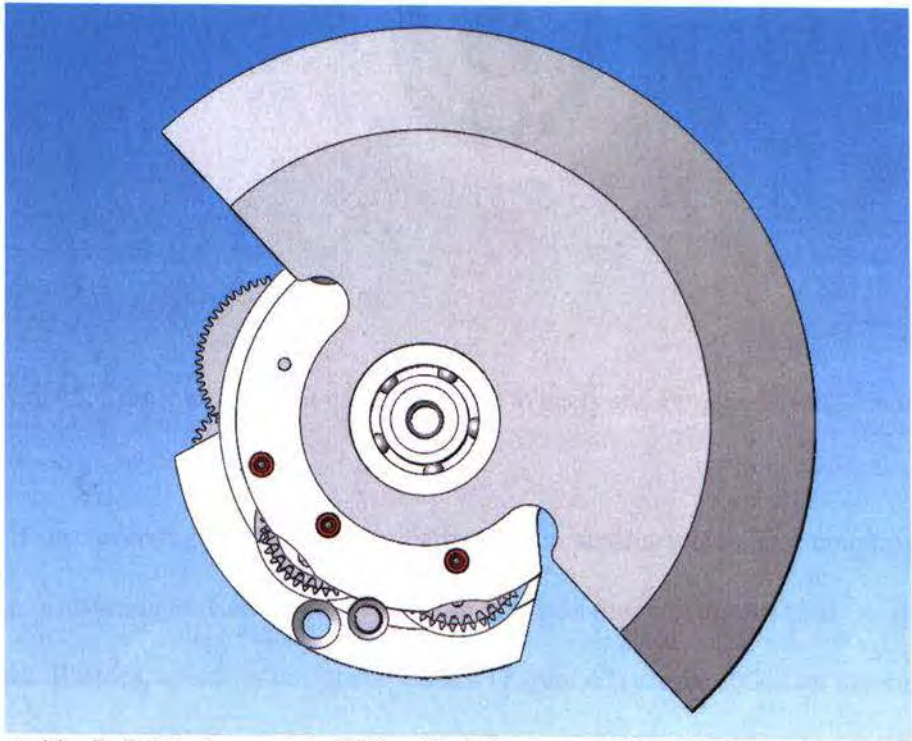


Figure 44: SolidWorks model of “Double Wheels and Pinions System” – Back side.

Transparent mode of the “Double Wheels and Pinions System” model (Figure 45) gives an insight into the structure of the winding system. Besides the reversing wheel pairs, the auxiliary reversing wheel pairs and the ball bearings on the rotor, other components are shown in transparent mode.

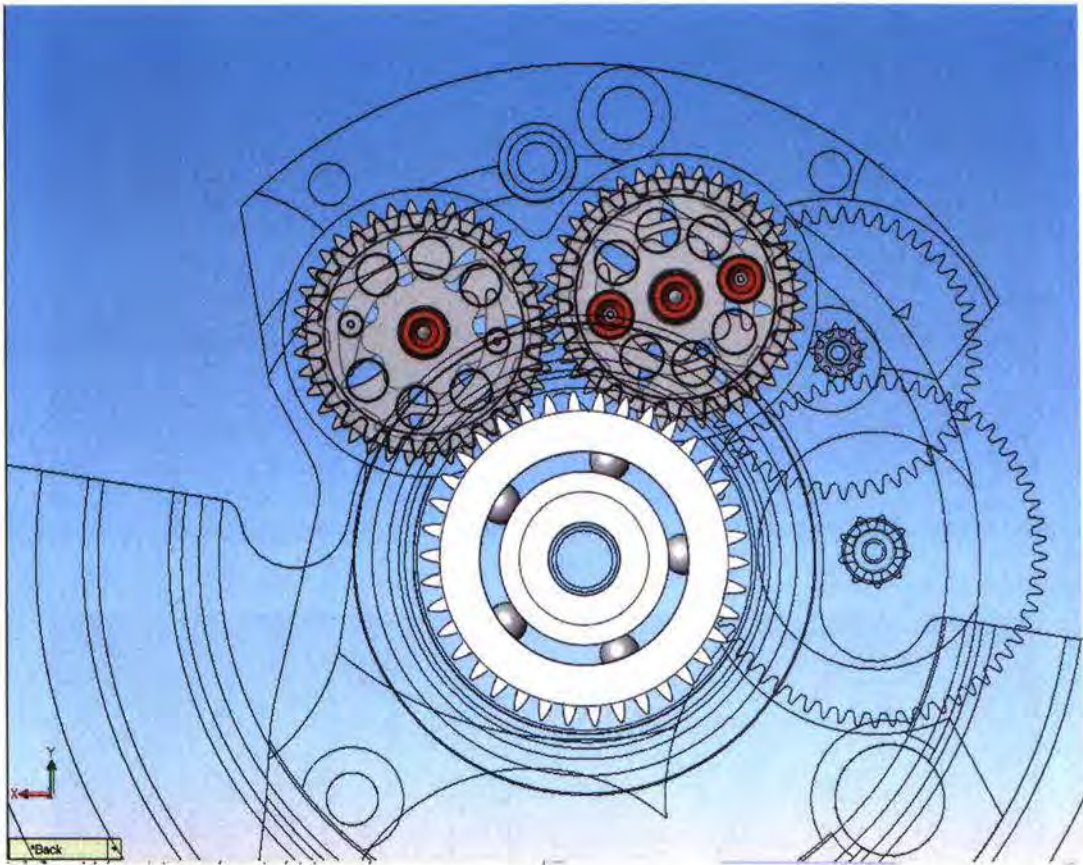


Figure 45: Transparent mode of the “Double Wheels and Pinions System” model.

If the reversing coupling wheel pairs and the auxiliary reversing coupling wheel pairs are disassembled, four pawls can be found inside the structure in total, as shown in Figure 46. Besides, specially designed patterns (Figure 47) can be found on the inner wall of the reversing wheel and the auxiliary reversing wheel. The tailor-made pattern can fix

the position of the pawls and so control the rotation direction of the reversing coupling wheel and the auxiliary reversing wheel. This makes the winding of mainspring by the rotor rotating in both directions achievable.

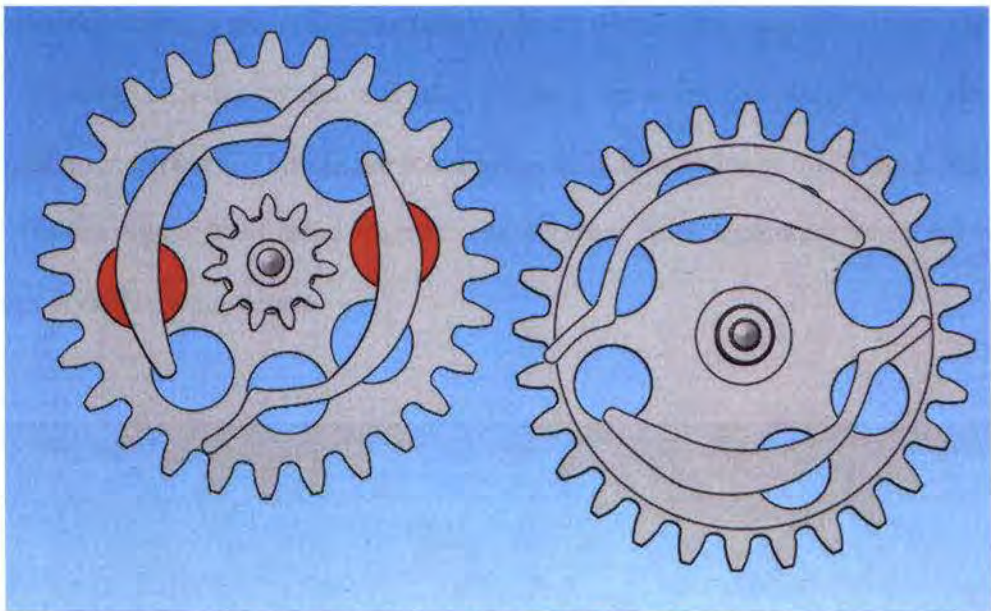


Figure 46: Reversing coupling wheel and the auxiliary reversing coupling wheel with pawls.

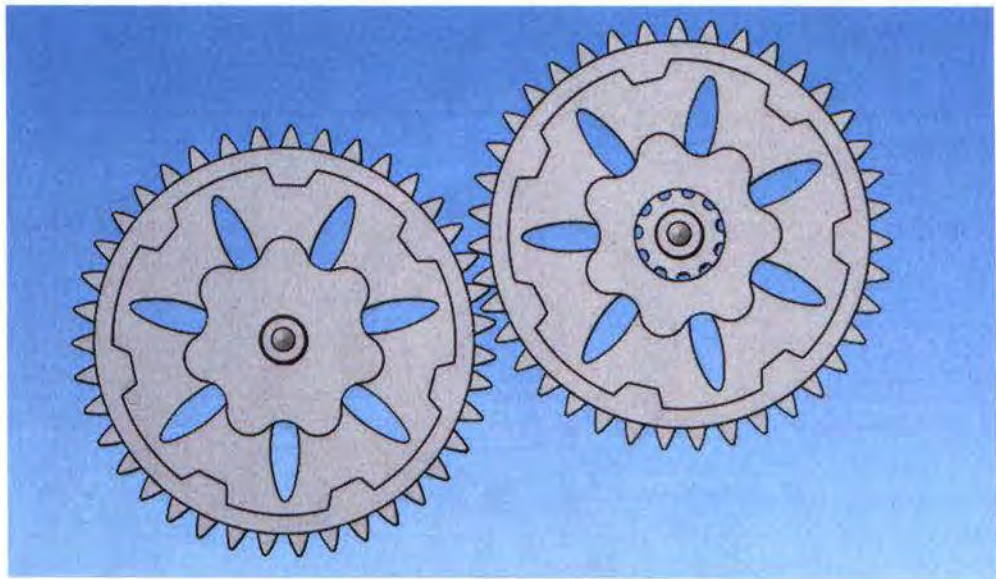


Figure 47: Reversing wheel and auxiliary reversing wheel with specially designed patterns.

The assembly of “Double Wheels and Pinions System” and the ball bearings of rotor give clues in how the mechanism works. From Figure 48, the ball bearing gears work with the reversing coupling wheel and the auxiliary reversing coupling wheel, but not with the reversing wheel and auxiliary reversing wheel. One more point to note is that the reversing coupling wheel and the auxiliary reversing coupling wheel has no connection in between. This feature is crucial to the functionality of the “Double Wheels and Pinions System” allowing the two sets of gears work separately when the rotor rotates in different directions.

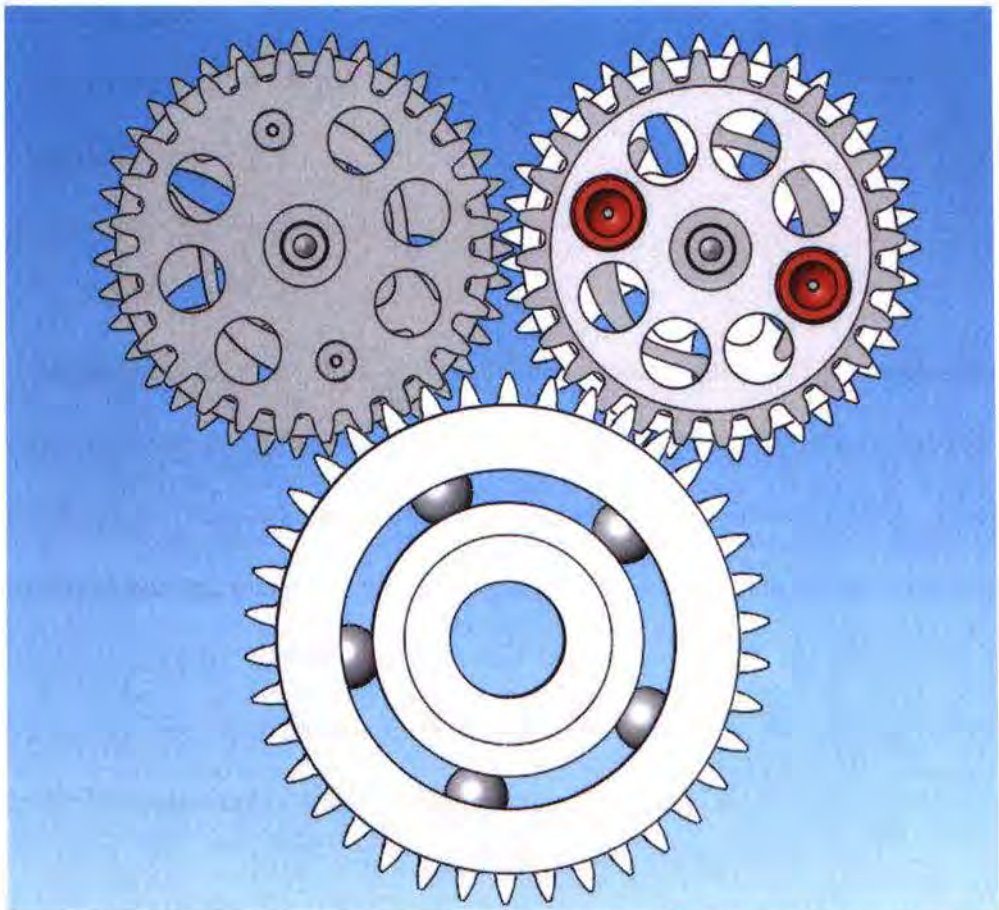


Figure 48: Assembly of ball bearings and the “Double Wheels and Pinions System”.

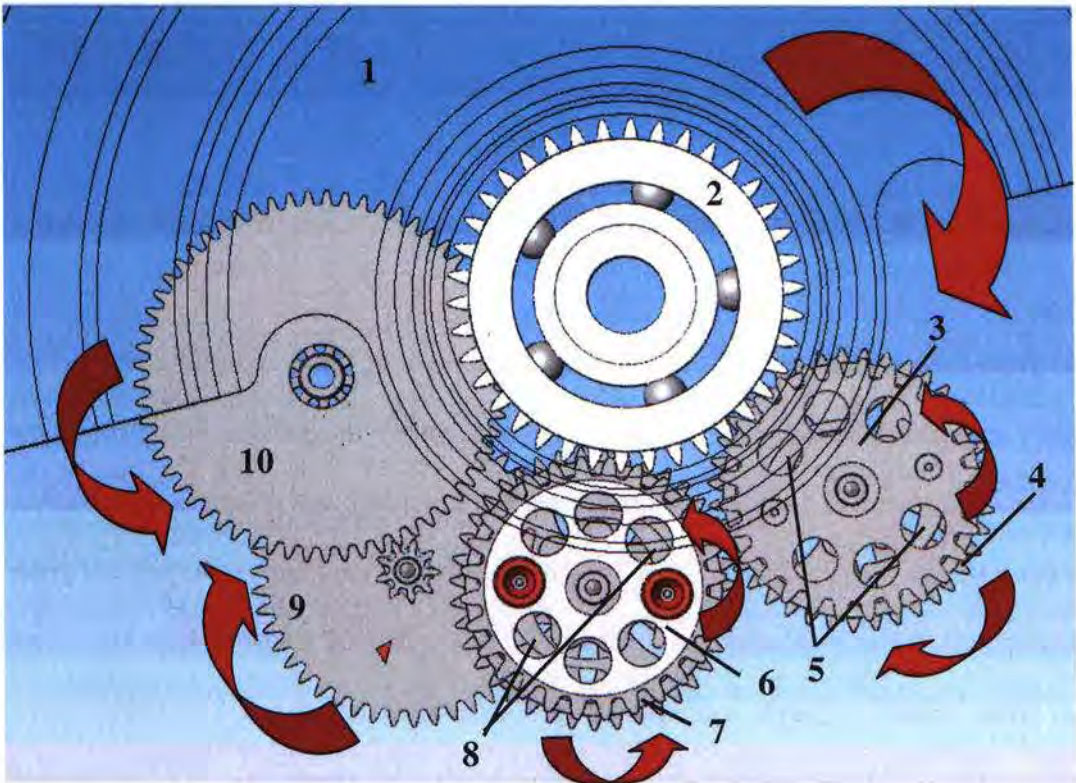
“Double Wheels and Pinions System” is such an intricate mechanism that its movements are so complicated. Shown in Figure 49 are its working principles when the rotor turns in the clockwise direction. Numbers are marked on components for easy indication. They are:

- (1): Rotor
- (2): Ball bearing with gears
- (3): Auxiliary reversing coupling wheel
- (4): Auxiliary reversing wheel
- (5): Pawls in auxiliary reversing wheel pair
- (6): Reversing coupling wheel
- (7): Reversing wheel
- (8): Pawls in reversing wheel pair
- (9): Reduction wheel
- (10): Ratchet wheel driving wheel

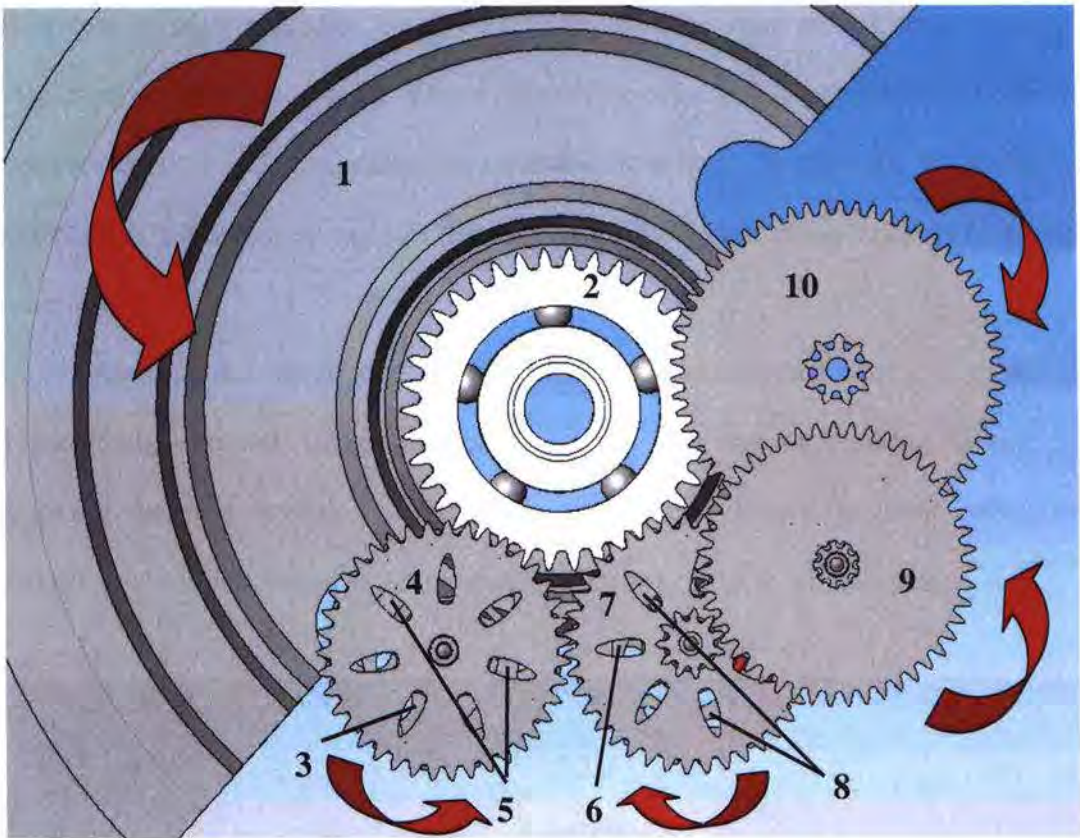
When the rotor turns clockwise, the ball bearing with gears (2) would drive the auxiliary reversing coupling wheel and the reversing coupling wheel marked with number 3 and 6. The pawls number 5 and 8 placed between wheels number 3 and 4 as well as wheel number 6 and 7 drive the wheel number 4 and 7. However, if the direction of rotation leading by wheels number 3 and 6 are undesirable, the mainspring cannot receive energy from that direction, pawls number 5 and 8 would regulate the rotation direction of wheels number 4 and 7 respectively.

For example, the rotation directions of wheels number 3 and 4 are different when rotor rotates along the clockwise direction, as stated in Figure 49(a). This is because of the pawls in-between wheels number 3 and 4 regulating their rotation directions. In this case, the auxiliary reversing wheel (4) is not driven by any part and follows the movement of the reversing wheel (7).

After the rotation direction is regulated, the pinion on wheel number 7, shown in Figure 49(b), transmits energy to reduction wheel with number 9. With the help of specially designed reversing wheel pairs and auxiliary reversing wheel pairs, the reduction wheel must rotate in the particular direction for winding the mainspring.



(a) Front side



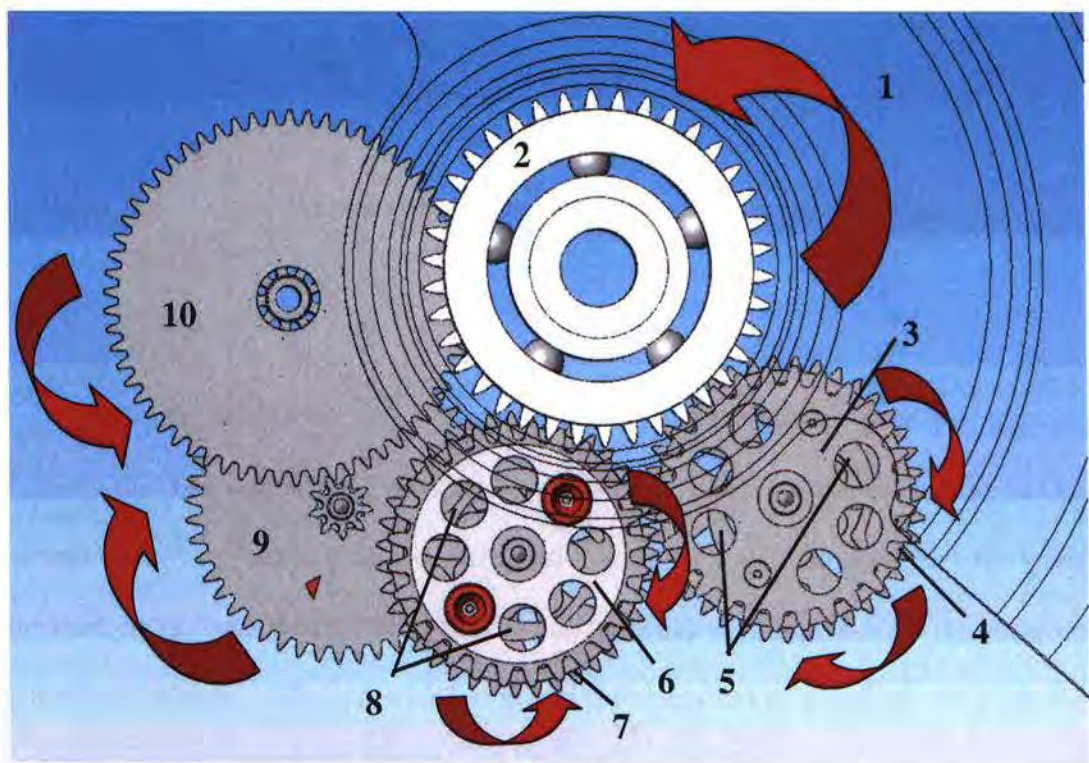
(b) Back side

Figure 49: “Double Wheels and Pinions System” when rotor turns in clockwise direction.

When the rotor turns in anti-clockwise direction, the ball bearing with gears (2) would drive the auxiliary reversing coupling wheel and the reversing coupling wheel marked with number 3 and 6 which is the same as the situation while the rotor is rotating along the clockwise direction. The pawls number 5 and 8 placed between wheels number 3 and 4 as well as wheel number 6 and 7 drive the wheel number 4 and 7. However, if wheels number 3 and 6 fail to rotate along the desirable direction, which allow the mainspring to receive energy from the movement, pawls number 5 and 8 would regulate the rotation direction of wheels number 4 and 7 respectively. For instance, the rotation

directions of wheels number 6 and 7 are different when rotor rotates along the anti-clockwise direction, as stated in Figure 50(a). This is because of the pawls in-between wheels number 6 and 7 regulating their rotation directions. In this case, the reversing wheel (7) is not driven by any part and follows the movement of the auxiliary reversing wheel (4).

After the rotation direction is regulated, the pinion on wheel number 7, shown in Figure 50(b), transmits energy to reduction wheel with number 9. With the help of specially designed reversing wheel pairs and auxiliary reversing wheel pairs, the reduction wheel must rotate in the particular direction in order to wind the mainspring.



(a) Front side

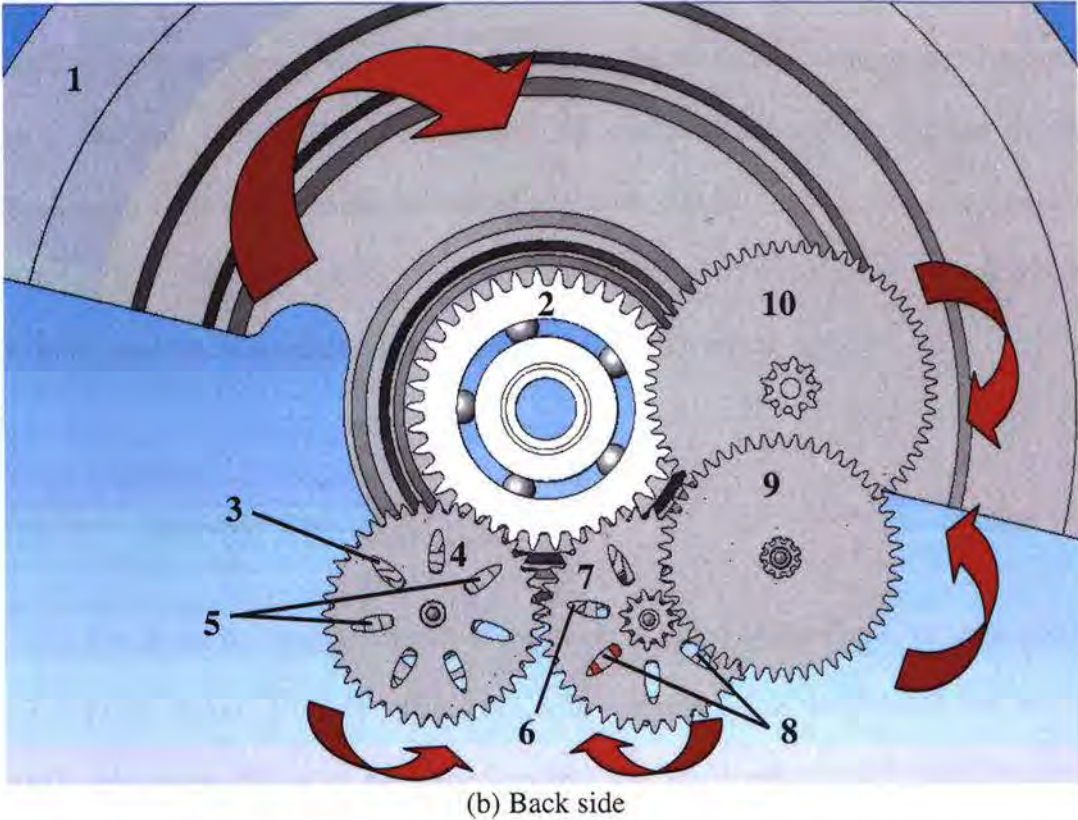


Figure 50: “Double Wheels and Pinions System” when rotor turns in anti-clockwise direction.

With the help of “Double Wheels and Pinions System” ensuring the gear train in-between the rotor and barrel always rotates in the same direction, the mainspring can be wound by the rotor rotating in both directions. No matter which direction the rotor goes, the moment of force would finally turn in one particular direction through the coupling wheels and pinions. All in all, winding in both directions can be achieved. Although the two-way winding system has a much more complicated structure and uses more energy to overcome the winding torque in both directions, this design can increase the efficiency on the mainspring winding and hence the energy storage.

No matter which design is used, the efficiency of the automatic winding system is highly depending on the type of wearer. Degree of activity, state of health and temperature of the wearer vary the winding rate a lot. Generally, three types of wearers can be defined. They are the weak wearer, the strong wearer and the average wearer. People have a sedentary job can be defined as a weak wearer, their winding rate would be relatively low due to the low degree of activity. On the contrary, athletes are categorized as strong wearers who are supposed to gain the greatest winding rate. [37]

3.4.2. Moon Phase Mechanism

The shape of illuminated part of the moon is called Moon Phase, or some people call it Lunar Phase. Mechanical watches with a moon phase mechanism can tell the appearance of the Moon of the day. However, the moon phase mechanism is not an essential part of a typical mechanical watch. The existence of the moon phase mechanism is for the esthetics and artistic appreciation purpose. So, the moon phase mechanism is categorized as an accessory of a mechanical watch.

The appearance of the Moon changes according to the relative positions of the Earth, the Sun and the Moon. The moon's phase cycle repeats every 29.53 days (29 days, 12 hours, 44 minutes), but the moon phase dial indicator usually shows it as 29.5 days for easy indication. One more point to note is that phases of the Moon are different when it is seen from the Northern Hemisphere and the Southern Hemisphere. They are exactly symmetrical. As shown in Figure 51 is the phases of the Moon observed from the Northern Hemisphere.



Figure 51: Phases of the Moon, as seen from the Northern Hemisphere. [42]

The moon phase pattern is printed on a moving disc, and then the pattern would be shown on the mechanical watch dial through a small window. The Patek Philippe Calibre 89 (Figure 52) is a prominent representative. The window showing moon phase pattern can have vary designs. For instance, the moon phase window for Calibre 89 is in semi-circular shape with two small semi circles; however, in Figure 53, another moon phase window design, occupying a small sector of the moon phase dial indicator, is found. As mentioned before, the moon phase mechanism is for decoration purpose, so there are no standard rules or guidelines on the moon phase window designs.



Figure 52: The Patek Philippe Calibre 89 with moon phase mechanism [43]



Figure 53: A mechanical pocket watch with moon phase mechanism. [27]

The moving disc with moon phase patterns on it is called the moon phase indicator. There are two types of moon phase indicator, one with 59 teeth, and the other one with 135 teeth.

1. 59 teeth moon phase disc design

The moon phase mechanism having a moon phase disc with 59 teeth is a relatively simple design. Usually, moon phase indicator shows the moon's phase cycle as 29.5 days, implying the moon phase disc moves two teeth per day. Comparing with the actual moon's phase cycle of 29.53 days, it is obvious that this design has an error of 0.03 day. This results an accumulative error of 1 day for every three years.

This design is studied and made as a record in the Virtual Library. As shown in Figure 54 is a moon phase mechanism with 59 teeth moon phase disc simulation done with SolidWorks. The moon phase window is in transparent mode in order to illustrate what is happening behind it. On the moon phase disc, two moon patterns are there, which is crucial to the continuity of the moon's phase cycle presentation.

Its movement is not complicated compared with the design having a 135 teeth moon phase disc. Red arrows, in figure 54, indicate the rotating directions of different components. A series of gear train transmits movements to the moon phase disc. Then, the third wheel with a red pin pushes the moon phase disc to move. Finally, the moon phase disc rotates along the clockwise direction and changes the moon phase pattern, showing through the moon phase window.

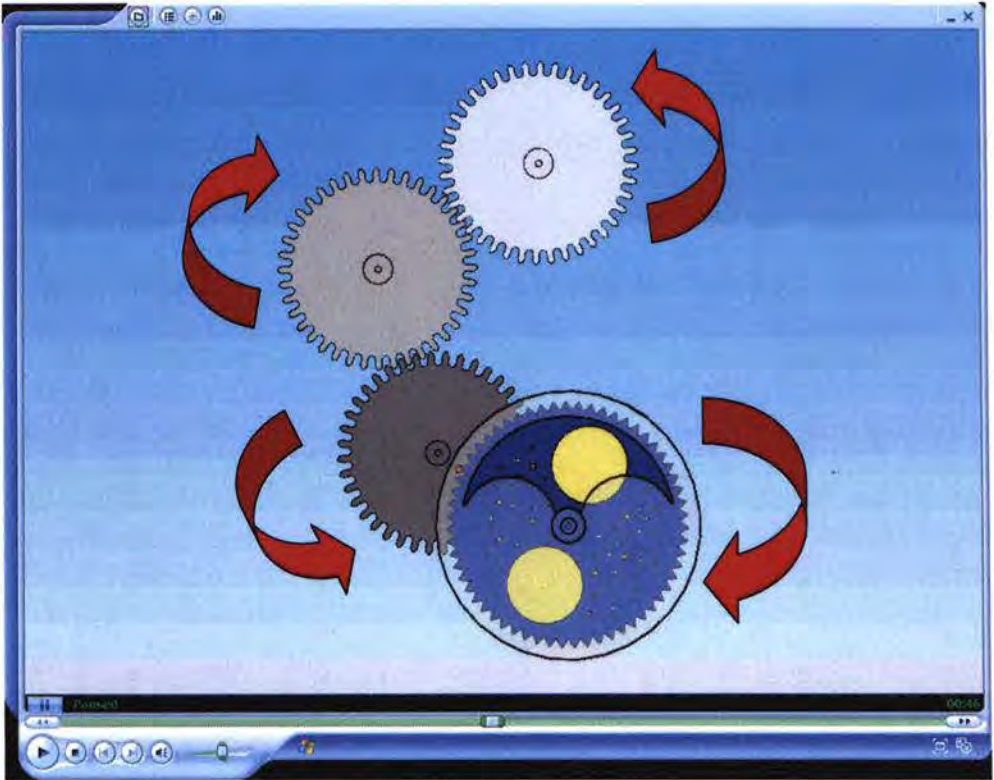


Figure 54: Moon phase mechanism with 59 teeth moon phase disc simulation.

2. 135 teeth moon phase disc design

Mechanical watch having a 135 teeth moon phase disc design is relatively more intricate in structure and more precise in presenting the moon phases. Figure 55 shows the components of a mechanical watch with a 135 teeth moon phase mechanism. Error on moon’s phase cycle is largely reduced to 11 minutes and 26.4 seconds per year.



Figure 55: Moon phase mechanism components with 135 teeth moon phase disc. [27]

All in all, no matter which moon phase mechanism is used, manual regulation on the movement is required in order to keep the accuracy. It is especially important in circumstances such as moving from the Northern hemisphere to the Southern hemisphere or reactivating a stopped mechanical watch. The most appropriate time to adjust the moon phase mechanism is at the middle of the Moon's phase cycle.

3.5. Chapter Summary

Mechanical timepiece movement is a complicated mechanical device. In order to help the engineering professionals and general publics to understand its working principle and find the related information, a Virtual Library of Mechanical Timepieces is developed.

The Virtual Library of Mechanical Timepieces was divided into three sections. They are the Mechanical Clock Escapements, the Mechanical Watch Escapements and the Accessories. Presently, the Virtual Library of Mechanical Timepieces consists of nine records. The Mechanical Clock Escapements section has a record of the Graham Escapement, which is the oldest and the most common escapement for clocks. While the Mechanical Watch Escapements section has six records, including the English Lever Escapement, the Swiss Lever Escapement, the Daniels Co-Axial Double-Wheel Escapement, the Spring Detent Escapement, the Cylinder Escapement and the Verge Escapement. At this moment, there are two records in the Accessories section within the Virtual Library of Mechanical Timepieces. They are the Automatic Winding System and the Moon Phase Mechanism.

For each record, detailed information is given, including the invention background, the 3D solid models, the video clips and the explanation of the working principle. The future work will include:

1. Adding more escapements, such as the Brocot Escapement, the Tic-Tac Escapement, the Glashuetten Lever Escapement, the Muller Escapement, the Denison Escapement, the Haldmann Escapement, the Strasser Escapement and etc.
2. Developing an interface so that users can interactively manipulate the 3D models and the animations. Converting solid models into VRML (Virtual Reality Modeling Language) format can be one of the possible solutions.
3. The Virtual Library can develop into an open source database that allows the public to contribute their entries, just like the open-sourced online encyclopaedia Wikipedia. It would be an effective way to increase the number of records, however, a complete management system has to be developed to monitor the quality of entries.

Finally, a paper entitled “Virtual Library of Mechanical Watch Movements” was accepted by the Computer-Aided Design & Applications 2007 (CAD’07) which had been held at Honolulu, Hawaii in June 2007.

4. Implementations

This chapter describes the implementations of the Virtual Library of Mechanical Timepieces. Issues from CAD models building procedures to website design will be discussed. After that, this chapter will show an application of the Virtual Library.

4.1. CAD Modeling of the Escapement Structure

Building a record in the Virtual Library takes several steps. In this section, the process is demonstrated through an example: the Graham Escapement. The steps are as follows:

- Step 1: Disassemble the part

Examine the real part of the Graham Escapement and then disassemble the system. The three main components, the escape wheel, the pallet fork and the pendulum, of the Graham Escapement are identified. Record the position and relationship between components.

- Step 2: Measure each component

This step is to identify the shape and measure the dimension of each component. It needs special equipment and professional techniques to achieve this task. Extra

attention should be paid upon the gear profile design which can not be determined by simply measuring the gear size.

Obviously, it is quite a big challenge as the shapes of mechanical timepiece components are irregular and their sizes are very small. Therefore, special equipment is used to achieve this task. In this research project, the Coordinate Measuring Machine (CMM), as shown in Figure 56, is used to identify the shape of components and depth gauge in Figure 57 is used to measure the vertical distance of the part.



Figure 56: Coordinate Measuring Machine (CMM) with an accuracy about one micrometer.



Figure 57: Depth Gauge.

During the measuring process, issues including lighting and projection angle are needed to be considered. The prefect case is to adjust the lighting exactly above the part to avoid projection shadow being generated around the part. As mechanical timepiece components are very small in size, dimension errors caused by projection shadow can be significant.

Besides, irregular shape of components increases the difficulty to get the exact contour of the part. Especially for gear profile, it follows the standard design. Module (m) is used to standardize the gears with the equation:

$$m = d / z$$

where d is the pitch diameter and z is the number of teeth.

The gear profile used in this case is the cycloidal gear (Figure 58) with its addenda constructed of convex epicycloidal curves and dedenda of concave hypocycloidal curves. This design ensures local constant angular velocity and provides large gear ratio without creating an undercut on gear teeth.

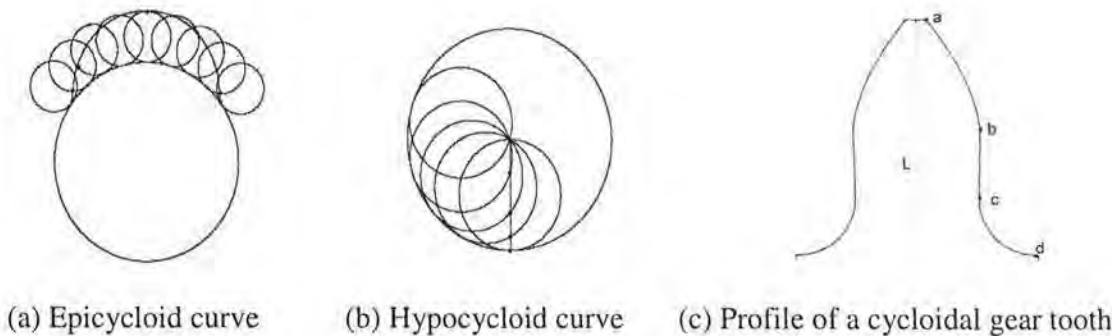


Figure 58: Cycloidal gear.

- Step 3: Build 3D CAD model part by part using SolidWorks®

After measuring data are obtained through step 2, 3D CAD models of each component are built by SolidWorks®. Then, the components are assembled in the CAD software. The assembly diagram of the Graham Escapement is shown in Figure 59. Proper setting of boundary conditions is crucial to ensure the smooth operation.

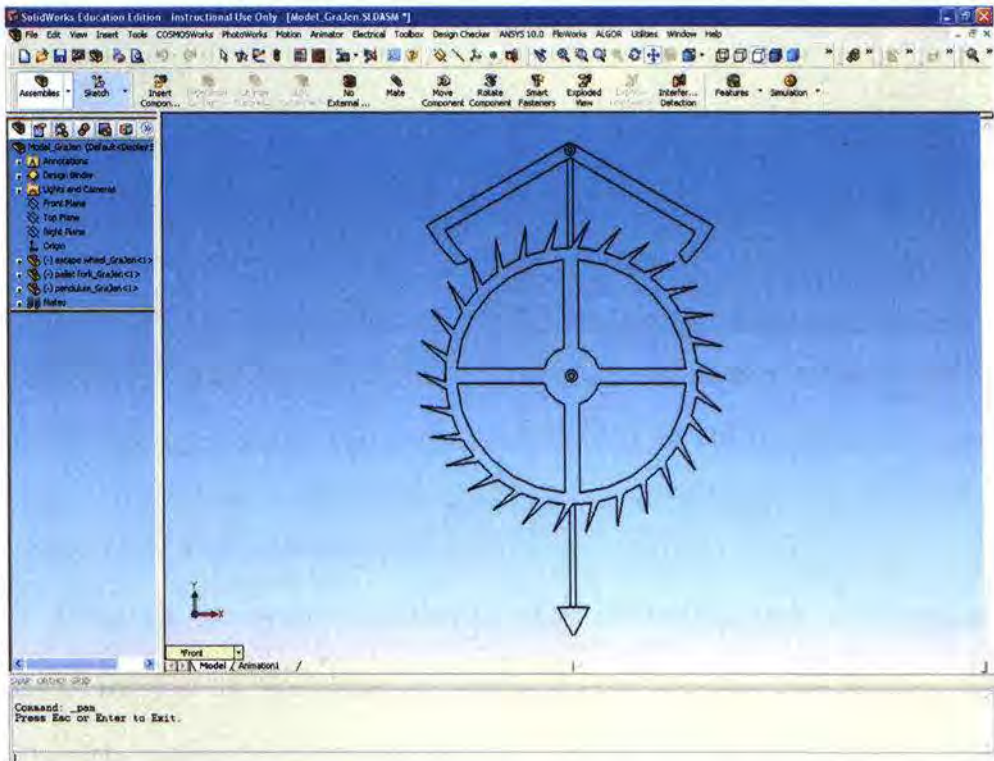


Figure 59: Assembly diagram of Graham Escapement in SolidWorks®

- Step 4: Setup animation

Then, movements of the targeted mechanism is studied and set on the 3D CAD models in SolidWorks®. The simulation is done step by step (Figure 60). In each step, the escape wheel is rotated by a small angle, followed by the pallet fork and the pendulum.

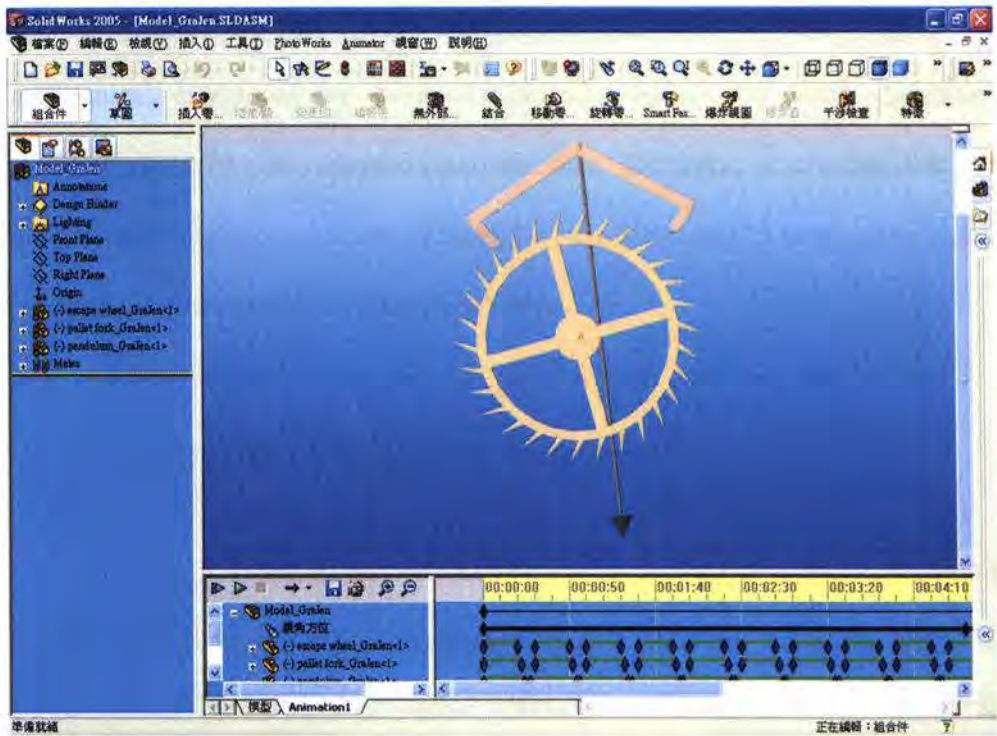


Figure 60: The animation setting interface in SolidWorks® with the Graham Escapement.

- Step 5: Add other information

When the movement animation is ready, information such as background of inventor, history of the mechanism, existing product in the mechanical timepiece market is gathered to build a webpage for the record.

- Step 6: Upload to the internet

The last step is to upload the page to the Internet and make it as part of the Virtual Library of Mechanical Timepieces.

Records of the Virtual Library of Mechanical Timepieces are all based on existing designs of mechanical timepieces. If design of an existing model is provided, manufacturing errors are able to be simulated by this method. However, it has a

practical problem to generate a new design or preview errors for a non-existing model. As mechanical timepieces are extremely intricate device, too many variables and probabilities can affect the operation performance. Therefore, it is impossible to test every cases with tolerance added on different holes/ edges/ teeth on every component and then to examine every possible assembly situation.

4.2. Website Design

The Virtual Library of Mechanical Timepieces homepage is shown in Figure 61. It has both the English and Chinese versions.



Figure 61: Website of the Virtual Library of Mechanical Timepieces.

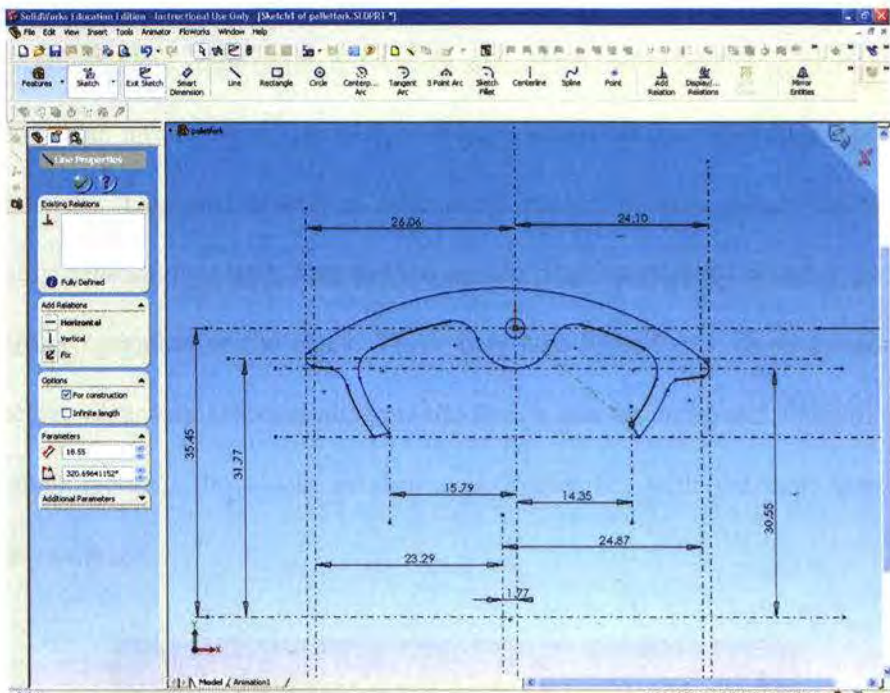
It contains CAD models about the nine mechanisms presented in the previous sections, 3D animation video clips, as well as related information. The website is accessible at the address below: http://www.ipe.cuhk.edu.hk/projects10_library.html.

4.3. An Application

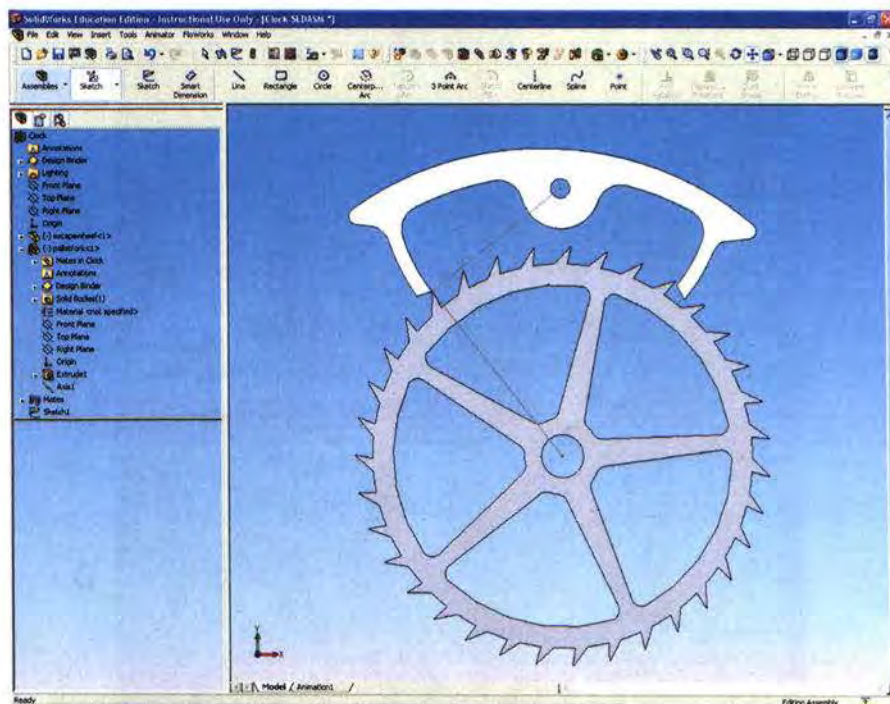
The Virtual Library is a multi-functional tool that benefits many users. First, it can be used as an educational tool for mechanical engineering students and vocational school students who wish to study different kinds of mechanical watch/ clock movements. Second, it acts as an online library for general public to search information about escapements and some well-known horologists. Last but not the least, it helps watchmaker to diagnose design and assembly errors when building a mechanical watch movement.

Recently, a clock manufacturing company made an inquiry about their mechanical clock escapement design. The company provided engineering drawings of a Graham Escapement, which is the most common type of clock escapement, for design validation. They hoped to diagnose the design error before starting the mass production of the clock.

Using the data provided, a 3D CAD model was constructed with SolidWorks® as shown in Figure 62(a). Then, a movement simulation was conducted to visualize the operation situation of the design, detecting if interferences exist. Figure 62(b) shows the assembly diagram of the escapement model. Effect of the manufacturing / assembly tolerance had also been considered.



(a) Draft of pallet fork



(b) Assembly diagram with two black lines showing the relevant distance between components

Figure 62: Converting the construction blueprint into a CAD animation in SolidWorks®

About 50 key steps of the movement simulations were picked up and considered. The locking and unlocking of the teeth on escape wheel by the pallet fork was the main focus to study. This was crucial to take some numerical data to test the interactive relationship between the pallet fork and the escape wheel and verify whether interference occur during operation of the clock. These data also helped to give suggestions to the clock factory regarding issues about how the design can be improved. Finally, the clock factory manufactured the clock, as shown in Figure 63, with the captioned Graham Escapement design.



Figure 63: A clock with the Graham Escapement.

5. Conclusions

This thesis presented a Virtual Library of Mechanical Timepieces. The main part of the library is the CAD models of various mechanisms used in the mechanical watches / clocks. These models are drawn using a commercial CAD software system, SolidWorks®. Accordingly, 3D animations are generated. In addition, explanations and related information are given.

The Virtual Library is an educational tool for engineers or anyone who are interested to understand the working principle of mechanical timepiece movements. Since the CAD models are drawn in exact size, it can be used to help watchmakers for design and manufacturing as well.

The Virtual Library of Mechanical Timepieces can be divided into three sections. They are the Mechanical Clock Escapements, the Mechanical Watch Escapements and the Accessory Mechanisms. Currently, the Virtual Library of Mechanical Timepieces consists of nine records, including one mechanical clock escapement (the Graham Escapement), six mechanical watch escapements (the English Lever Escapement, the Swiss Lever Escapement, the Spring Detent Escapement, the Verge Escapement, the Cylinder Escapement, and the Daniels Co-Axial Double-Wheel Escapement), and two accessory mechanisms (automatic winding system and moon phase mechanism).

Escapement is undoubtedly the most important part. It regulates motions by converting the rotary motion of the gear into oscillatory motion and controls the timekeeping accuracy by distributing an equal amount of energy for the impulses. Among various escapements, the most common escapement is the Swiss Lever Escapement as it is adopted by 95% of the products. It consists of an escape wheel, which receives energy provided by the mainspring through the gear train, a pallet fork, which controls the oscillation, and a balance wheel with hairspring, which controls the timekeeping frequency. The Swiss Lever Escapement works in a delicate sequence of five steps: (a) the balance wheel is turning clockwise while a tooth of the escape wheel locked on the right leg of the pallet fork, (b) The impulse pin on the balance wheel enters and impulses the pallet fork pushing the pallet fork to unlock the escape wheel. (c) The escape wheel moves forward under the driving of the external torque until it contacts the right pallet. At the same time, the pallet fork pushes the impulse pin, which in turn pushes the balance wheel to move forward. (d) The escape wheel halts when a tooth reaches the left leg of the pallet fork. After that the impulse pin leaves the pallet fork. The escape wheel continues to lock the pallet fork until it is stopped by the banking pin. (e) The balance wheel continues to turn clockwise until its energy is exhausted. This finishes the half-period, after which the balance wheel returns in the counter-clockwise direction following the same states in reversed order. The Virtual Library shows this working sequence by means of computer animation.

The other important mechanism is the automatic winding mechanism. Three different designs are studied: the Rolex design, the Seiko design and the ETA design. Each design has its advantages and limitations.

The Virtual Library of Mechanical Timepieces is accessible on the Internet at:
http://www.ipe.cuhk.edu.hk/projects10_library.html.

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Appendix A

L. C. Tam, Y. Fu and R. Du, "Virtual Library of Mechanical Watch Movements,"
Computer-Aided Design & Applications 2007, June 25-29, 2007, Honolulu, Hawaii,
USA.

Virtual Library of Mechanical Watch Movements

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ABSTRACT

Mechanical watch is one of the most intricate mechanical devices that men have ever invented. Throughout the history, it has been studied by many such geniuses as Galileo and Huygens. It still attracts many people today. In general, a mechanical watch movement may consist of some 100 components. Among these components, the escapement is the most important. It determines the timekeeping accuracy, and is often regarded to as the brain of the movement. According to literatures, there are over 100 different types of escapements. In this paper, we present a virtual library of mechanical watch movements. Our objective is to provide an educational tool for mechanical engineers or anyone who are interested to understand the working principle of the mechanical watch movement. Currently, it consists of four different escapements: the Graham escapement, the English lever escapement, the Swiss lever escapement, and the Daniels co-axial double-wheel escapement. For each escapement, the detailed background information, CAD models, and video clips are given. The virtual library is accessible on the Internet at: http://www.ipe.cuhk.edu.hk/projects10_library.html.

Keywords: Mechanical watch movement simulation, escapement, CAD modelling

1. INTRODUCTION

The mechanical watch is one of the most intricate mechanical devices that men have ever invented. The first mechanical watch appeared in the middle of the sixteen century. Since then, it has been studied by many people, including such geniuses as Galileo, Huygens and Hooke. Today, it still fascinates people around the world. As a result, the watch industry continues to grow in recent years. For example, Swiss watch exports grow at a steady rate of 12% in 2005 [1].

Generally speaking, a mechanical watch is made of five parts as shown in Figure 1. These include: the winding mechanism, the power supply (mainspring), the gear train, the display and the escapement. Among them, the escapement is the most important and is often referred to as the brain of the watch movement. According to literatures, there are over one hundred different types of escapements. Though, they share the same function: to provide a stable oscillation feedback to regulate the timekeeping accuracy.

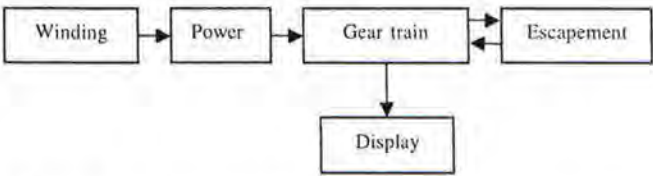


Fig. 1: The five parts of a mechanical watch movement

Presently, dozens of information sources about the mechanical watch movements are available on the Internet. Followings are two of the popular ones.

(1). Clock-Watch: History and Technique of Clocks and Watches [2]. This website contains a number of 2D animations about different types of escapements with the help of Microsoft Flash. It even allows users to interact with some of the animations to change the model parameters, such as the oscillating angles and the size of the components. However, it is just animations that cannot show the detailed design and the working principle of the escapements.

(2). Mark Headrick's Horology Page [3]. This is the homepage for the book "Clock and Watch Escapement Mechanics" authored by Headrick in 1997. The book showed how to draw an escapement step by step. Both escapements of mechanical clocks and watches are covered. Its descriptions are so detailed that one can learn the geometry and the drawing techniques. Although it gives detailed explanation of the escapement, the animations on the website are rather crude. It shows only a simple wireframe model missing all the details. Hence, it is impractical to learn the details through these animations.

We build a virtual library of the mechanical watch movement to provide a convenient and reliable source of information to demonstrate the working principles of the watch and clock designs. The virtual library contains 3D models, video clips, as well as other information, such as the history of the invention and current models in the market.

The rest of the paper is organized as follows. Section 2 is the main body of the paper containing the structure of the virtual library and four different escapements. Section 3 presents the way to build the virtual library and its applications. Section 4 includes the conclusions and future work.

2. THE VIRTUAL LIBRARY

The structure of the virtual library is shown in Figure 2. Currently, it contains four different escapements belonging to two different categories. They are the Graham escapement, the English lever escapement, the Swiss lever Escapement and the Daniels co-axial double-wheel escapement. The details are presented in the subsequent sections.

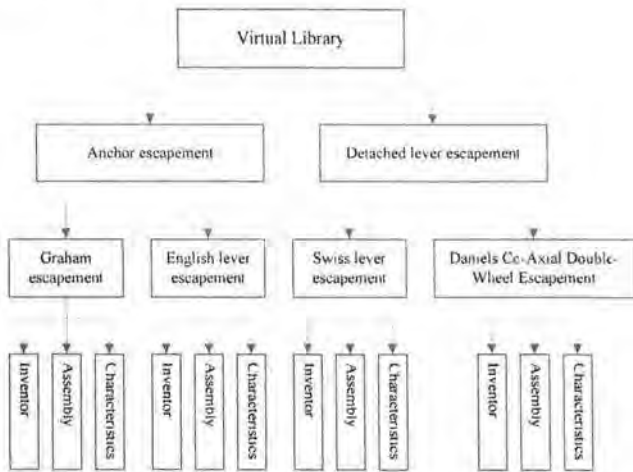


Fig. 2: The structure of the virtual library

2.1 Graham Escapement

In 1715, English watchmaker George Graham (1673-1751) invented the Graham Escapement. Born in Hethersgill, England, Graham was one of the most well-known horologists of the eighteenth century. In 1688, he became an apprentice to Henry Aske who was a clockmaker in London. Seven years later, he worked with another renowned horologist Thomas Tompion. Besides the Graham escapement, he is also the inventor of the mercury compensation pendulum, the cylinder escapement for watches and the first chronograph. The mercury pendulum can achieve accuracy

within a few seconds per day. Graham refused to patent these inventions because he felt that they should be used by other watchmakers. He is a very talented and generous inventor.

The Graham escapement is also called the deadbeat escapement. It is modified from the anchor escapement by eliminating recoil [4]. Graham Escapement is mainly used in pendulum clocks but not wrist watches. This is because it requires the use of a pendulum and could only work well in the upright position. This escapement is still widely used today.

Figure 3 shows the assembly of the Graham escapement. It consists of the escape wheel, the pallet fork, and the pendulum.

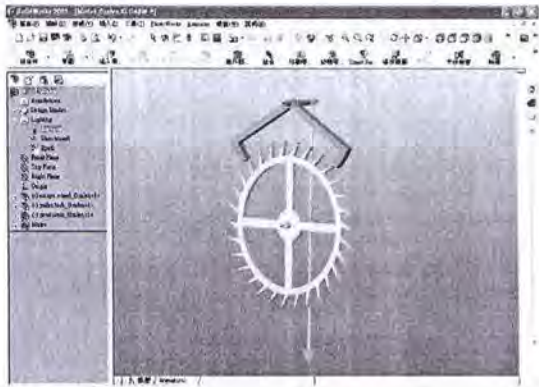
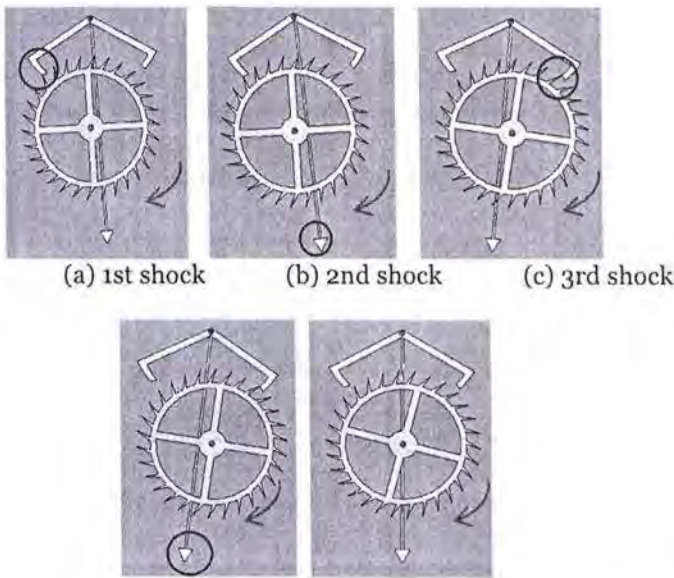


Fig. 3: The model of Graham Escapement

The working principle of the Graham Escapement is straightforward. Figure 4 shows the steps that the escapement goes through in a complete cycle. Note that in the figure the circle indicates the points to be noticed and the arrow shows the rotation direction of the escape wheel. Figure 4(a) shows the 1st shock, which is the contact of a tooth on the escape wheel onto the entry pallet of the pallet fork. Figure 4(b) shows the 2nd shock, at which the pendulum reaches the farthest point and begins to move to the opposite direction. Figure 4(c) shows the 3rd shock, another tooth on escape wheel touches the exit pallet of the pallet fork. Figure 4(d) shows the 4th shock, the pendulum reaches the other farthest point. Finally, Figure 4(e) shows the 5th shock, the pallet fork and pendulum return to their original position completing a cycled.



(d) 4th shock (e) 5th shock

Fig. 4: The five shocks of Graham Escapement

2.2 English Lever Escapement

This is one of the first lever escapements invented by an English clockmaker Thomas Mudge (1715 - 1794) in 1754. Mudge was apprenticed to George Graham. His work was treated as a mark of quality at that time. Since he is an Englishman, this escapement design is referred to as the English lever escapement. It is one of the earliest detached level mechanisms that do not require a pendulum [5].

The English lever escapement is composed of four parts: the escape wheel, the anchor, the pallet fork, and the balance wheel (with the hairspring). It is assembled in the right-angled triangle form. The axis of balance wheel, pallet fork and the escape wheel forms a right-angled triangle as shown in Figure 5.

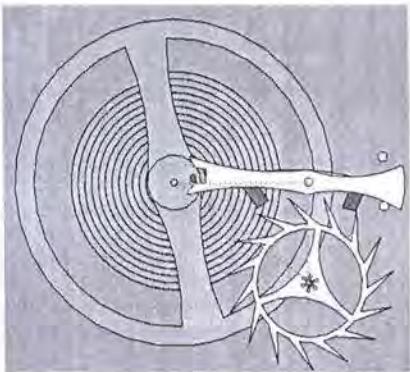


Fig. 5: The model of English level escapement. The dotted lines indicated the right-angled relationship of the balance wheel, the pallet fork and the escape wheel.

Figure 6 shows the two levels of the pallet fork. Level One works with the balance wheel and it has a slot to hold the ruby on the balance wheel. Level Two works with the escape wheel and there are two rubies on the pallet fork.

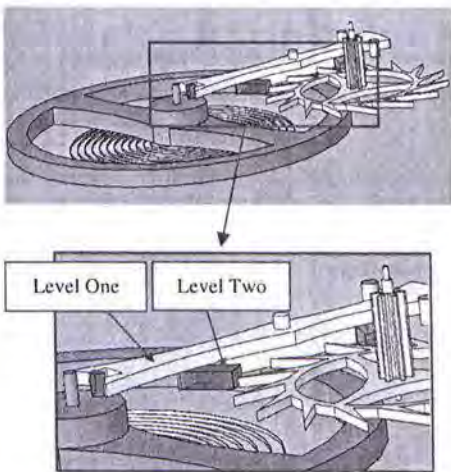


Fig. 6: The two levels of pallet fork

Figure 7 shows the movements of the English lever escapement in a complete cycle. The 1st shock is the contact of the impulse pin (the half-circle shaped ruby on the balance wheel) with the entry of the pallet fork. At the meantime, the tail of the pallet fork touches one of the banking pins as shown in Figure 7(a). Then, the escape wheel is stopped by one of the rubies on the pallet fork causing the locking of the escape wheel. This is the 2nd shock as shown in Figure 7(b). Figure 7(c) shows the 3rd shock. At this time, the tooth of escape wheel contacts the exit pallet of the pallet fork. The escape wheel is stopped until the impulse pin on the balance wheel collides with the entry of the pallet fork again. As shown in Figure 7(d), the 4th shock is the situation that another side of the tail of the pallet fork touches another banking pin. At the same time, the balance wheel pauses and then starts rotating to the opposite direction. The 5th shock is the last one, the impulse pin hits the other side of the entry of the pallet fork. This is shown in Figure 7(e).

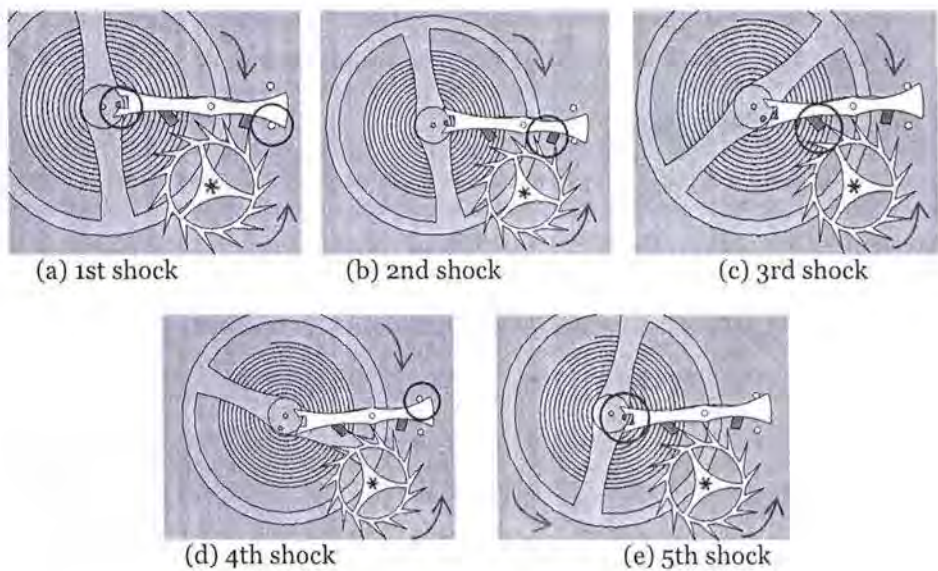


Fig. 7: The five shocks of English Lever Escapement

2.3 Swiss Lever Escapement

Appeared in the middle of the nineteenth century in Switzerland, the Swiss lever escapement is a modification of the English lever escapement. It is the most common escapement in the world. In fact, at least 95% of the existing mechanical movements use this escapement because of its high accuracy and reliability.

The model of the Swiss lever escapement is shown in Figure 8. It consists of the balance wheel, the hairspring, the pallet fork, and the escape wheel. Swiss lever escapement may have many different versions. For this model in Figure 8, there are 15 club teeth on the escape wheel, therefore: $360 / (2 \times 15) = 12$; that is, the angle for each impulsive movement is 12.

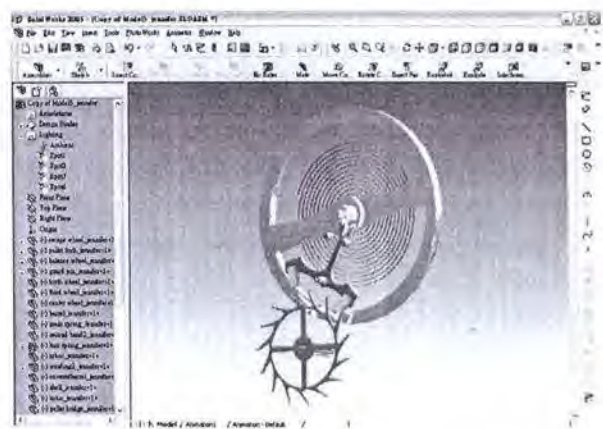


Fig. 8: The assembly model of English Lever Escapement

Similar to the English lever escapement, during a complete cycle, five shocks occur. The 1st shock (Figure 9(a)) corresponds to the contact of the impulse pin (the ruby on the balance wheel) with the entry of the pallet fork. The 2nd shock is shown in Figure 9(b). It is caused by the contact of the escape wheel tooth with the impulse plane of the entry pallet of the pallet fork. As shown in Figure 9(c), the 3rd shock is the situation when the other side of the entry of the pallet fork contacts the impulse-pin. Figure 9(d) shows the 4th shock. It happens when the escape wheel tooth touch the locking-plane of the exit pallet of the pallet fork. The last stage is the 5th shock (Figure 9(e)). It is the situation that the pallet fork contacts the banking pin. The whole cycle is completed by then.

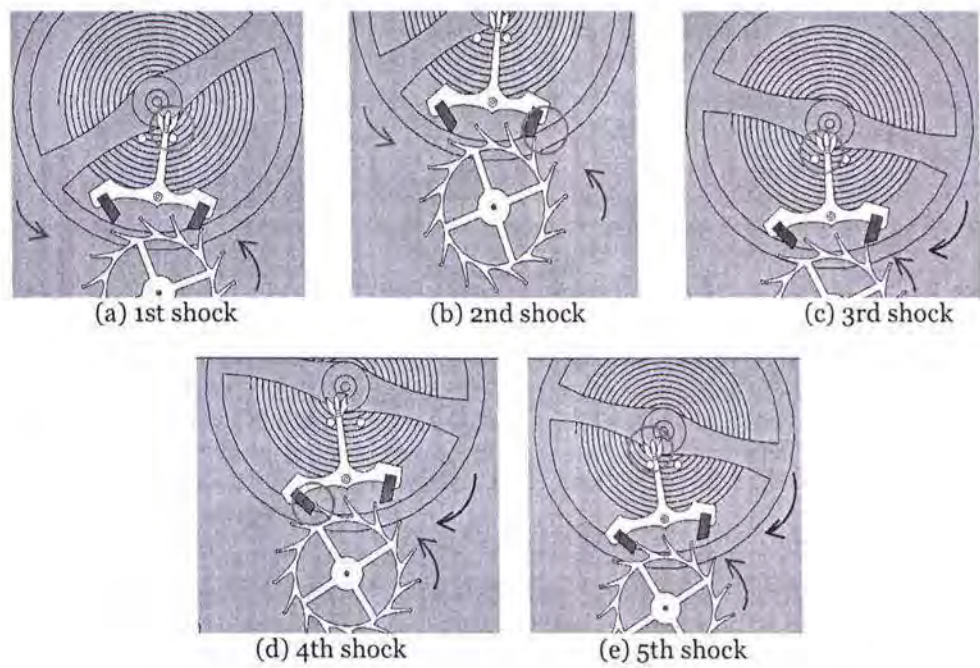


Fig. 9: The five shocks of the Swiss lever escapement in a cycle

2.4 Daniels Co-Axial Double-Wheel Escapement

The Daniels co-axial double-wheel escapement is the masterpiece of Dr. George Daniels (1926 – Now). Dr. Daniels is a professional horologist with rich experiences. Besides inventing the co-

axial escapement, he is also a famous author on mechanical watch movements and the past President of the Horological Institute. He has received a number of prestigious international awards [6].

The Daniels co-axial double-wheel escapement is much more complicated than the Swiss lever escapement. In order to show the structure and movements in a clear way, a wire-frame view of this escapement is shown in Figure 10. With the wire-frame mode, all the three rubies on the pallet fork could be seen at the same time. It helps to gain better understanding of the whole structure and its movements.



Fig. 10: The wire-frame model of the Daniels co-axial double-wheel escapement

The escapement (Figure 11) consists of two escape wheels, a pallet fork, and a balance wheel (with hairspring),

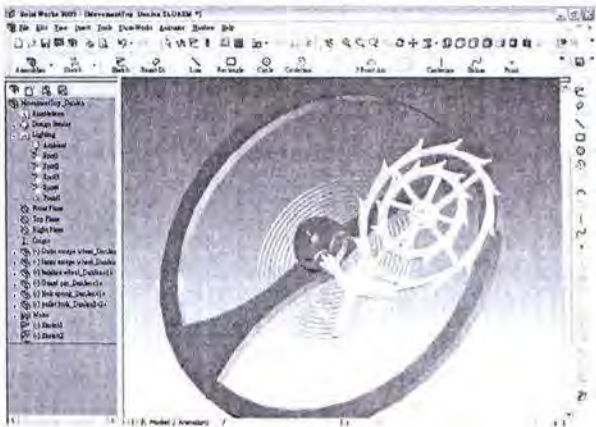


Fig. 11: The model of Daniels co-axial double-wheel escapement

Figure 12 shows the details of the escapement. From the figure, it is seen that the escapement has three levels. In Level One, the balance wheel contacts the pallet fork. The banking pins are also at this level. The escape wheel has two levels, called the inner escape wheel and the outer escape wheel, with 12 teeth in each level. In Level Two and Level Three, the pallet fork contacts the inner and outer parts of the escape wheel.

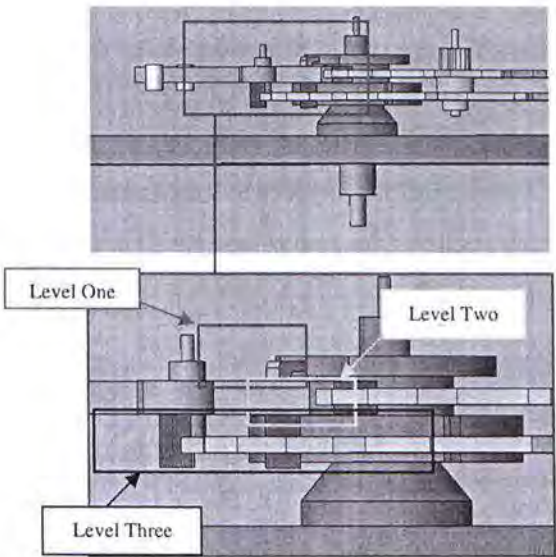


Fig. 12: This is the top view of the assembly showing the relationship of the balance wheel, the pallet fork and the escape wheel in three levels.

As shown in Figure 13, the Daniels co-axial double-wheel escapement has five shocks in a complete cycle. The cycle of movement start from the 1st shock as shown in Figure 13(a). It is the contact of the semi-circular impulse-pin with the entry pallet of the pallet fork. In the meantime, the trapezium shape ruby on the balance wheel pushes the outer escape wheel to move in the clockwise direction. Figure 13(b) shows the 2nd shock. It happens when the outer escape wheel stopped by the impulse stone at the head of the pallet fork. The inner escape wheel touches the trapezium shape impulse stone of the pallet fork. The next stage is the 3rd shock, shown in Figure 13(c). It is the situation when the other side of the entry pallet of the pallet fork contacts the semi-circle shaped impulse-pin on the balance wheel. Figure 13(d) shows the 4th shock. It occurs when the outer escape wheel is stopped by the locking-stone on the right arm of the pallet fork. The 5th shock (Figure 13(e)) is the situation that the pallet fork contacts one of the banking pins. The cycle of the escapement is then completed [7].

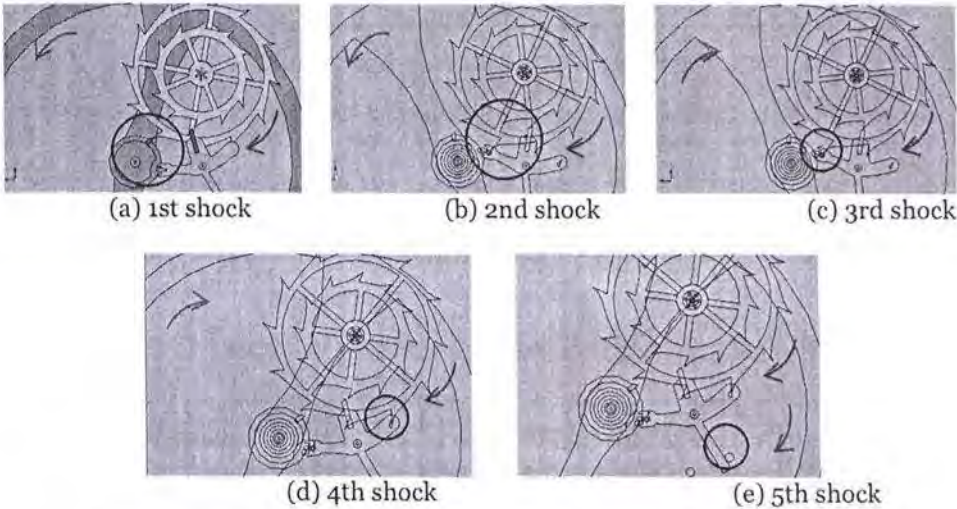


Fig. 13: The five shocks of Daniels Co-Axial Double-Wheel Escapement

2.5 Website Design

Our virtual library of mechanical watch movement homepage is shown in Figure 14. It contains some CAD models about the four escapements presented in the previous sections, 3D animation video clips, as well as related information. It has two versions: English and Chinese. The website is accessible at the address below: http://www.ipe.cuhk.edu.hk/projects10_library.html.



Fig. 14: There are four escapement records available in the Virtual Library of Mechanical Watch Movements.

3. HOW TO BUILD THE VIRTUAL LIBRARY AND ITS APPLICATIONS

In this section, we present the process of building the virtual library and its applications through an example: the Graham Escapement.

3.1 Modelling of the escapement structure

Building the virtual library for the Graham Escapement takes several steps. Firstly, we identify the three main components of the Graham Escapement including the escape wheel, the pallet fork and the pendulum. Then we build the solid models of each component with the CAD software SolidWorks®. After that, all the components are put together in the assembly file according to the geometry as shown in Figure 15.

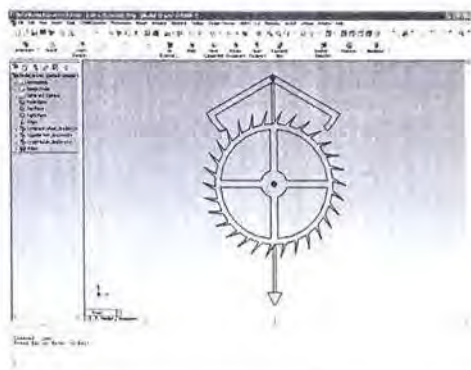


Fig. 15: The assembly diagram of Graham Escapement in SolidWorks®

After the solid model of escapement is done, the next step is studying the relationship between components. The simulation is done step by step (Figure 16). In each step, the escape wheel is rotated by a small angle, followed by the pallet fork and the pendulum. Note that the attention must be taken in dealing with the shocks, at which times, the escape wheel, the pallet fork and the pendulum may change their motion, velocity and acceleration. The details of the change can be found in [7].



Fig. 16: The animation setting interface in SolidWorks® with the Graham Escapement

After the animation of movements is finished, it would be uploaded to the Virtual Library on the website.

3.2. An Application

The virtual library is a multi-functional tool that benefits many users. First, it can be used as an educational tool for mechanical engineering students and vocational school students who wish to study different kinds of mechanical watch movements. Second, it acts as an online library for general public to search information about escapements and some well-known horologists. Last but not the least, it helps watchmaker to diagnose the design and assembly error when building a mechanical watch movement. Recently, we receive an inquiry from a clock manufacturing company on validate their design. Using the data they provided, we constructed a 3D CAD as shown in Figure 17. Then, we run a simulation step by step to visualize the operation of the design. We also analyze the effect of the manufacturing / assembly tolerance.

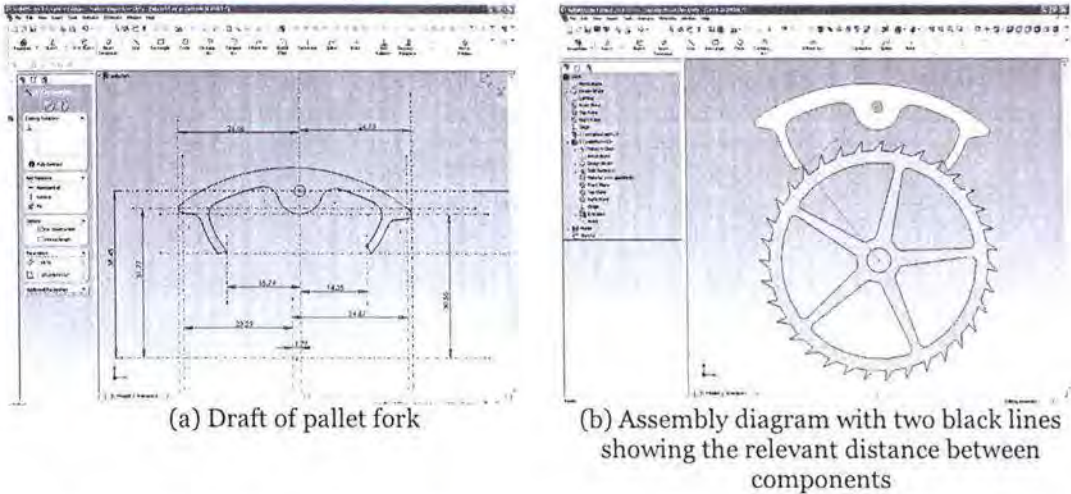


Fig. 17: Converting the construction blueprint into a CAD animation in SolidWorks®

4. CONCLUSIONS AND FUTURE WORK

Mechanical watch movement is a complicated mechanical device. In order to help the engineering professionals and general publics to understand its working principle and find the related information, we develop a virtual library. Presently, the library consists of four different kinds of escapements: the Graham escapement, the English lever escapement, the Swiss lever escapement and the Daniels co-axial double-wheel escapement. For each escapement, detailed information is

given, including the invention background, the 3D solid models, the video clips and the explanation of the working principle.

The future work will include:

- (1). Adding more escapements, such as the Brocot escapement, the Tic-Tac escapement, the Glashuetten Lever Escapement, the Muller escapement, the spring detent escapement, the Denison escapement, the Haldmann escapement, the Strasser escapement and etc.
- (2). Developing an interface so that users interactively manipulate the 3D models and the animation.

5. REFERENCES

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Appendix B

L. C. Tam, Tom Kong and R. Du, “Physical-based Simulations of Mechanical Watches and Clocks,” the ASME International Mechanical Engineering Congress and Exposition, November 11 - 15, 2007, Seattle, Washington, USA.

**Proceedings of the ASME International Mechanical Engineering Congress
and Exposition
ASME
November 11-15, 2007, Seattle, Washington, USA**

IMECE2007-41771

**PHYSICAL-BASED SIMULATIONS OF MECHANICAL WATCHES AND
CLOCKS**

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ABSTRACT

Mechanical watches and clocks are intricate mechanical devices that fascinate millions of people around the world. In general, a mechanical watch is made of some 100 components. Among these components, the escapement plays a vital role in controlling the timekeeping accuracy. An escapement usually consists of an escape wheel, which receives energy provided by the mainspring through the gear train, and a pallet fork, which controls the oscillation. Owing to its complex nature, few have built a mathematical model for the escapement. In this paper, we present a physical-based simulation model for the Graham Escapement (the oldest and the most common escapement for clocks), and a model for the Swiss Lever Escapement (the most popular escapement for mechanical watches). The models are developed based on a commercial software system RecurDyn® [1]. The simulation helps to understand the kinetics as well as the dynamics of the escapements.

KEYWORDS

Mechanical watch, escapement, physical based modeling.

1. INTRODUCTION

Invented some four hundred years ago, mechanical watches / clocks are fascinating timepieces that still attract millions of people today. In fact, the mechanical watch / clock business is still a billion dollar business in this electronics / information age. The heart of a mechanical watch / clock is the escapement. It gives rhythms to the motions by converting the rotary motion of the gear train into oscillatory motion and

Page 102 of 113

controls the timekeeping accuracy by distributing the impulses with equal energy. In fact, as energy “escapes” each time when a gear tooth is released, it is called “escapement” [2, 3].

The development of escapements has a long history. Verge Escapement, which is believed to be the oldest escapement, appeared at around the 13th century. This escapement is also called the crown-wheel-and-verge escapement. It is a simple type of escapement used by mechanical clocks. The escape wheel, in a crown shape, rotates about a horizontal axis. A vertical shaft, which is called a verge, is placed at the middle of another horizontal bar with two small weights one on each side. Around 1657, Robert Hooke (1635 - 1703) designed the first Anchor Escapement. It consists of a pallet fork rotating about a pivot shaft and an escape wheel. This design allows a smaller swing angle than the Verge Escapement and so less energy is needed to maintain the movements.

The Graham Escapement was invented by the English watchmaker George Graham (1673 -1751) in 1715 [4]. George Graham was one of the most well-known horologists of the eighteenth century. He was born in Hethersgill, Cumberland. George was the son of a farmer. In 1688, he became an apprentice to clockmaker Henry Aske in London. Seven years later, he worked with another renowned horologist Thomas Tompion. The Graham Escapement is also called the deadbeat escapement. It is a modified design of the anchor escapement by eliminating recoil. Recoil interferes with the action of the pendulum. The amplitude of oscillation would also be reduced. A successful escapement design should be able to give maximum energy to the pendulum to keep it swinging with least interference. This is the intension of the Graham Escapement. Though, it is mainly used in pendulum clocks but not the wrist-type mechanical watches because the pendulum could only work well in the upright direction. Graham Escapement is still used today.

Nowadays, the Swiss Lever Escapement is the most common escapement utilized in mechanical watches. This design appeared in the middle of the nineteenth century in Switzerland. It is modified from the English Lever Escapement and is very popular because of its reliability and high accuracy [5, 6].

While there are a number of books and papers that describe the design of the escapements, according to our literature survey, however, few have developed physical-based models of escapement, which can simulate the kinetics and dynamics of the escapement. Lepschy first studied the escapement from the feedback control point of view [7]. Roup and his colleagues developed a model for the Verge escapement [8, 9]. In this paper, we present a study on the physical-based models of the Graham Escapement and the Swiss Lever Escapement. It can be used for educational purposes, by which students and the general public can learn the basics of mechanical watches / clocks. It can also be used for industry purpose, by which watchmakers can optimize their designs.

The rest of the paper is organized as follows. Section 2 presents the model of the Graham Escapement and the simulation results. Section 3 presents the Swiss Lever Escapement and the simulation results. Finally, Section 4 contains conclusions.

2. THE GRAHAM ESCAPEMENT

It is interesting to note that the watch and clock escapements are similar in the way that they both have symmetrical designs: the impulses received by both sides of the pallet would be equal. On the other hand, the major difference between clock and watch escapements is that the clocks use a pendulum, while the watches use a balance wheel with a hairspring.

As shown in Figure 1, the Graham Escapement mechanism consists of three main components: a pallet fork, a pendulum and an escape wheel. Note that the end of the pendulum is attached to the rotational axis of the pallet fork. The pallet fork swings under the driving force from the pendulum. Theoretically, once the pendulum starts moving by the first push, it would never stop under the frictionless condition. However, if recoil is present, the action of the pendulum would be interfered and slow down little by little until finally it completely stops. To achieve the best performance, minimum interference is desirable, and therefore recoil has to be minimized.



Fig. 1: Model of Graham Escapement in RecurDyn®.

Figure 1 shows the model of Graham Escapement generated by a commercial software system RecurDyn®. In the Graham escapement, the teeth of the escape wheel points towards the direction of rotation. It is noted that the escape wheel would not be pushed backward during unlocking.

The arm of the entry and exit pallet is specially design to put the gravitational center on the axis of rotation of the pallet fork. The angle of the impulse faces of both pallets is set based on the direction of impulse force given by the tooth of escape wheel when it slides along the pallets.

The Graham Escapement requires a push to jump start. The whole movement launches by a push on the pendulum. Once the pendulum swings, the cycle starts. The entry pallet unlocks the tooth of escape wheel and lets the escape wheel move freely until the pallet fork rotates at a certain angle with the exit pallet locking one of the teeth on the escape wheel. At the same time, the pendulum swings in phase with the pallet fork. When the pendulum reaches the farthest position, it stops and swings to the other direction due to the elasticity of the suspension spring and the gravitational force. The pallet fork also rotates to another direction at this time and unlocks the tooth of escape wheel from the exit pallet. In each cycle, the energy transfer from the escape wheel to the pallet fork is just enough to overcome the friction.

Figures 2 - 4 show the displacement, velocity and acceleration versus time of the escape wheel. From Figure 2, it is seen that the angular displacement increases step by step in the negative direction. There are eight steps in one second, while two steps represent one moving cycle of the pendulum. Every complete cycle lasts for 0.25 second. From Figure 3, it is seen that two impulses are found within one cycle which correspond to the escape wheel colliding against the pallet fork twice in one cycle. The acceleration is more complex because it involves vibration.

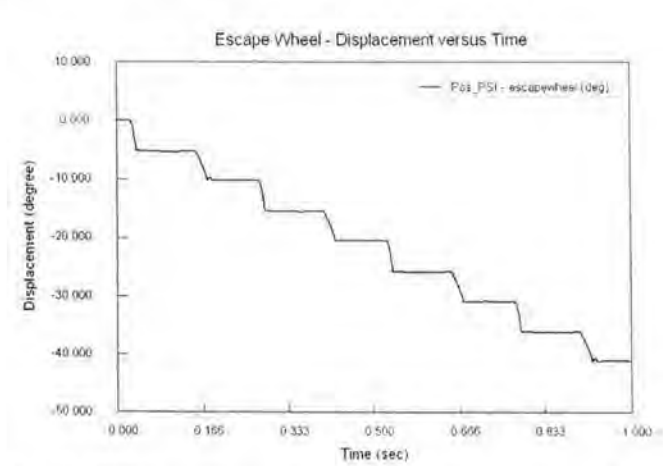


Fig. 2: Displacement versus time of the escape wheel.

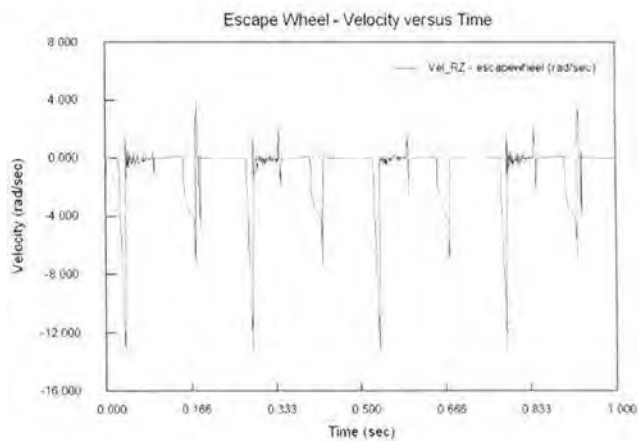


Fig. 3: Velocity versus time of the escape wheel.

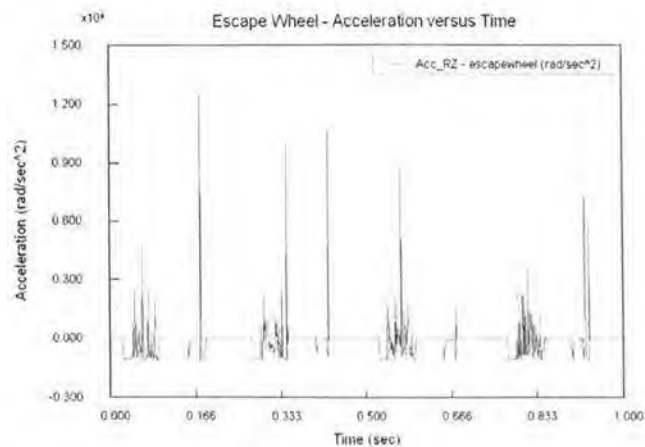


Fig. 4: Acceleration versus time of the escape wheel.

Figures 5 and 6 show the displacement of the pendulum and the pallet fork. It is found that the motion of the pendulum and the pallet fork are in phase with the same amplitude and frequency. This proves the synchronous behaviour of the pendulum and pallet fork.

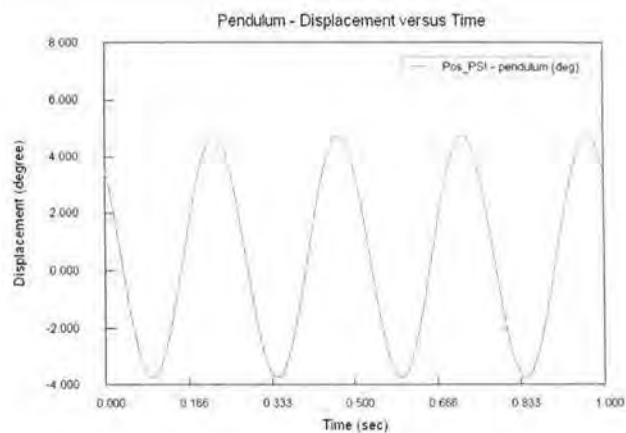


Fig. 5: Displacement versus time of the pendulum.

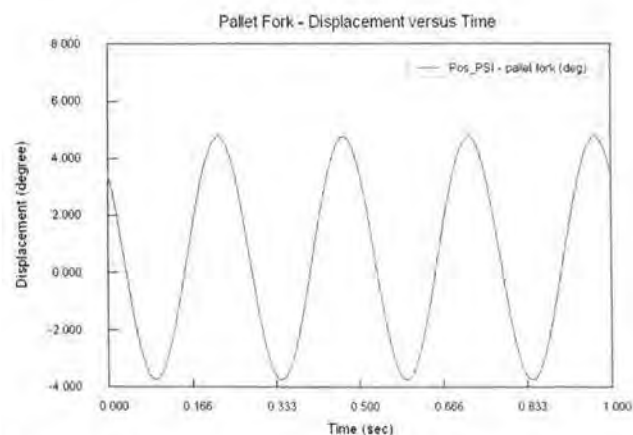


Fig. 6: Displacement versus time of the pallet fork.

3. THE SWISS LEVER ESCAPEMENT

The Swiss Lever Escapement is a kind of detached lever escapements for mechanical watches. As shown in the Figure 7, the escapement is connected to the barrel through a series of gear train. The barrel is an energy storage providing power to the mechanical watch movements. Energy is then transferred from the barrel to the escape wheel and drive the whole device. It has the advantage of self-start by which if the balance is interrupted by any mean, the operation would resume by a slight movement of the watch. There are a few design features in the Swiss Lever Escapement to ensure the smooth movement. The rotation axes of the balance wheel, the pallet fork and the escape wheel of the Swiss Lever Escapement lie on a straight line so that this design is symmetric. The symmetric design has the advantage that balance wheel receives the same magnitude of energy in both direction. The club-tooth escape wheel is effective in reducing drop. The reduction in drop helps a better transfer of energy from escape wheel to balance wheel. Therefore, Swiss Lever Escapement is more reliable than other escapement designs.

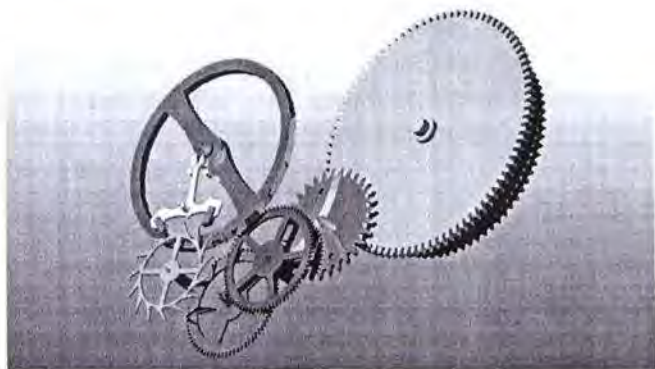


Fig. 7: The model of Swiss Lever Escapement connected to the gear train and the barrel. The escapement is on the left side while the barrel is on the right.



Fig. 8: Model of Swiss Lever Escapement in RecurDyn®.

Figure 8 shows the model drawn using a commercial software system RecurDyn®. In one period of movement, five shocks occur. The 1st shock refers to the unlocking. At the very beginning, the pallet fork provides the first torque to the balance wheel by a push. The balance wheel swings to the highest position and then descends to hit the entry of the pallet fork by the impulse pin on the roller table. This action makes the pallet fork swings to the opposite direction and causes the entry pallet unlock the escape wheel. When unlocking occurs, the escape wheel recoils slightly. The 2nd shock is impulse situation. The escape wheel is driven forward by the gear train. One of the teeth on the escape wheel slides along the impulse plane of the entry pallet by which it pushes the pallet fork upward. The pallet fork gives an impulse to the impulse pin on the balance wheel. In the 3rd shock, the exit pallet of the pallet fork would lock a tooth of the escape wheel. At the same time, the pallet fork reaches its farthest position and lies on the banking pin. The 4th shock is the situation that the exit pallet unlocks the escape wheel. When the balance wheel starts to rotate toward the other direction, the impulse pin on it hits the entry of the

pallet fork and unlocks the tooth of the escape wheel. The escape wheel recoils slightly. The last step is the 5th shock during which a tooth on the escape wheel slides along the impulse surface of the exit pallet and gives an upward force to the pallet fork. The impulse is transferred to the impulse pin on the balance wheel through the pallet fork. This completes the cycle [5].

Figures 9 – 17 show the displacement, the velocity, and the acceleration versus time of the balance wheel, pallet fork and escape wheel demonstrating how the Swiss Lever Escapement operates within one period. In this simulation model, a force input is added on the balance wheel to simulate the effect of hairspring. From Figures 9 – 11, it is seen that the balance wheel operates along a smooth sinusoidal curve. For the pallet fork, as shown in Figures 12, it experiences a gradual change in displacement within the range of 0° to 15.4°. As a result, two shape velocity / acceleration changes occur during the cycle. The simulation results of the escape wheel are shown in Figure 15 – 17. In the figure of displacement of the escape wheel, two recoils occur during one complete cycle at 0.055 sec and 0.187 sec. The occurrences of recoils could be identified by the small triangles in the figure. This result fits our expectations that the escape wheel would recoil slightly during the unlocking of the pallet fork. The Figure 15 also shows the displacement of the escape wheel during one cycle is 18°. As there are 20 teeth on the escape wheel, it is reasonable that the wheel rotates 18° in each step.

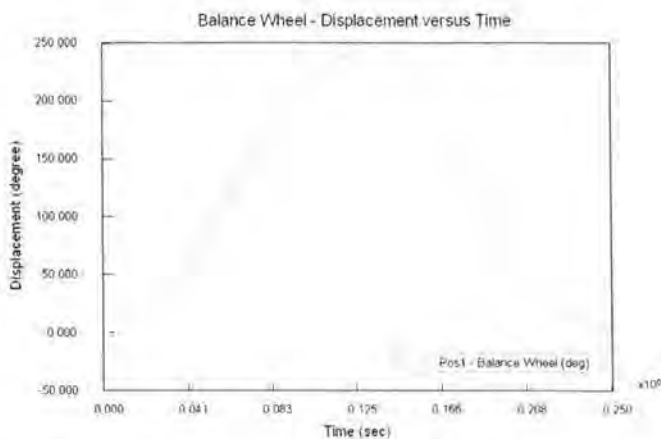


Fig. 9: Displacement versus time of the balance wheel.

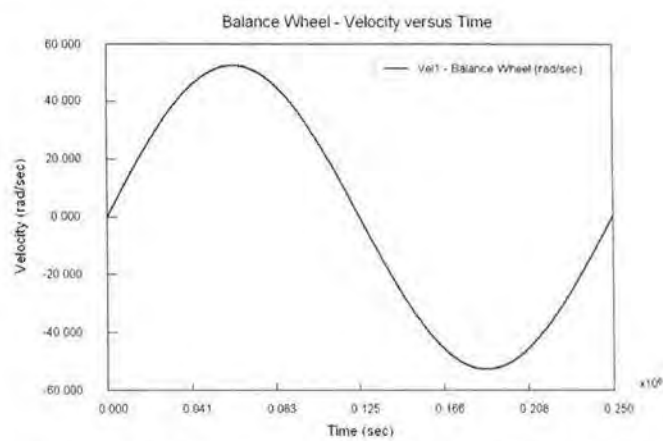


Fig. 10: Velocity versus time of the balance wheel.

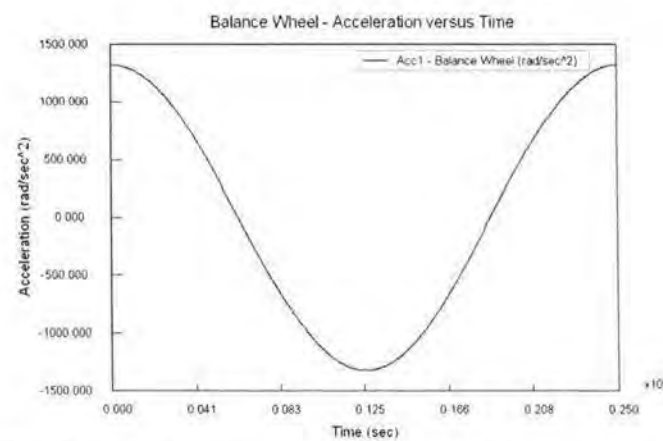


Fig. 11: Acceleration versus time of the balance wheel.

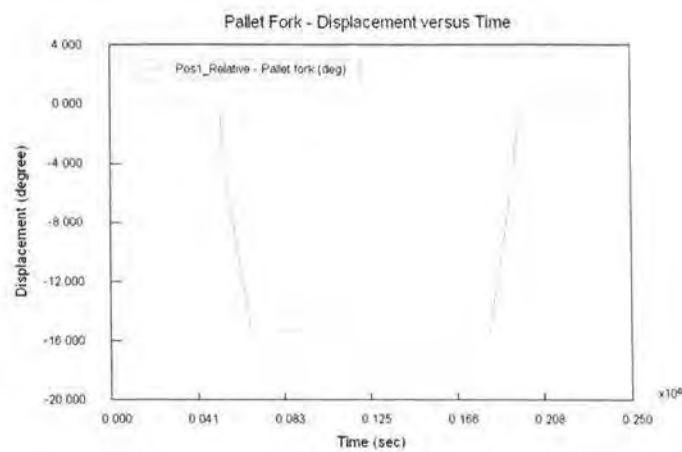


Fig. 12: Displacement versus time of the pallet fork.

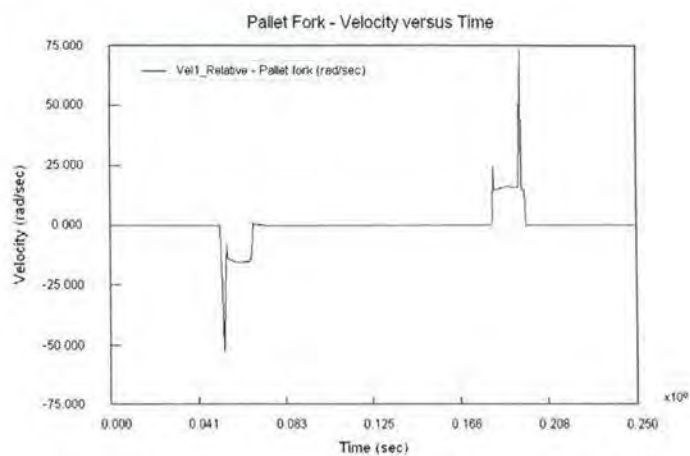


Fig 13: Velocity versus time of the pallet fork.

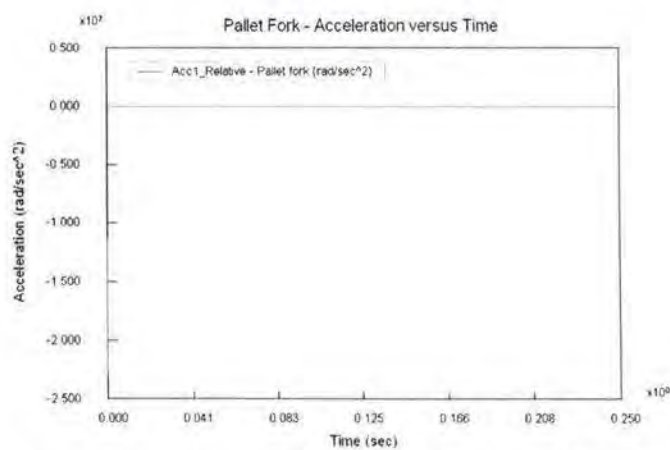


Fig. 14: Acceleration versus time of the pallet fork.

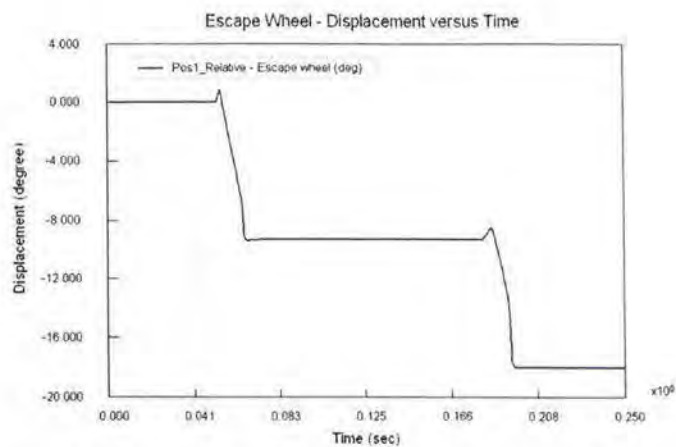


Fig. 15: Displacement versus time of the escape wheel.

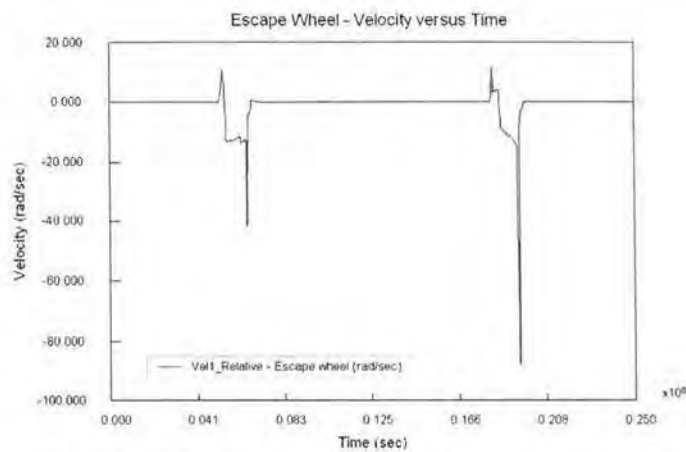


Fig. 16: Velocity versus time of the escape wheel.

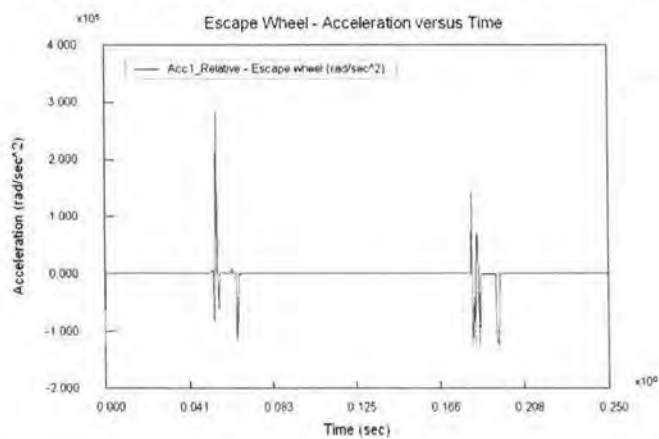


Fig. 17: Acceleration versus time of the escape wheel.

4. CONCLUSIONS

Based on the discussions above, the following conclusions are drawn:

- (a) The design of clocks and watches are similar in that their structures are symmetrical. In both cases, the pallets receive equal numbers of impulses, while their major difference is that the pallet is driven by pendulums in clocks while it is driven by the balance wheel with a hairspring in watches.
- (b) The intricate motions of the Graham Escapement in clocks and of the Swiss Lever Escapement in watches can be modeled by RecurDyn[®]. This commercial software system can also be applied to other kinds of escapements.
- (c) From the simulation results, the periodical behaviour of the escapement is shown. Once the first push is applied, the escapement starts its motion automatically and functions cyclically. Theoretically, it would never stop in the case of no external force or friction being added to the system.
- (d) The simulation results provide a way for watchmakers or anyone who are interested in mechanical watch, with an innovative insight. These results can be further used to optimize the design.

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