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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 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.

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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.

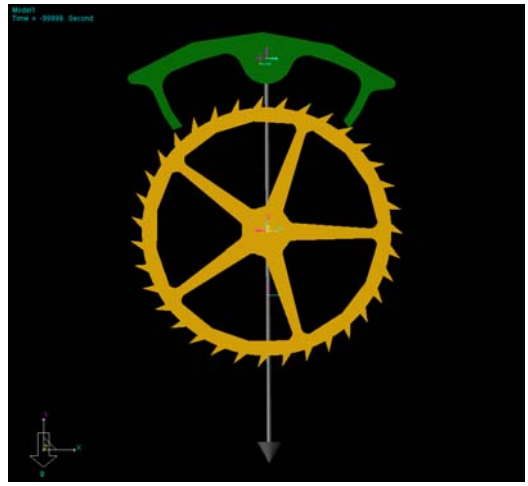

Fig. 1: Model of Graham Escapement in RecurDyn®.

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.

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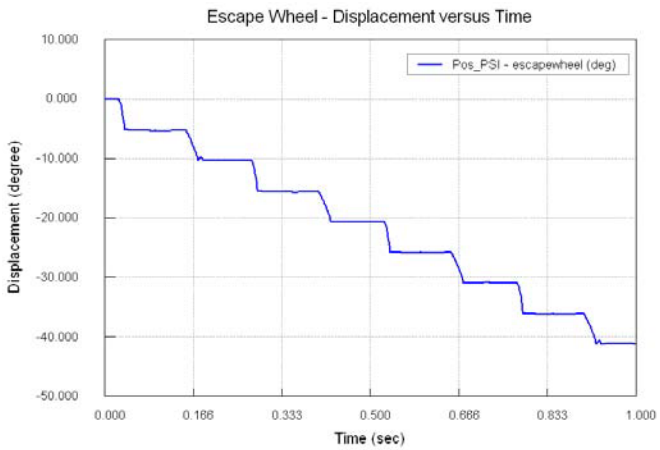

Fig. 2: Displacement versus time of the escape wheel.

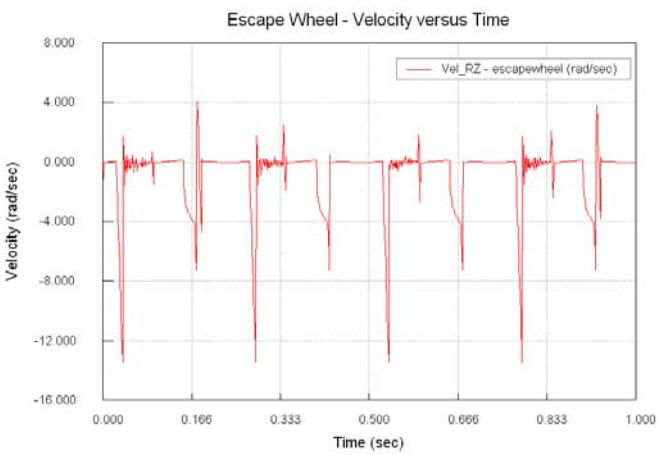

Fig. 3: Velocity versus time of the escape wheel.

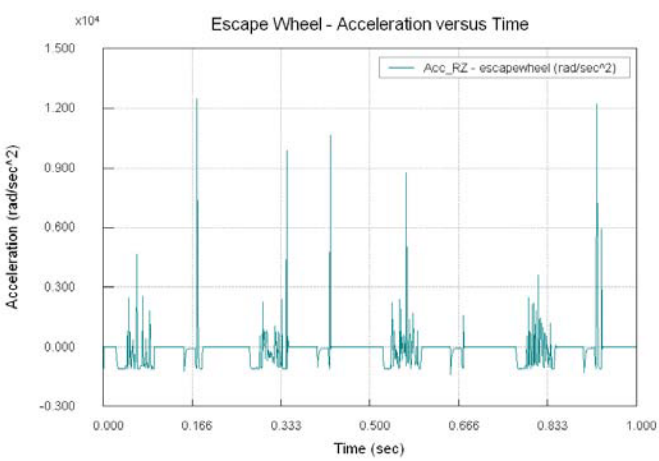

Fig. 4: Acceleration versus time of the escape wheel.

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.

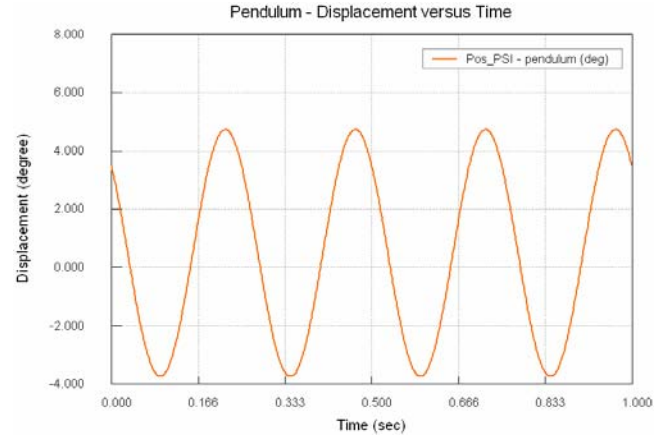

Fig. 5: Displacement versus time of the pendulum.

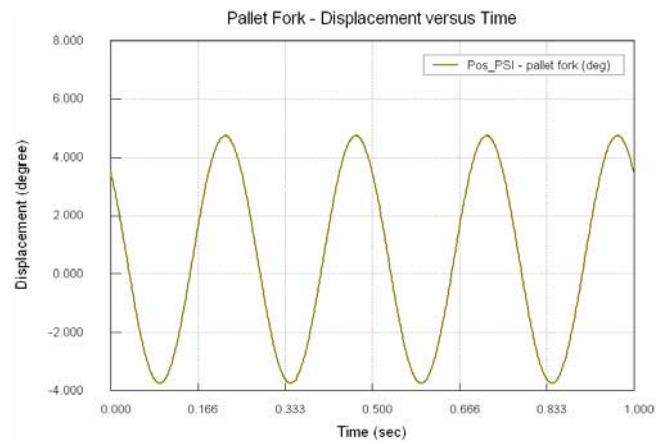

Fig. 6: Displacement versus time of the pallet fork.

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.

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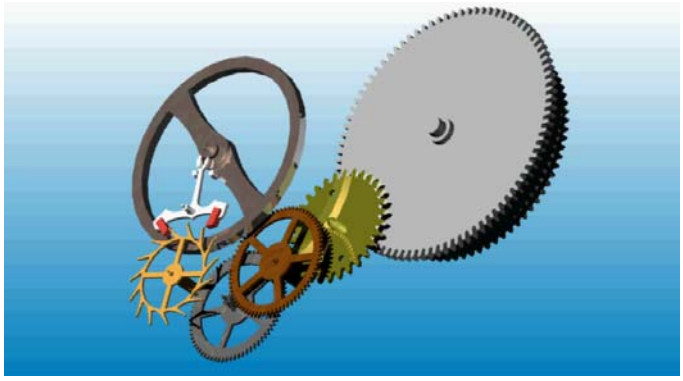

Fig. 7: The model of Swiss Lever Escapement connected to the gear train and the barrel. The escapement is on the left side while the barrel is on the right.

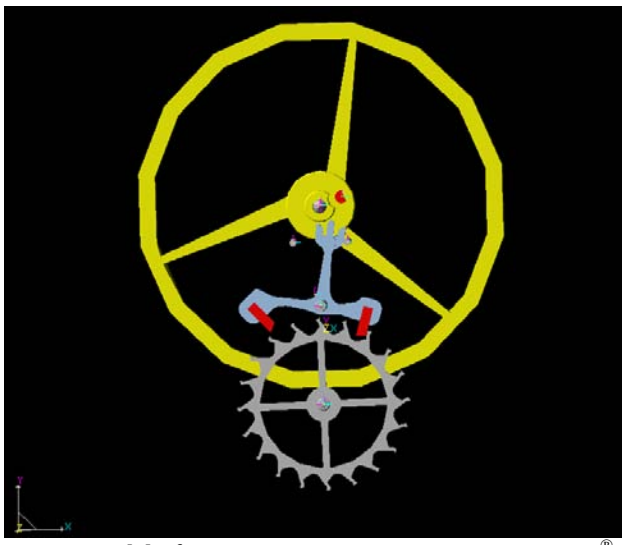

Fig. 8: Model of Swiss Lever Escapement in RecurDyn®.

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 0º to 15.4º. 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 18º. As there are 20 teeth on the escape wheel, it is reasonable that the wheel rotates 18º in each step.

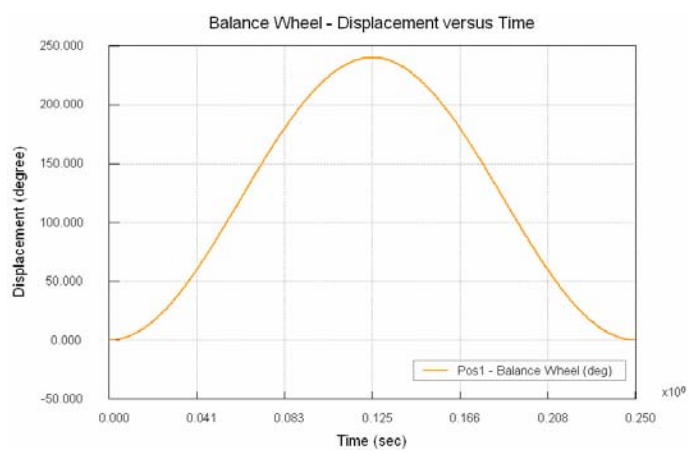

Fig. 9: Displacement versus time of the balance wheel.

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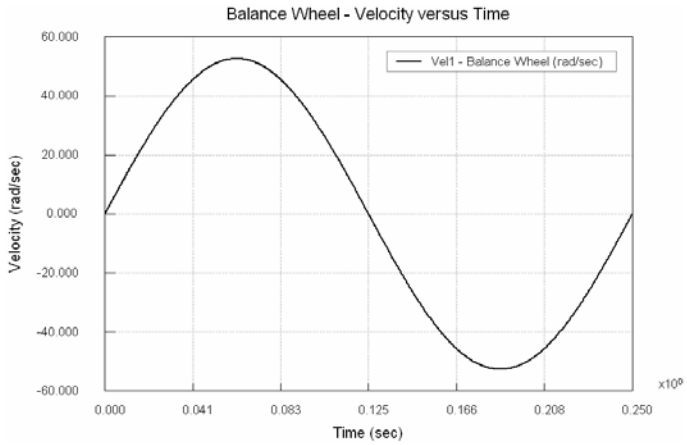

Fig. 10: Velocity versus time of the balance wheel.

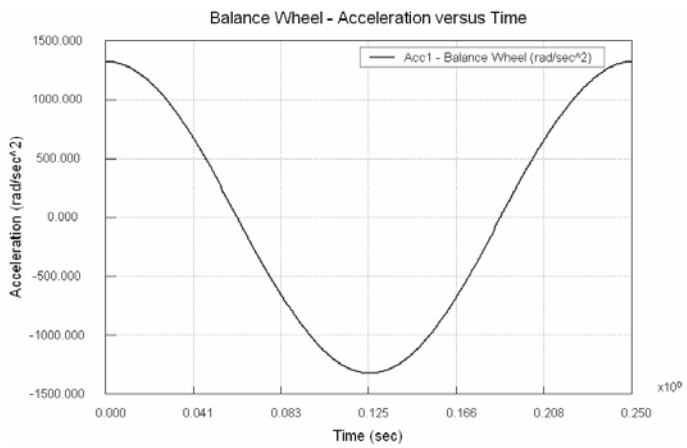

Fig. 11: Acceleration versus time of the balance wheel.

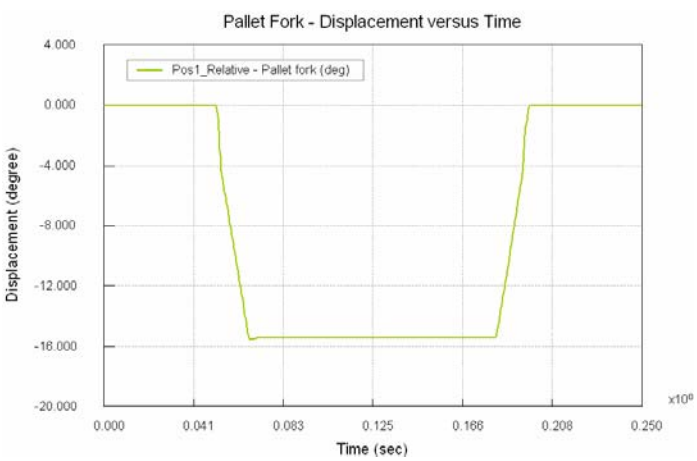

Fig. 12: Displacement versus time of the pallet fork.

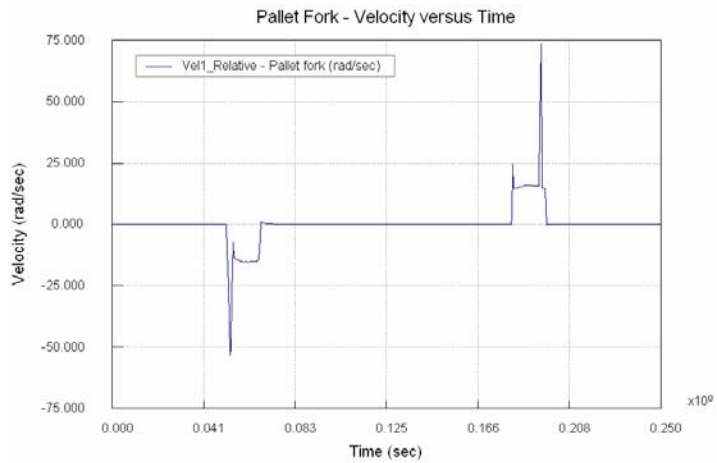

Fig 13: Velocity versus time of the pallet fork.

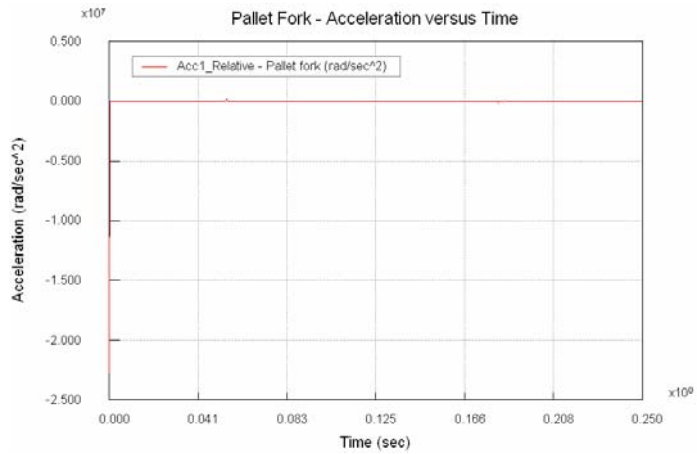

Fig. 14: Acceleration versus time of the pallet fork.

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

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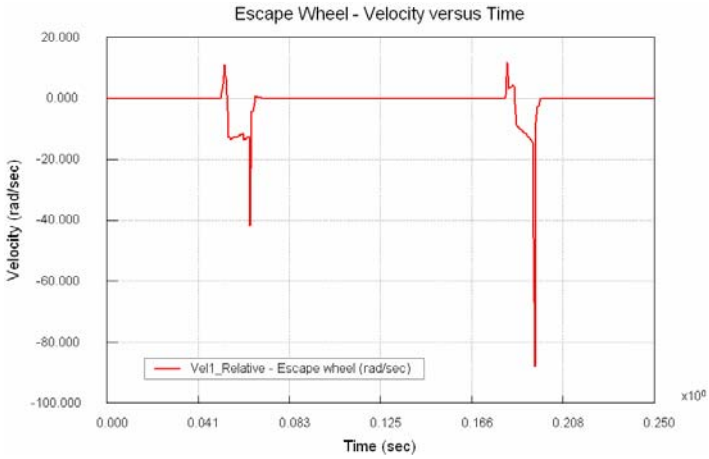

Fig. 16: Velocity versus time of the escape wheel.

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.

ACKNOWLEDGMENTS

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REFERENCES

[1]. The official homepage of FunctionBay, Inc., http://www functionbay.co.kr/rd_about htm, RecurDyn, 2007.

[2]. Mark V. Headrick, "Origin and Evolution of the Anchor Clock Escapement," *IEEE Control Systems Magazine*, April 2002.

[3]. Mark V. Headrick, *Clock and Watch Escapement Mechanics*, Abbey Clock Clinic, 1997.

[4]. Virtual Library of Mechanical Watch Movements, http://www.ipe.cuhk.edu.hk/projects10_library html, Graham Escapement, 2006.

[5]. Wei Koh, "Unlocking the Secret of the Escapement," Revolution Press, pp.284- 296, 11th July 2006.

[6]. Y. Fu and R. Du, "A Study on the Swiss Lever Mechanism," *2006 International Mechanisms and Machine Science Conference (2006 CCMMS)*, pp. 308 – 311, Yingchuan, China, Aug. 14 – 16, 2006.

[7]. Lepschy, A. M., Mian, G. A. and Viaro, U. "Feedback Control in Ancient Water and Mechanical Clocks," *IEEE Transactions on Education*, Vol. 35, Iss. 1, February, pp. 3 – 10, 1992.

[8]. Roup, A. V. and Bernstein, D. S. "On the Dynamics of the Escapement Mechanism of a Mechanical Clock," *Proceedings of the 38th IEEE Conference on Decision and Control*, Vol. 3, December, pp. 2599 – 2604, 1999.

[9]. Roup, A. V., and et al., "Limit Cycle Analysis of the Verge and Foliot Clock Escapement Using Impulsive Differential Equations and Poincare Maps," *Proceedings of the 2001 American Control Conference*, Vol. 4 , June, pp. 3245 – 3250, 2001.

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