Berthold Schlecht, Benjamin Röseler, TU Dresden, Institute of Machine Elements and Machine Design (IMM); Lutz Reichel, NOMOS Glashütte/SA

Calculation and Simulation of an Anchor Escapement in Mechanical Watches

Since 2009, the Institute of Machine Elements and Machine Design (IMM) at TU Dresden, and the watchmaking manufacturer NOMOS Glashütte/SA, have been collaborating on two projects concerning mechanical watches: special gear tooth profiles of the train, and the optimization of the assembly escapement-balance wheel system. These projects were financed by the Sächsische AufbauBank (SAB) with financial support from the European Union and the European Regional Development Fund (ERDF).
In order to develop a new balance wheel system for NOMOS Glashütte/SA, the detailed investigation of the escapement in the form of a Swiss anchor escapement was done. The results are presented in this article. These specifications include the theoretical basics: the calculation and simulation of the motion sequences as well as the appraisal of optimized geometrical parameters.

CONSTRUCTION AND FUNCTION OF A MECHANICAL WATCH

The basic construction of a mechanical watch can be classified into four main groups. These are the energy storage (barrel), the train (gear wheels from the barrel to the escapement pinion), the escapement (escape wheel and anchor) and the balance wheel system (balance wheel with a spiral spring), which are shown in Fig. 1.
The potential energy of the main spring in the barrel is transmitted stepwise by the train and the escapement to the balance wheel system. The escapement of a watch is the connector between the train and the balance wheel. In summary, the function of the escapement can be described as the controlled supply of energy to the balance wheel system and the blockade of the train. So, the rotational oscillation of the balance wheel will be ensured and the time-keeping of the watch will be correct since the spiral spring on the balance wheel oscillates at a constant frequency.

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MOTION SEQUENCES OF A SWISS ANCHOR ESCAPEMENT

The components of a Swiss anchor escapement are the escape wheel on the end of the train, the anchor with the pallet, the banking pin, and the shaft of the balance wheel with the impulse jewel. The components are shown in Fig. 2. In the action of the rotational oscillation of the balance wheel, the train will be released twice per oscillation. As a result, the energy transmits from the escape wheel to the anchor to the balance wheel. In every half period of the balance wheel, different characteristic motion sequences of the escapement components will be passed, see Fig. 3.
In the "Activation" phase, the anchor — which first rests against the banking pin and blocks the train — will start moving with the help of the impulse jewel. A relative movement between the pallet of the anchor and the escape wheel begins. Due to the geometry of the pallet, the wheel and the train are powered for a small time period against

their common orientation turn. The balance wheel system dispenses energy. After this, the tip tooth of the escape wheel comes in contact with the pallet faces of the entry or exit pallet. This phase is called "Impulse", and the energy will transmit from the train to the anchor and the impulse jewel to the balance wheel. The balance wheel receives energy. The backlash between the impulse jewel and the anchor fork will be passed. The "Impulse" can be divided into two phases. First the "Pallet Impulse", and second, the "Wheel Impulse", which are characterized by the contact faces of the escape wheel and the pallet on the anchor. After the "Impulse", the anchor of the outgoing pallet falls ("Fall"), the impulse jewel oscillates out of the anchor fork, the train blocks, and the anchor is up to the banking pin of the exit pallet side. The balance wheel oscillates freely to its stationary point. Finally, the second half period of the oscillation starts.

CALCULATION OF THE FORCE TRANSMISSION FROM THE BARREL TO THE BALANCE WHEEL SYSTEM

With the geometrical parameters of the escapement, the motion sequences will be calculated analytically and quasi-statically without the influence of the velocity of the escapement components. In every rotational position of the escape wheel, the anchor and the balance wheel, the contact forces between the anchor and the escape wheel, as well as between the anchor and the impulse jewel, will be calculated. Also, the torque of the rotary axes and the efficiency of the escapement will be determined. These calculations show significant kinematical characteristics of the contact partners, see blue line in Fig. 4. For instance, the force or torque required to displace the anchor from the banking pin in the "Activation" phase, as well as the torque, transmitted from the anchor to the balance wheel in the motion sequence Impulse, may be determined. Furthermore, it is possible to calculate the length of the different motion sequences to show meshing interferences between the contact partners and to analyze the influence of geometrical parameter variations.

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Due to minuscule weight, the small moments of inertia of the escapement components, and the impulsive energy transmission, it is recommended to consider the dynamic motion of the components. The influences of the velocity of the components will be determined in the force transmission of the contact partners and simulated within SIMPACK. This is very important information for the development of the assembly escapement-balance wheel system because it influences the amplitude and the oscillation time of the balance wheel and the efficiency of the escapement.

SIMULATION MODEL DESCRIPTION AND PARAMETERS

To determine the contact between the escapement components and to calculate the contact forces within SIMPACK, the Force Element 45 (curve-curve-contact) is used, see Fig. 2. To generate a contact between the components, their curves must be defined using coordinates. With the parameters contact stiffness, damping, and a friction coefficient, Force Element 45 calculates the contact forces in each position.

On the escape wheel, a drive torque of $M_{an,max} = 1.4 \cdot 10^{-6}$ Nm is defined, and on the balance wheel, the torque of the spiral spring is used as a function of its amplitude. The torque of the spring is calculated within SIMPACK by the spiral stiffness, the damping, and by the friction loss of the free rotational balance wheel.

At the beginning of the simulation, the balance wheel starts from a user defined position and oscillates to a constant amplitude. This is dependent on the driving torque and on the efficiency of the escapement. Due to the slight mass parameters of the simulated watch components, the challenge was to define and adjust the damping parameters in SIMPACK. The values of the mass parameters and the moments of inertia are shown in Table 1.

Component	I_{zz} [kgm²]	m [kg]
Escape Wheel	$3.24 \cdot 10^{-11}$	$1.05 \cdot 10^{-5}$
Component	$1.20 \cdot 10^{-11}$	$6.00 \cdot 10^{-6}$
Balance Wheel	$1.00 \cdot 10^{-9}$	$7.00 \cdot 10^{-5}$

Table 1: Values of the mass parameters and the moments of inertia

The results of the simulation with SIMPACK are, for example, the rotational angle of the different components and the contact forces of the contact partners as a function of simulation time; see the green graph in Fig. 4. Furthermore, the difference between

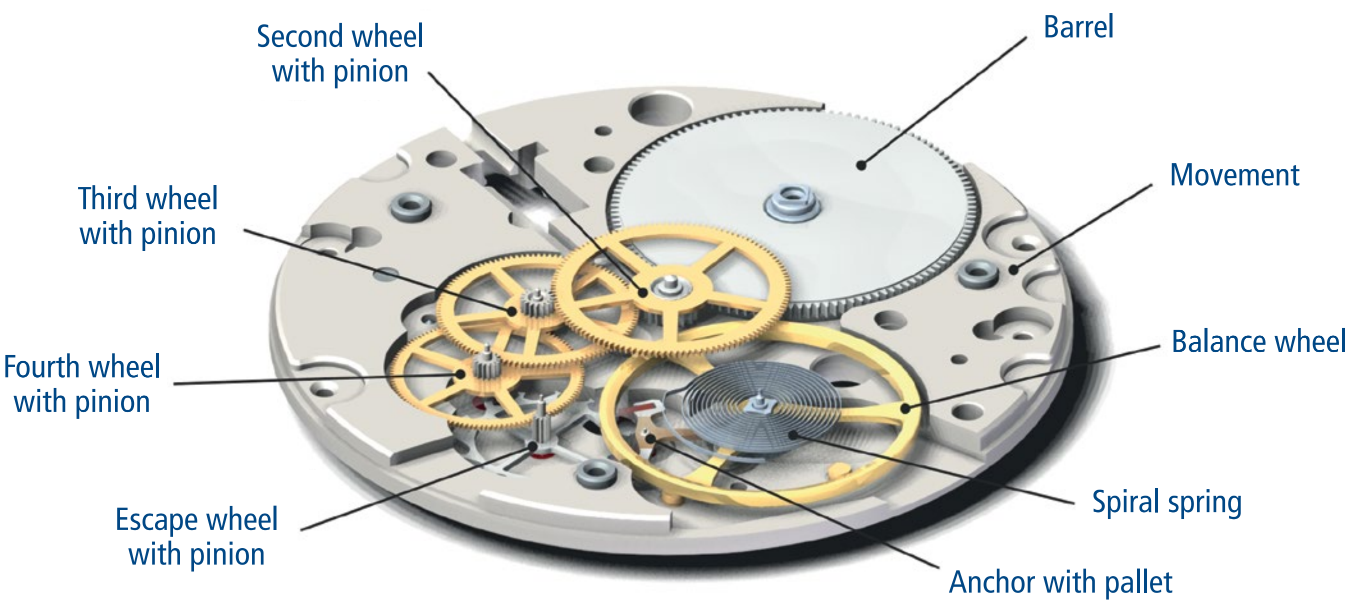

Fig. 1: Construction and components of a mechanical watch

the oscillation time and the theoretical frequency of the spiral spring, as well as the efficiency of the escapement, are determined. The efficiency of a Swiss anchor escapement is normally between 30 % and 40 %. This is defined as the rate of the lost energy of the balance wheel to the available energy on the escape wheel. To influence the efficiency of an anchor escapement, it is recommended to increase the amplitude of the balance wheel system.

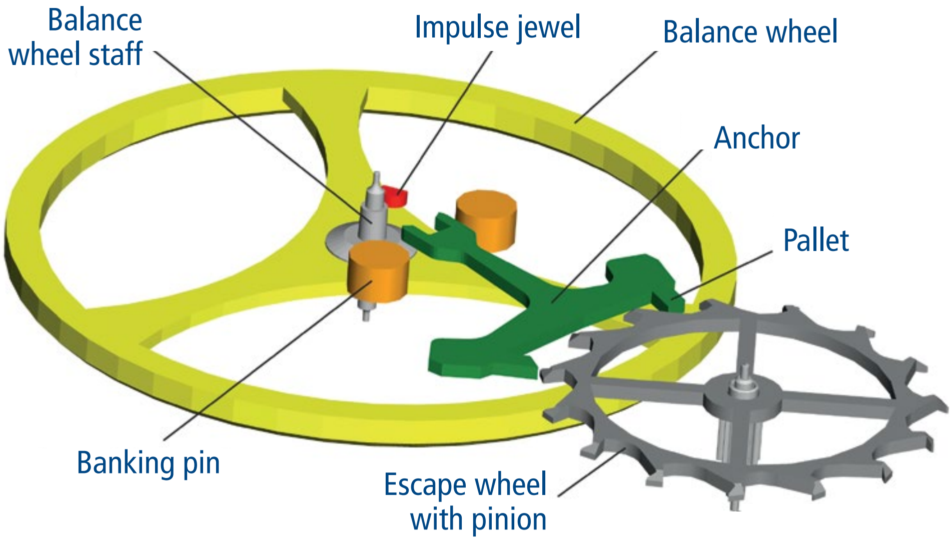

Fig. 2: Simulation model and components of a Swiss anchor escapement

RESULTS OF THE SIMULATION AND INFLUENCE ON THE FORCE TRANSMISSION

The comparison between the quasi-static calculated and simulated contact force of the different motion sequences, see Fig. 4, shows similarities and differences in the graphs because of the influence of the velocity of the components.

In the "Activation" motion sequence, the required force to displace the anchor is the same in both methods, but the lengths of the phases are different. The results of the dynamic simulations show the contact release between the escape wheel and the anchor pallet. This is defined as the time phase "Fligh". So, the balance wheel dispenses less energy than the statical investigation determines. After this, the tip tooth of the escape wheel does not fall at the beginning of the pallet face. The contact between the escape wheel and the pallet takes place one third of the width of the pallet displaced from the theoretical contact point, because of the rotation of the anchor in this short period of time ("Fligh"). As a result, the length of the "Impulse" phase is shorter than the results of the quasi-static calculations indicate. Less energy will transmit from the escape wheel to the balance wheel, and the efficiency is lower. This effect is also shown in a high-speed video of a real escapement in the watches from NOMOS Glashütte/SA. After the first contact between the escape wheel and the pallet face, the backlash between the anchor fork and the impulse jewel has passed. This time no force was transmitted to the balance wheel. At the end of the "Pallet Impulse", the quasi-static and dynamic results show the same transmitted force. The next difference occurs at the change from "Pallet Impulse" to "Wheel Impulse". The dynamic simulation shows a short period of time in which no force is transmitted from the train to the anchor. Furthermore, the length of the "Wheel Impulse" is shorter. In summary, the differences between the quasi-static and dynamic investigations are the period of times where no force transfers from the barrel to the balance system. The balance wheel gets less

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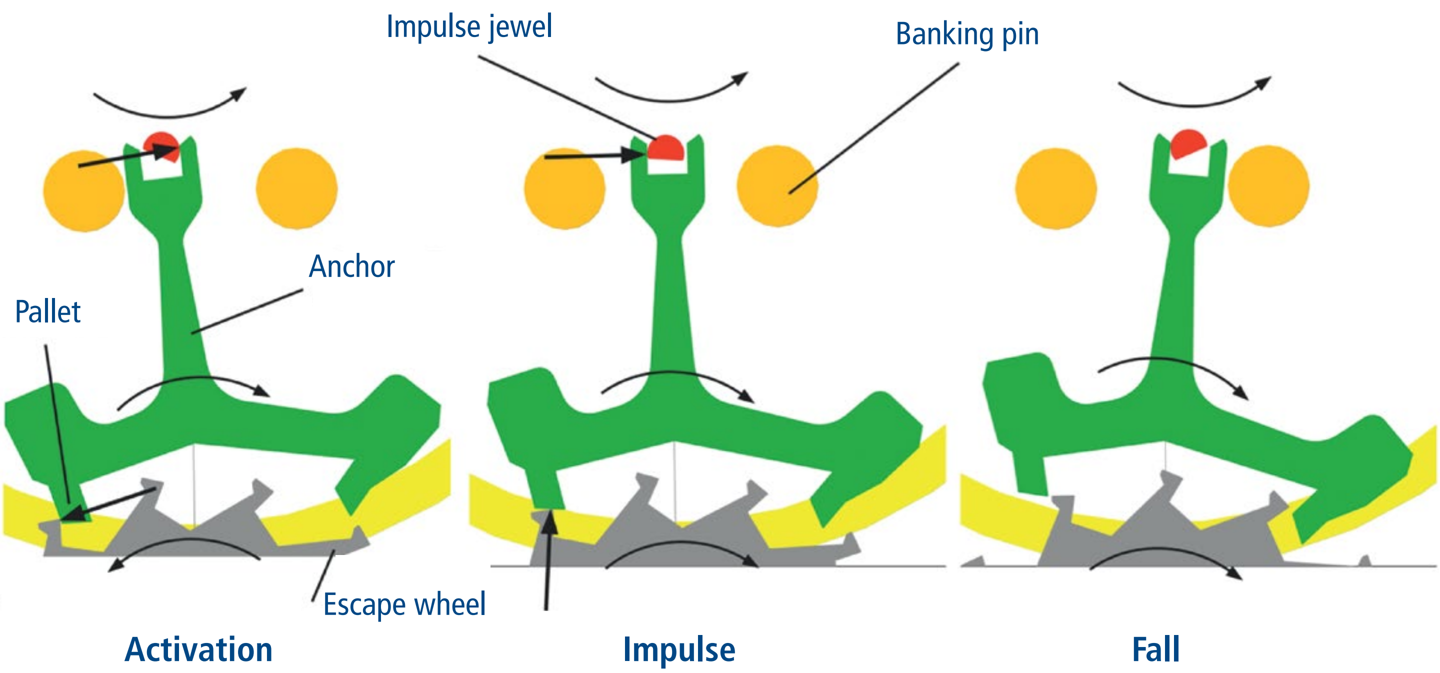

Fig. 3: Motion sequences of a Swiss anchor escapement; f.l. Activation, Impulse, Fall

energy and the amplitude and the efficiency is lower than the quasi-statical results determine. A comparison between the calculation methods show differences of 6 % for the efficiency of the escapement.

GEOMETRY OPTIMIZATION

With the help of the escapement simulation, different constructions can be compared and the influence of geometrical parameter modifications can be discussed on the force transmitting graphs and the amplitude of the balance wheel. The intentions of this investigation were to determine optimal geometrical parameters for a high escapement efficiency and a high amplitude of the balance wheel. Fig. 5 shows the results of an example to increase the efficiency of the escapement. A reduction of the backlash between the anchor fork and the impulse jewel raises the length of the impulse phase and, in this way, also the amplitude of the balance wheel. The efficiency of the watch increases with the same drive torque in the barrel. Many other geometrical modifications can be done to increase the efficiency.

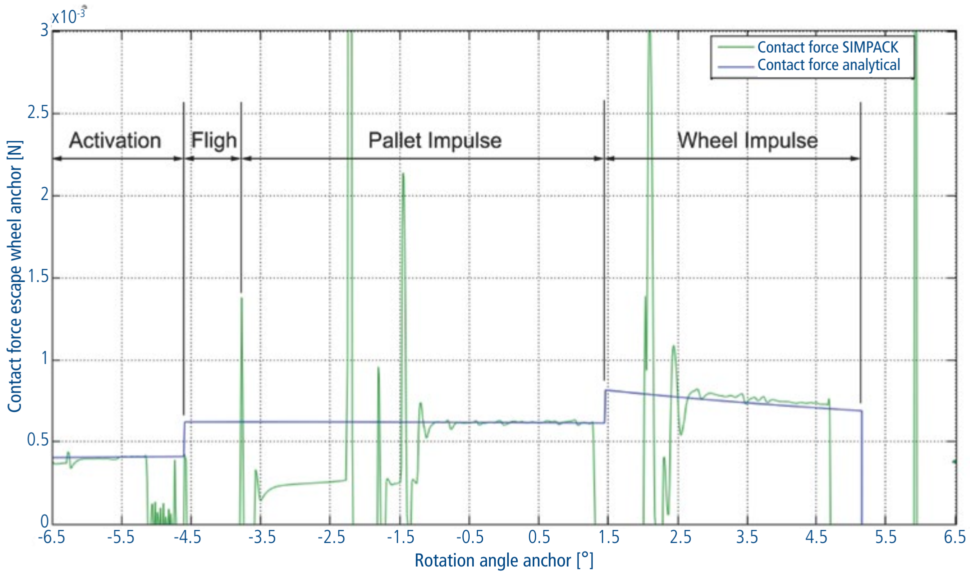

Fig. 4: Contact force as a function of the rotational angle of the anchor between the escape wheel and the anchor

CONCLUSIONS

The analysis, the calculation, and the simulation of the motion sequences of a Swiss anchor escapement show that quasi-statical consideration alone is inaccurate in determining the force transmitted from the train to the balance wheel system in a mechanical watch. With the help of simulations in SIMPACK, it is possible to get optimized geometrical parameters for the escapement with the intension of raising the efficiency and the amplitude of the balance wheel. The investigations described in this article were used in a new balance wheel system for the company NOMOS Glashütte/SA. The new system, available since 2014 within the METRO watch model, is called the "NOMOS Swing System".

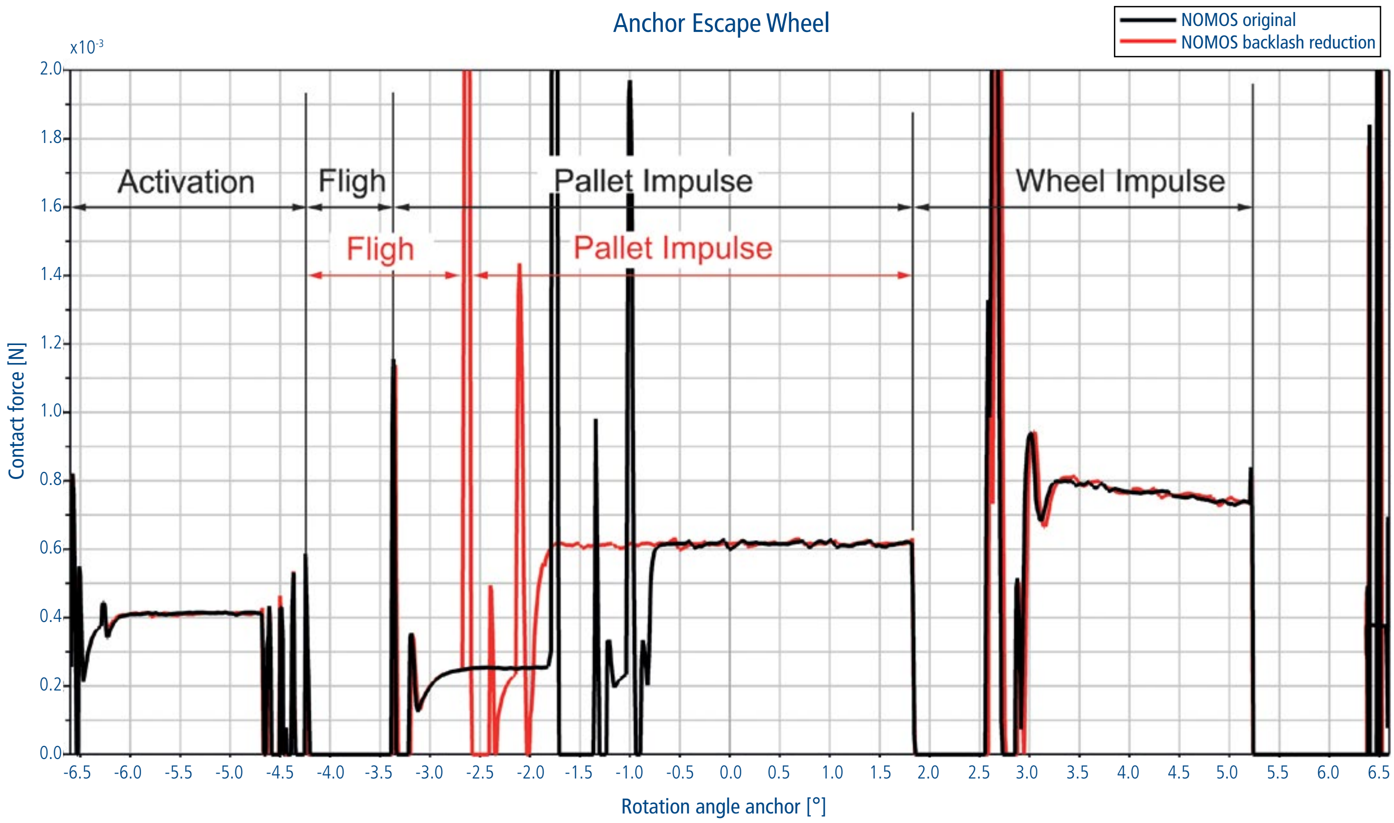

Fig. 5: Comparison of the contact force