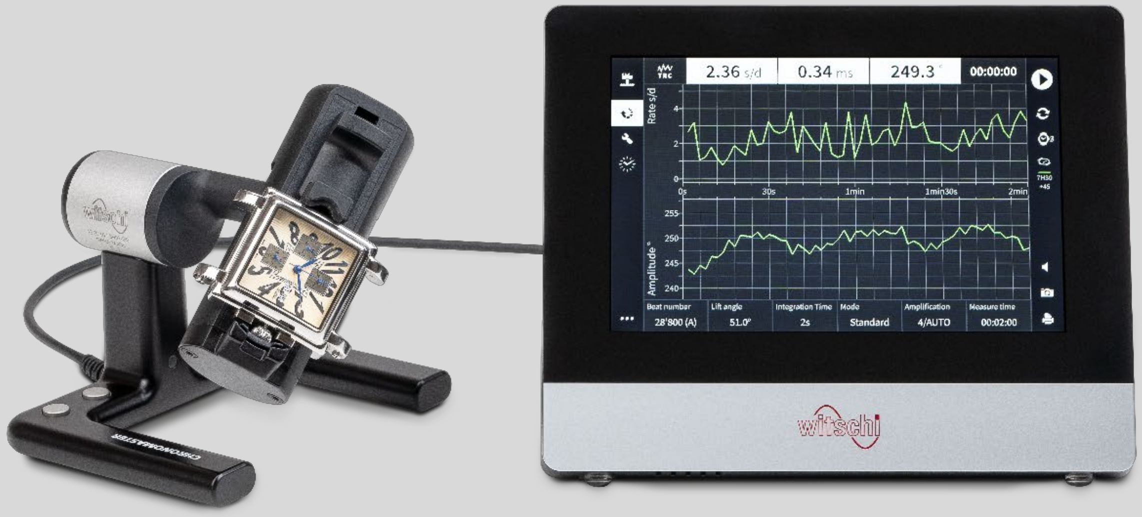

Testing Methods for Mechanical Watches

Witschi Electronic AG, 2025

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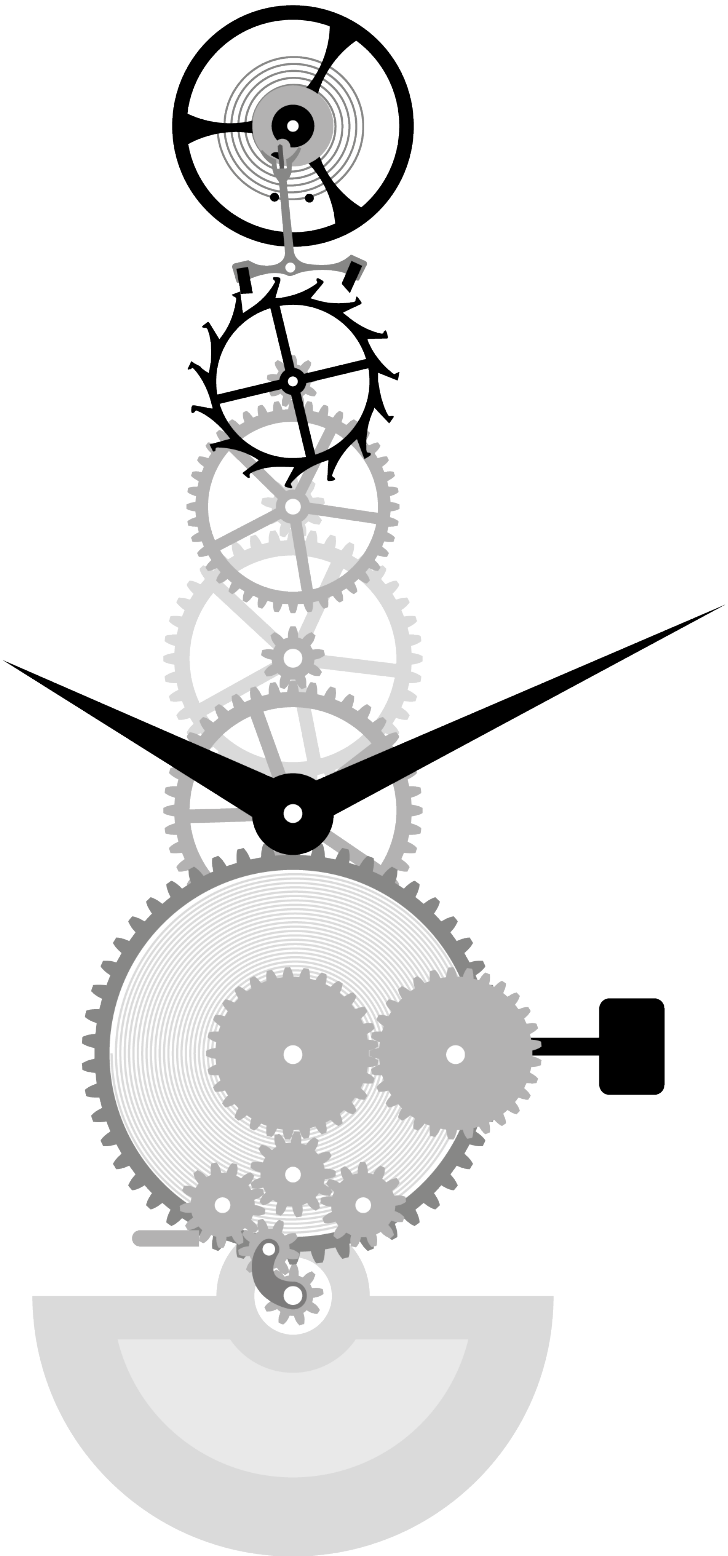
Basics

Structure of a Mechanical Watch

Oscillator

The oscillating system of a mechanical watch, consisting of the balance and the hairspring, determines the rate through its precise oscillations.

Typical frequencies:
2.5 - 5 Hz = 18,000 - 36,000 A/h
(A/h for vibrations per hour)



Escapement

"The escapement, consisting mainly of the escape wheel and pallet fork, interacts with the roller of the balance to release energy at precise intervals."

Gear train and dial train

The gear train transmits energy from the mainspring to the escapement. The motion work (dial train) translates rotational motion to the hands and ensures accurate time display on the dial.

Mainspring barrel

The mainspring barrel stores and delivers energy to drive the entire movement. The power reserve typically ranges from 48 to 70 hours; watches with extended power reserves can run for up to 8 days without rewinding.

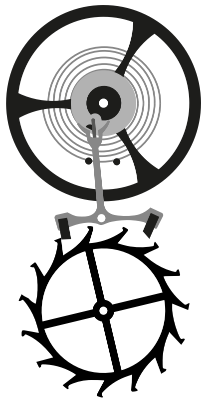
Crown and winding stem

Turning the crown winds the mainspring manually – a function also available on most automatic watches.

Automatic winding

Automatic winding uses an oscillating weight and a reduction gear to wind the mainspring via wrist movement (only in automatic watches).

Oscillator and Escapement



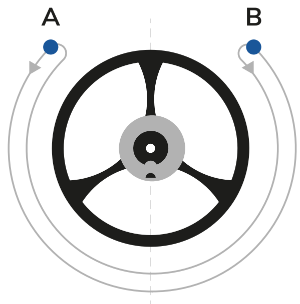
In mechanical wristwatches, a **rotating oscillator (balance)** usually serves as the timekeeping element. The escapement **controls the release of the gear train at precisely timed intervals** and simultaneously delivers impulses to the balance to sustain its oscillation.

There are various types of escapements. The most widely used in modern mechanical wristwatches is the **Swiss lever escapement**. The following description of its function and the corresponding acoustic signals refers to this type.

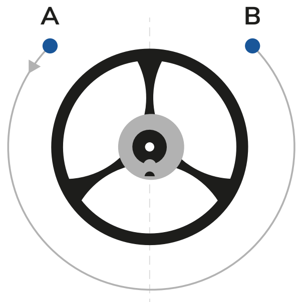
Frequency

The number of oscillations per second of the balance is defined as its frequency and is measured in hertz (Hz). Frequency is the reciprocal of the period, i.e. the duration of one complete oscillation.

The **beat rate** of a movement is often specified in **vibrations per hour (A/h)**. This refers to the total number of impulses the balance makes per hour).



The **oscillation** of the balance describes the movement of a point from one extreme position to the opposite and back again (A – B – A).



One half of a full oscillation of the balance is referred to as a **vibration**, corresponding to the movement from one extreme position to the opposite (A – B).

Beat Number

The beat number (S, in vibration per hour) is converted into the frequency (f, in hertz) using the following formula:

(1) $$f = \frac{S}{2 \cdot 3600}$$

The usual beat numbers for wristwatches are:

Beat Number (A/h)	Frequency (Hz)
18,000	2.5
19,800	2.75
21,600	3
25,200	3.5
28,800	4
36,000	5
72,000	10

Measured Parameters

In time measurement, the **rate**, **beat error**, and **amplitude** of the balance are measured directly. These three parameters are defined in this chapter. The corresponding measurement methods are discussed later, depending on whether the measurement is acoustic or optical.

Additional information about the movement can be derived from these direct measurements. For example, periodic variations in amplitude may indicate irregularities in power transmission caused by tooth geometry in the gear train. Witschi measuring instruments offer a wide range of display and analysis functions for precise evaluation of such effects.

Figure: ChronoMaster Auto. Compact tabletop device for precise and user-friendly measurement of mechanical watches.

Rate Deviation

The **rate** or **rate deviation** indicates how much the time displayed on a watch deviates from the actual time over a given period, typically one day.
To determine this, the time interval T measured on the watch is compared with a reference duration T_0 (e.g. 86,400 s for 24 hours). The relative rate deviation G ([1]) is calculated as follows:

$$G = \frac{T - T_0}{T_0} \qquad (2)$$

To express the rate in practical terms, the dimensionless value G is multiplied by 86,400 to obtain the result in seconds per day (s/d).

With a reference duration of exactly 24 hours, this yields the **average daily rate**. Shorter reference intervals allow the analysis of short-term rate fluctuations, e.g. over hours or minutes.

A positive value indicates that the watch runs fast; a negative value means it runs slow.
The rate is a key parameter for evaluating the **timekeeping accuracy** of a watch. Minor systematic deviations can be corrected by **regulating** or **adjusting** the movement.

Example for assessing precision and reliability

A customer is looking for a high-quality wristwatch with high timekeeping precision.
To evaluate the quality of different models, he observes the time displayed by four watches in a shop window at 12:00 noon over the course of five consecutive days. The deviation from the actual time is documented.

	Watch 1	Watch 2	Watch 3	Watch 4
Day 1	12:00:00 (0 s)	12:01:10	12:03:30	12:05:00
Day 2	12:00:00 (0 s/d)	12:01:15 (+5 s/d)	12:03:25 (-5 s/d)	12:05:50 (+50 s/d)
Day 3	12:00:00 (0 s/d)	12:00:50 (−25 s/d)	12:03:30 (+5 s/d)	12:06:40 (+50 s/d)
Day 4	12:00:00 (0 s/d)	12:01:20 (+30 s/d)	12:03:35 (+5 s/d)	12:07:30 (+50 s/d)
Day 5	12:00:00 (0 s/d)	12:01:05 (−15 s/d)	12:03:30 (−5 s/d)	12:08:20 (+50 s/d)

Analysis of the watches:

- **Watch 1:** Constantly displays 12:00:00 – **most likely stopped**. No assessment of movement quality possible.
- **Watch 2:** Average rate acceptable, but the daily rate fluctuates considerably (from −25 s/d to +30 s/d).
  → **Low precision**, therefore unreliable and difficult to regulate.
- **Watch 3**: Shows a significant overall deviation (over 3 minutes), but the daily rate is relatively stable (±5 s/d).
  → **Good average rate**, but only moderate precision – not ideal for adjustment.
- **Watch 4:** Shows a clear but consistent deviation of +50 s/d across all five days.
  → **Very high precision**, easy to adjust or compensate.

The customer will most likely choose Watch 4.

It best meets his requirements: the watch shows **consistent rate performance with high precision** over all five days – despite a noticeable daily gain. Since maximum rate accuracy is important to him, he asks the retailer to adjust the rate before his purchase to compensate for the constant deviation.
This gives him a precisely running watch with a reliable time base.

[1] Witschi uses this convention throughout. In the literature, a different convention is sometimes found, namely G = (T – T0) / T.

Beat Error (Repère)

If the **resting position of the balance wheel** does not correspond to the central position of the pallet fork between the banking pins, the impulse does not occur exactly when the balance passes through its rest position.
This causes the time between the two beat noises (TIC and TAC) to differ.
This asymmetry is referred to as **beat error (repère)**.

The beat error can be expressed as:

$$\text{Rep} = \left|\frac{t_{TIC} - t_{TAC}}{2}\right| \qquad (3)$$

The measured value is usually multiplied by 1,000 and expressed in **milliseconds (ms)**.
In practice, the goal is to minimise this difference so that both sides of the escapement operate symmetrically.

Alternatively, the beat error can be converted into an **angular error** in degrees (°), taking into account the beat number and amplitude – referred to as the **geometric beat error**.

In pendulum clocks, the beat error can become so large that the asymmetry is **audible** as an uneven rhythm, known as **limping**.

Traditionally, the beat error is given **without a sign** and without assignment to the entry or exit pallet. However, some newer Witschi devices provide directional information when the **polarity of the beat error changes during adjustment**.

Amplitude

The amplitude describes the **angular range** of the oscillator and is defined as the **maximum displacement from the rest (equilibrium) position** of the balance.

It corresponds to the angle between the balance's equilibrium position and the turning point of its vibration. In most modern mechanical movements, the amplitude in a horizontal position is typically between 270° and 310° when fully wound.

Acoustic Measurement

Acoustic measurement is a widely used method for determining **rate**, **beat error**, and **amplitude**. It can be performed even on fully cased watches.
The procedure is simple: the watch is placed on a special **"pickup microphone"**. To obtain an accurate amplitude reading, the **lift angle** of the movement must be known.

This method is illustrated using the beat noise of the **Swiss lever escapement**. Other types of escapements may produce different acoustic patterns and require specifically adapted evaluation algorithms.

Figure: Chronoscope M20
Simultaneous measurement of 20 mechanical watch movements with integrated code scanner for automatic identification.

The Beat Noise of the Swiss Lever Escapement

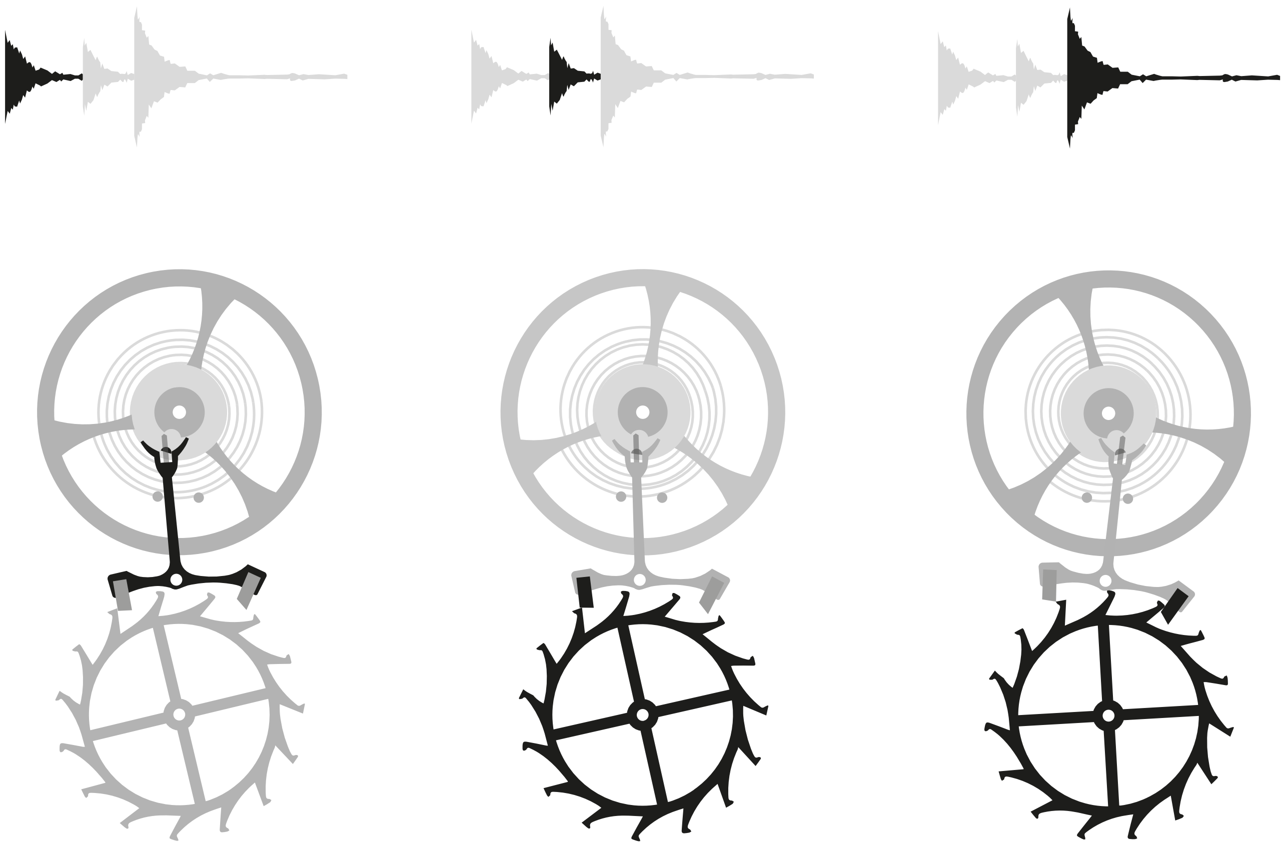
The beat noise of the Swiss lever escapement consists primarily of **three characteristic pulses**. Additional minor pulses may be present and can be attributed to specific mechanical events within the escapement.

However, for the purposes of explaining the acoustic measurement method, it is sufficient to focus on these three main pulses.

The **first** sound is produced when the impulse pin on the roller interacts with the slot of the pallet fork.
This sound occurs at a very precise moment and is therefore used for diagram recording as well as for calculating the rate and beat error.
It corresponds to the **unlocking** of the escapement.

The **second** sound occurs when a tooth of the escape wheel strikes the impulse face of the pallet, and the pallet fork contacts the impulse pin.
This sound – known as the **impulse** – is acoustically irregular and not used for evaluation.
It corresponds to the transmission of energy from the gear train to the balance.

The **third** and loudest sound occurs when a tooth of the escape wheel drops onto the locking face of the pallet, and the the lever strikes the banking.
This sound is used for evaluating the amplitude and corresponds to the **drop** of the escapement.



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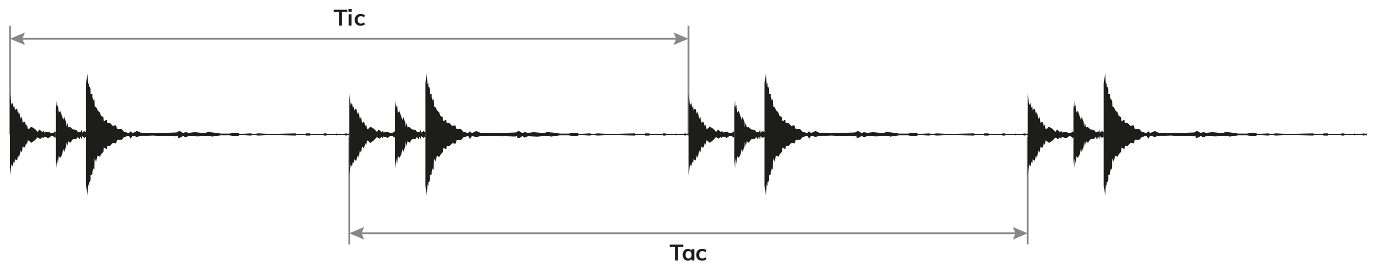
Rate Measurement

To evaluate the beat noise, a **measuring instrument** with a **high-precision reference frequency** is required.
It is essential that the onset of the first sound (unlocking) is detected reliably.
If this signal is very weak or if the watch produces significant background noise, the amplification must be adjusted accordingly.



To calculate the **rate**, the deviation between the measured period duration and the reference value is determined using formula (4) and converted into **seconds per 24 hours (s/d)**.
This calculation is performed **separately for the TIC and TAC rates** to eliminate the influence of beat error.

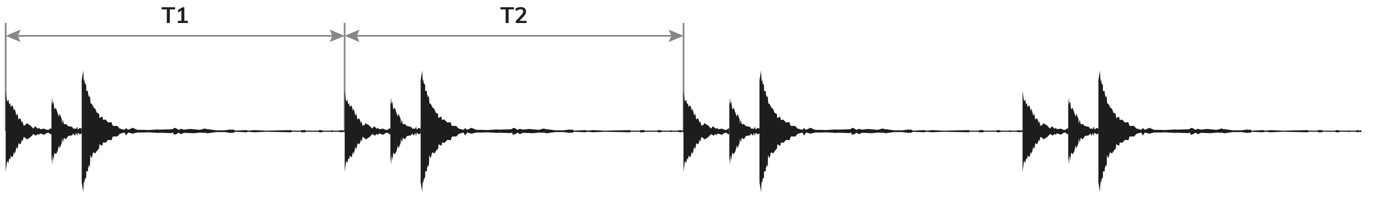
The individual rate values over the measurement period are averaged over the defined **integration time** and then displayed.

$$(4) \qquad \text{Rate} = \left|\frac{\text{Rate}_{\text{TIC}}+\text{Rate}_{\text{TAC}}}{2}\right|$$

Beat Error (Repère)

As previously described, the beat error results from **asymmetrical oscillation** when the rest position of the balance does not align with the centre position of the pallet fork. This causes the durations of the two half-oscillations to differ.

High-quality watches feature a **regulating device (porte piton)** for adjusting the beat.
The time difference is measured by the time base and is usually displayed in **milliseconds (ms)**.



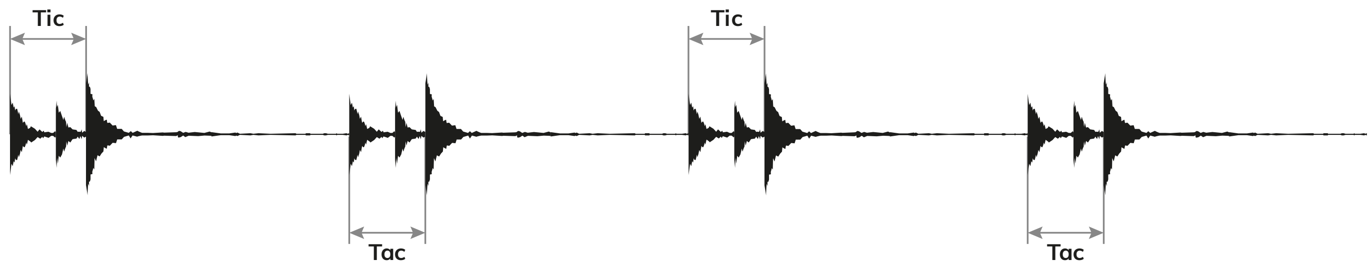
The graph shows a typical **beat error**.
If there were **no beat error (0.0 ms)**, the values of T_1 **and** T_2 would be **identical**.

$$(5) \qquad \text{Repère} = \left|\frac{T_1-T_2}{2}\right|$$

Amplitude

The amplitude (oscillation width) describes the angle between the equilibrium position of the balance and its turning point. In modern mechanical movements, it typically ranges between 270° and 310° when fully wound.
As lubricants age, the amplitude gradually decreases.

To calculate the amplitude, the **time between the first impulse (unlocking)** and the **third impulse (drop)** in the beat noise is measured.



The time between **unlocking and drop** approximately corresponds to the period during which the **impulse pin (ellipse)** is in contact with the **pallet fork** – the so-called **lift time** of the balance.
A small deviation arises due to the brief interval between the escape wheel leaving the pallet fork and striking the banking pin; this is known as **lost motion**.

During the lift time, the balance rotates through the **lift angle λ**, which is defined by the movement's design and serves as a parameter for calculating the amplitude.
In most modern movements, the lift angle is approximately **51°**.

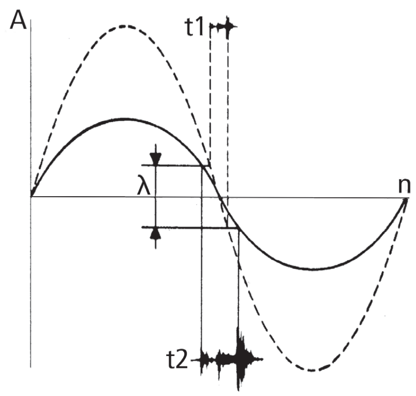
The lift time depends on the **speed of the balance at zero crossing**, which in turn is directly related to the amplitude:
→ the greater the amplitude, the higher the speed at which the balance passes through the lift angle, and the shorter the lift time.

To calculate the amplitude, it is assumed that the balance oscillation follows a **sinusoidal curve** – which holds true for a balance with a hairspring, provided that interference from the escapement is minimal.

The graph illustrates the momentary deflection over time:
– the **solid line** represents a low amplitude,
– the **dotted line** a high amplitude.

The lift angle **λ** is shown, assuming that the zero crossing occurs midway between unlocking and drop.

It is evident that the lift times differ for the two amplitudes:
→ **t_1** for the high amplitude is shorter than **t_2** for the low amplitude.



Under these assumptions, the amplitude A can be calculated from the lift time t, the lift angle λ, and the oscillation frequency f as:

$$A = \frac{\lambda}{2\sin(\pi f t)} \approx \frac{\lambda}{2\pi f t} \qquad (6)$$

.

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Measurement Parameters

Various parameters can be configured for **acoustic measurement**. Frequently used settings can be saved for quick access in the form of a **programme**. Depending on the device, between **20 and 99 programmes** can be stored and recalled as needed.

Beat Number Mode	Aut	Automatic selection from a predefined list of common beat numbers.
	Man	Manual input of any beat number between 3,600 and 43,200 A/h (up to 72,000 A/h on some devices).
	Frq	Automatic detection of an unknown beat number. The beat number is selected such that the calculated rate is close to 0 s/d.
Beat Number	nn	Numerical value of the beat number when Man mode is selected.
Test Mode	Stnd	Watch with Swiss Lever Escapement.
	Spe1	Watch with Co-Axial Escapement.
	Spe2	Watch with AP Escapement.
	Spe4	Mode with specific amplitude filter.
	Rate	Rate-only measurement (e.g. for pendulum clocks or watches with unusual beat patterns).
Lift Angle	xx°	Enter the lift angle, adjustable from 10° to 90°.
Measurement Time	xx s	Total duration of the measurement in seconds.
Integration Time	Aut	Time between updating the intermediate results Automatic selection of the integration time based on total measurement time.
	xx s	Manual entry of integration time in seconds.
	yy A/h	Manual entry of integration time in vibrations per hour
Stable. VV/HH	Aut	Automatic selection of Stabilisation Time based on beat number.
	Man	Manual setting of stabilisation time, between 1 and 99 seconds. → Applies to position changes within vertical positions (VV) or within horizontal positions (HH), where amplitude remains largely stable
Stable VH/HV:	Aut	Automatic selection of stabilisation time by beat number.
	Man	Manual setting of stabilisation time between 1 and 99 seconds. → Applies to position changes between vertical and horizontal orientations (VH/HV), where a drop or rise in amplitude is expected.
Resolution	s/d	Select the resolution for rate display, 1 s/d, 0.1 s/d, 0.01 s/d
Test Positions		Positions used during sequence measurement.
Signal		Signal amplification. The default value is 2. 1 for watches with very strong signals. 3 or 4 for watches with weak signals.

Optical Measurement with Laser

An alternative measurement method is based on **optical detection using a laser**. A laser beam is directed at a moving component, and a detector records the resulting changes in brightness caused by its movement.

Typically, a periodically moving part is targeted. If visible, the balance with its passing spokes is particularly well suited, as it enables direct amplitude measurement.
However, rate measurements can also be performed by tracking the motion of other components — for example, via the switching of the pallet fork or even by detecting the passage of a hand.

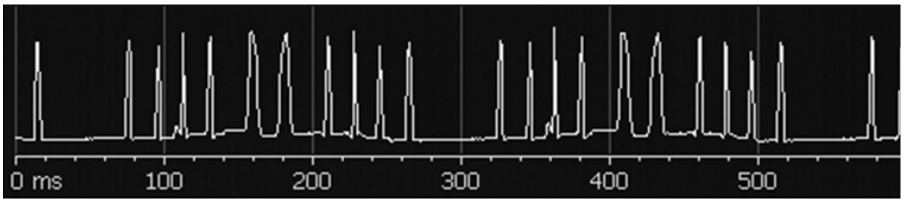
Figure: WisioScope S
Combined acoustic measurement of beat noise and optical laser-based measurement of the balance.

Optical Signal

The optical signal of the **WisioScope S** detects changes in brightness caused by the movement of a component illuminated by the laser. The signal quality therefore strongly depends on which component is targeted.

In the following, it is assumed that the balance is used as the reference and that the laser is aimed precisely at a location where only the spoke passages of the balance are detected.
This ensures that no signal components from the balance rim, pallet fork, or other moving parts are included.

Ideally, the signal appears as shown in the figure below, with each spoke passage clearly visible as a distinct deflection in the signal.



Rate Measurement (optical)

If periodic events can be identified in the optical signal, the **rate** can be calculated using the same method as for acoustic measurement:
The measured time between successive events is compared to a reference duration and converted into a **rate deviation**.

An alternative method uses the **autocorrelation** of the signal. Here, the time offset τ is determined at which the autocorrelation reaches its maximum.
Comparing τ with the nominal value allows the **rate deviation** to be calculated.

Amplitude (optical)

Measuring the amplitude requires a known and consistent signal structure with clearly identifiable features.
Only under these conditions can the amplitude be reliably determined using optical methods.

Measurement Parameters

Mode - Beat Number	Aut	Automatic selection from a list of common beat numbers.
	Manual	Manual entry of any beat number between 3,600 and 720,000 A/h.
Beat Number	nn	Numerical value of the beat number when manual mode is selected.
Test Mode	Off	No optical measurement
	balance wheel	Balance (oscillator) with visible spokes
	Test structure	Balance (oscillator) with applied artificial markings or line structure
	hands	Measurement based on a 1-second interval (e.g. for second hand detection)
	Asymmetrical	Balance with asymmetrically arranged spokes
Laser Position	x, y	Stepwise adjustment of the laser position in the X and Y directions

Optical Measurement with Camera

Hand Position

A direct method for determining the rate is to record the time displayed by the hands at fixed intervals — for example, every day at 12:00 noon. This allows the average daily rate deviation to be determined directly.

This method can be partially or fully automated:

- In a semi-automatic setup, a camera linked to a high-precision reference clock captures the images.
- In a fully automated system, image processing independently analyses the hand position and calculates the rate.

In its basic form, the measurement resolution is limited by the duration of a single vibration — assuming the seconds hand moves in discrete steps (saccades) corresponding to the beat rate.

For a typical watch running at 4 Hz (28,800 A/h), this yields a resolution of 3 s/d for a measurement duration of 1 hour, and 0.125 s/d for a 24-hour measurement.

To improve resolution, multiple images can be captured in rapid succession at each measurement point. This allows for a more precise determination of the exact hand movement timing.

Stroboscopic Effect

When an object undergoing periodic motion is illuminated by a stroboscope, its movement appears to slow down. The apparent frequency is the difference between the stroboscope frequency and the object's actual frequency.
If the object appears stationary, the two frequencies are either identical or harmonically related (i.e. the object's frequency is a multiple of the stroboscope frequency).

This effect enables highly accurate frequency comparison.

Instead of a stroboscope, a camera with sufficiently short exposure time can also be used.
In the Witschi WisioScope S, the image capture rate is automatically calculated based on the specified beat number, allowing the motion of the balance to be displayed in slow motion.

High-Speed Camera

A high-speed camera captures images at a high frame rate, enabling precise analysis of very short time intervals. This makes it possible, for example, to visualise the complete escapement sequence from unlocking to drop in detail.

For longer-term analyses — such as determining the average daily rate deviation — the required image processing effort increases significantly, since a large volume of image data must be handled.

.

Presentation of Results

Witschi devices present measurement results in a **graphical and user-friendly format**.
This chapter explains several display modes and their specific advantages for analysing watch performance.

Diagram (DIA)

The diagram shows a continuous recording of the beat noise and is particularly well suited for **regulation**, as every adjustment becomes visible in real time.

Each beat is represented by a point on the diagram. The time between two successive beats (i.e. the half-period duration) is measured and compared with the theoretical target value for an exact rate.
If the measured time matches the target, the new point appears **horizontally aligned** with the previous one.
If the beat occurs slightly earlier or later, the point is shifted **upwards or downwards** accordingly.
These points typically form a continuous line that reflects the rate behaviour.

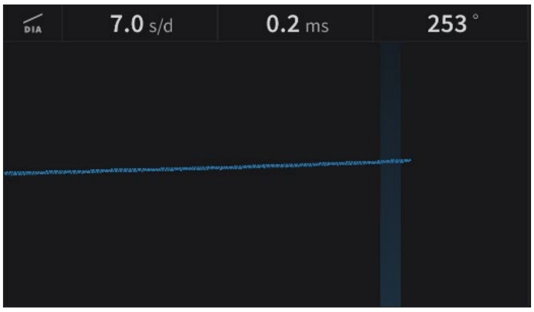
The **slope of the line** corresponds to the **rate deviation**:
an ascending line indicates a gain, while a descending line indicates a loss.

Occasionally, **two parallel lines** appear (as in Example 2), which indicates a **beat error** — that is, a difference between the two half-period durations (TIC and TAC).

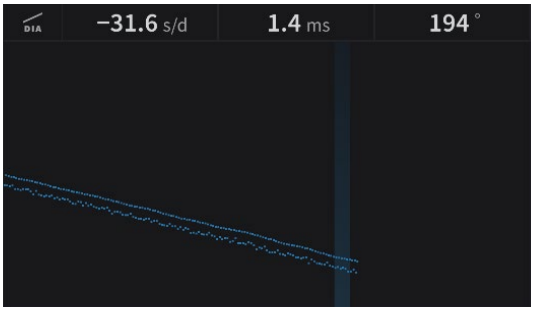
Individual **points above the line** indicate irregularities in the detection of the unlocking. Possible causes include a defective escape wheel tooth, premature noise (e.g. contact between the hairspring and the regulator), or external interference.
If such points occur frequently above the line, it is advisable to reduce the signal amplification.

Individual **points below the line** suggest that unlocking noises were not detected.
If these occur repeatedly, the signal amplification should be increased.

Example 1: Regular diagram
Slight gain, consistent over time. Virtually no beat error.



Example 2: Irregular diagram
Loss, fluctuating over time. Significant beat error.



Further examples can be found in the section “Fault Diagnosis Using the Diagram”.

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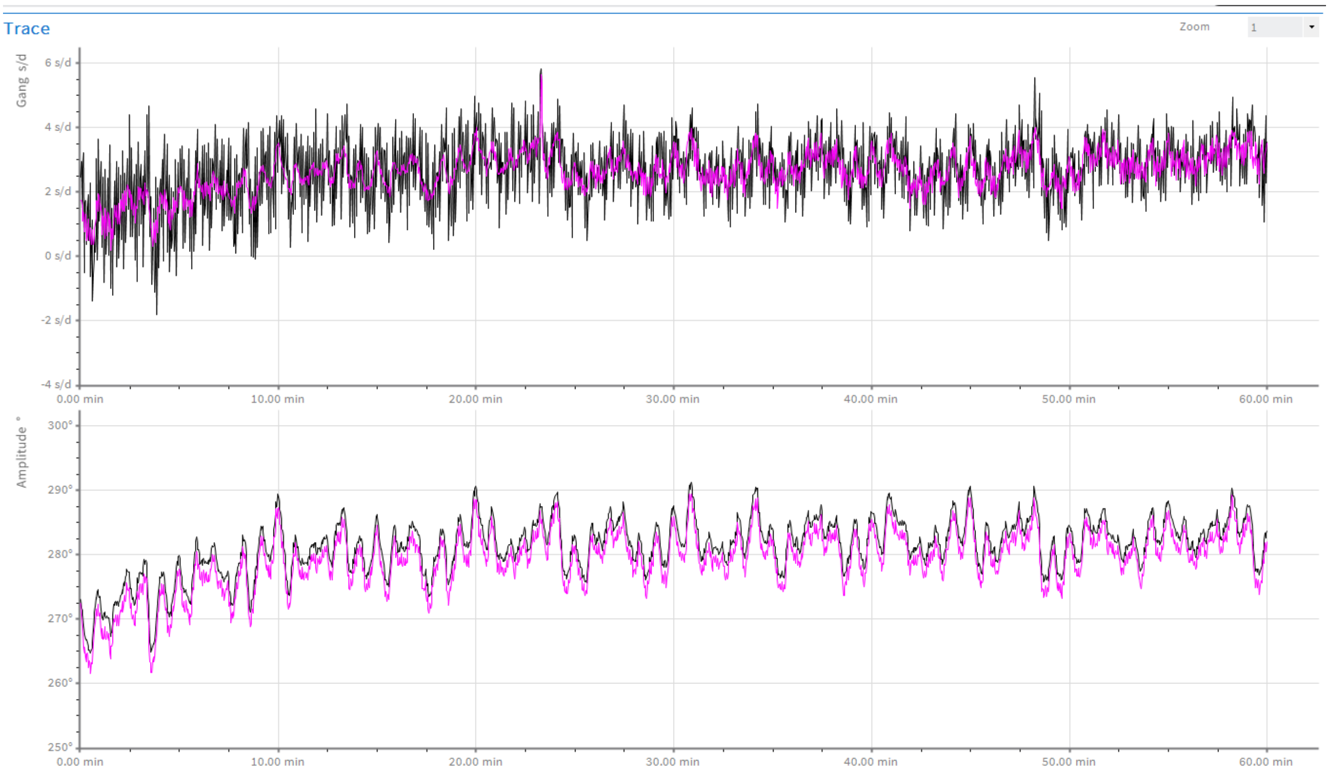
Trace (TRC)

The **trace view** shows the time-based progression of **rate and amplitude variations** over an extended period and is used to assess the stability of a movement.
Measurement durations of up to **300 hours** are possible.

The integration time – i.e. the interval between two data points – ranges from 2 to 60 seconds and is usually determined automatically based on the total measurement time.

For laboratory applications, an integration time of 4A can be selected, where one data point is recorded every 4 vibrations. In this mode, the total measurement duration is typically limited to 8 minutes on most devices.



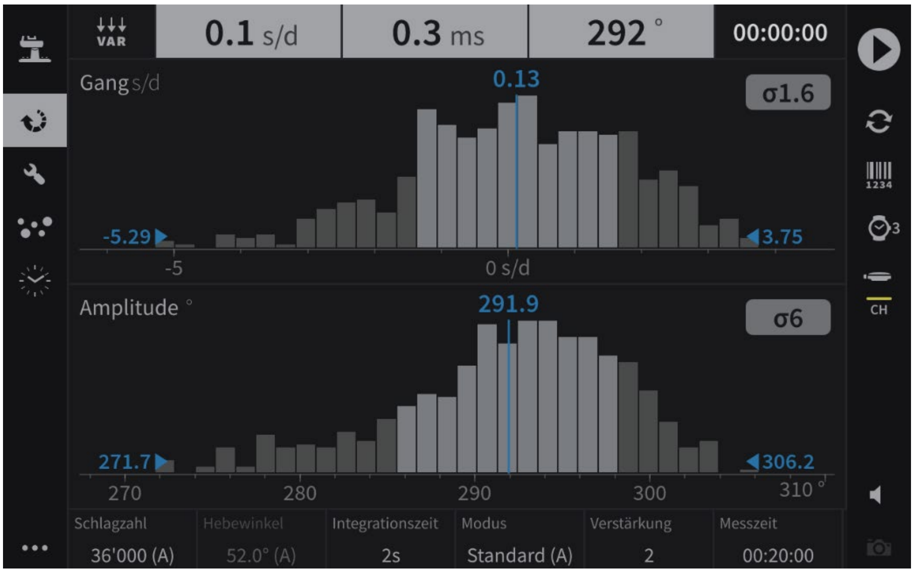
In the example shown, the amplitude increases during the first 10 minutes, accompanied by a slight increase in rate.
As the measurement continues, periodic fluctuations appear — caused by variations in driving force at the escape wheel.

Vario (VAR)

The Vario mode visualises the measurement results over a period of up to 300 hours using a **histogram of the distribution function**.
This display does not allow direct interpretation of time but provides a clear overview of the distribution of the measured values.

The **most frequent value**, the **mean value**, the **minimum**, and the **maximum** can be seen at a glance.

The histogram facilitates the identification of **rate variations** over longer time periods. In addition, the **standard deviation (σ)** is displayed to assess the stability of the measurement results.



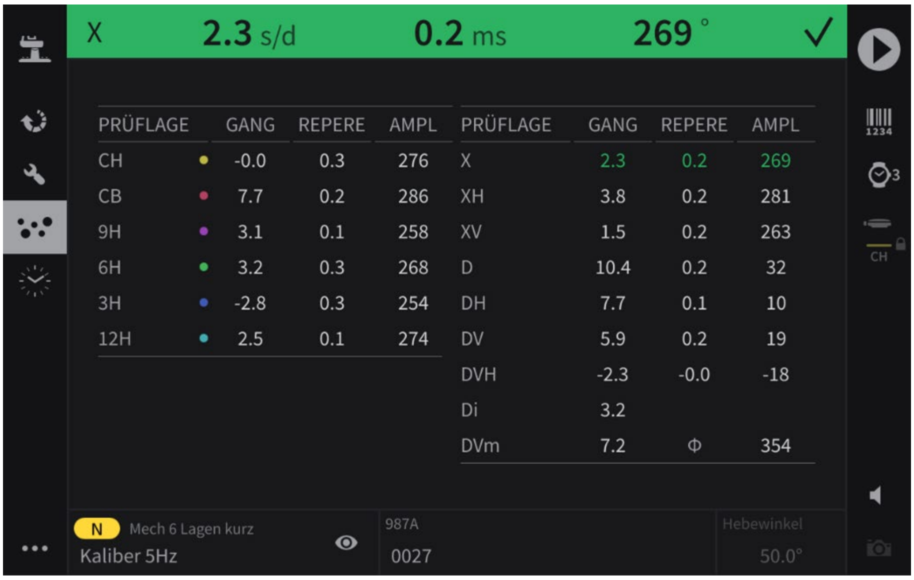
Vario mode is particularly suitable for detecting systematic deviations caused by changes in driving force, friction effects, or lubrication conditions, without the need to analyse individual measurement times.

Sequence (SEQ)

Mechanical watches are measured in different test positions to assess their rate accuracy and stability under realistic wearing conditions.

Reasons for measuring in multiple test positions (sequence mode):

- Influence of gravity
  The balance and escapement system are affected differently by gravity depending on whether the watch is lying horizontally (dial up/down) or held vertically (e.g. crown left/right). This can result in rate deviations between position.
- Imbalance of the balance
  Even precisely manufactured balance wheels may exhibit slight imbalance, which affects the rate differently depending on the position of the watch.
- Friction in the jewels
  Friction in the balance bearings varies with the position of the watch, leading to changes in both amplitude and rate accuracy.
- Practical rate evaluation
  Since a watch constantly changes position while worn on the wrist, measurement in multiple test positions enables a realistic assessment of the average timekeeping accuracy.
- Quality control and regulation
  High-quality watches are regulated in multiple test positions to achieve the most consistent rate performance possible across all positions.



Typical test positions are:

Dial up (CH), dial down (CB)
Crown down (9H), crown left (6H), crown up (3H), crown right (12H)

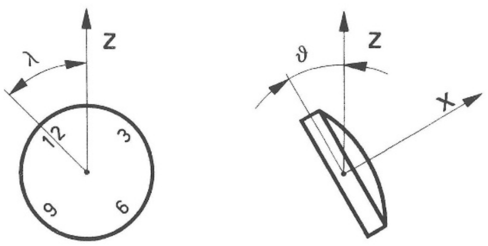
Regulation in the three main test positions — CH, 9H, and 6H — ensures realistic rate stability, as these positions represent the most common orientations during wear and are critical for actual timekeeping performance in daily use.

With microphones that support automatic test position changes (e.g. *ChronoMaster Auto*), the measurements are performed automatically, and the results from all test positions are compiled and displayed together.

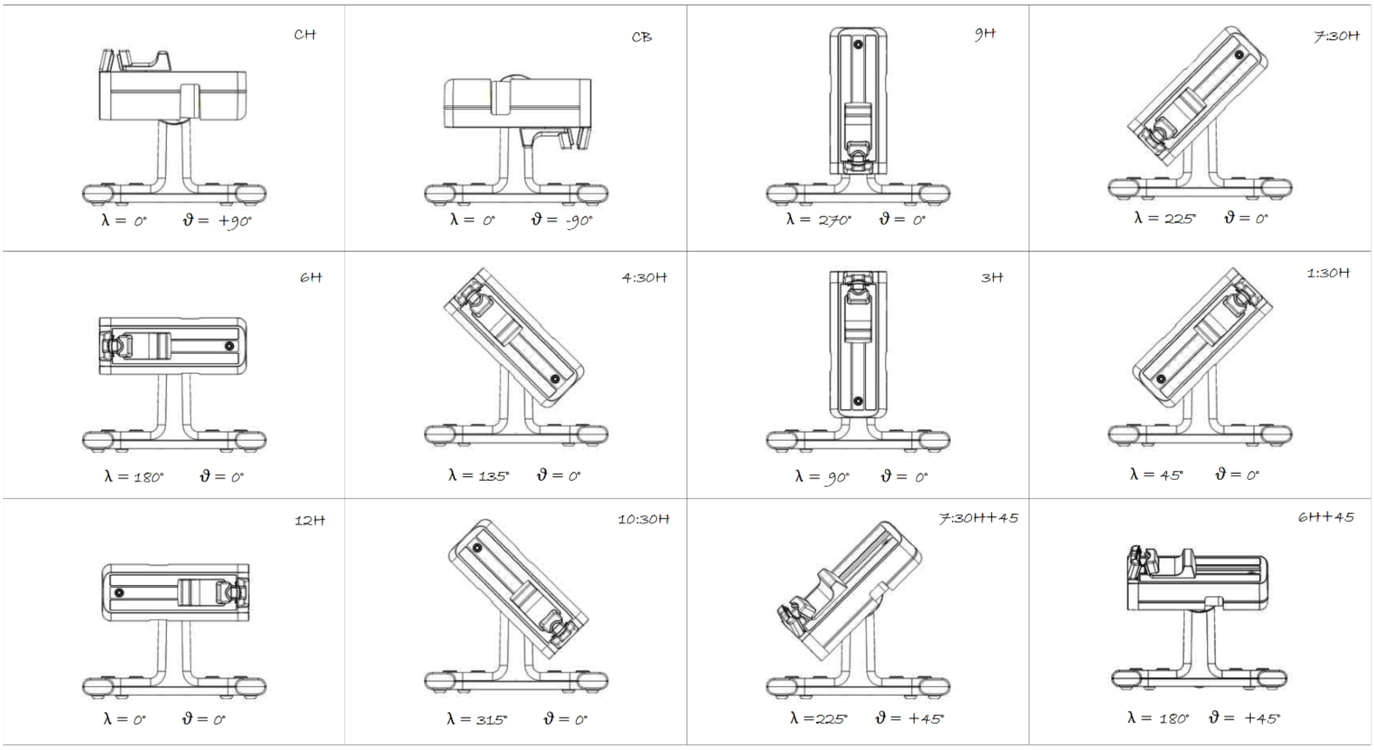
For microphones with **manual test position change** (e.g. *ChronoMaster*), a sequence mode is available in some cases. In this mode, the device prompts the user to change the test position and automatically detects when the new position has been reached, at which point the next measurement starts.

When using ChronoMaster devices in combination with **Wicotrace 360°**, mechanical watches can be tested in freely definable test positions.
For each position, the **rotation angle** (**λ**, lambda) and the **tilt angle** (**ϑ**, theta) are defined, enabling a comprehensive analysis of the watch's performance in various spatial orientations.

The flexible combination of these two angles allows any conceivable test position to be defined — from classical orientations such as dial up (CH) or crown down (9H) to customised special positions.



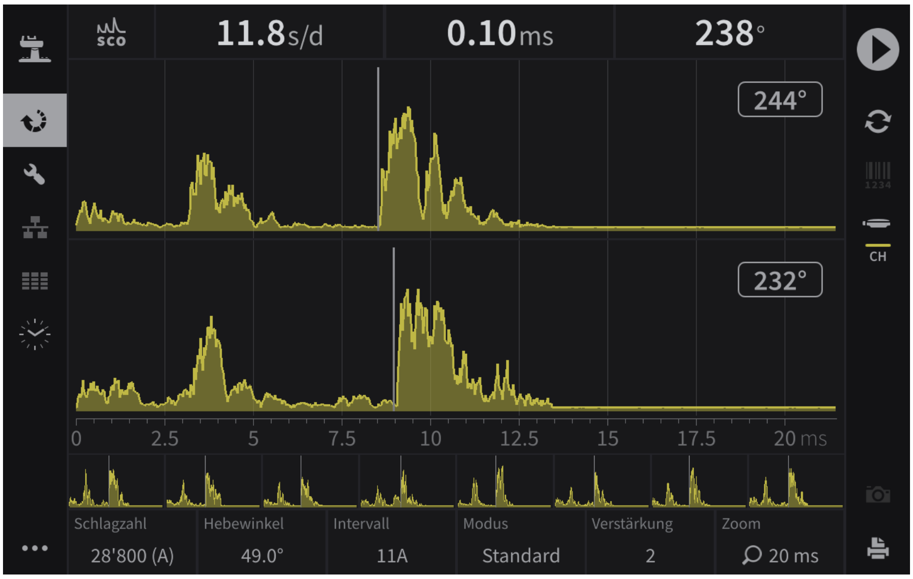
The figure below shows 12 typical test positions used in the watch industry for quality control.



λ = rotation angle ϑ = tilt angle

Scope (SCO)

The graphical representation of the beat noise in scope mode shows two pulses — one for the TIC vibration and one for the TAC vibration. The display can be set to time intervals of 20, 200, or 400 milliseconds, with 20 ms as the default setting.



The scope enables detailed analysis of beat noise by recording the acoustic signals at defined intervals. In the example shown, the display is updated every 11 vibrations (11A), allowing periodic patterns and deviations to be precisely identified and analysed.

The scope is also used to verify device settings, ensuring that signal intensity and signal quality are sufficient for accurate and reliable measurement.

For each vibration, the corresponding amplitudes are displayed alongside the beat noises. The amplitude is calculated based on the time interval between the first and third pulses in the beat noise.
These pulses are highlighted with vertical markers and serve as references for determining the exact vibration amplitude.

Additionally, the last 8 beat noises are displayed in a small preview band beneath the current signal.
After stopping the measurement, any of these previous beat noises can be enlarged by clicking on the corresponding preview image.

Further examples of fault analysis using the scope view can be found in the section “Fault Detection with Scope”.

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Fast Fourier transform (FFT)

The **FFT display** (Fast Fourier Transform) calculates the **frequency spectrum** based on the recorded **rate** and **amplitude** values and presents it graphically. This allows **periodic fluctuations** to be detected that would otherwise remain barely visible in conventional time-based displays.

Such periodic deviations are often caused by **mechanical influences within the gear train**, particularly by the way the gears mesh with one another. Each meshing produces slight variations in torque — typically around 5 to 10%. Across multiple gear stages, this can result in amplitude variations of up to 30°. These effects are design-related and are generally considered normal.

FFT analysis makes such influences visible by decomposing the measurement data into its individual frequency components – much like a musician breaks down a chord into its individual notes.

An example from WiCoTRACE 3 shows 15 distinct periodic components identified during an amplitude measurement conducted over several hours.

The display is particularly useful for:

- Identify regular fluctuations in rate or amplitude
- Detecting **irregularities** in **gear meshing** or **power transmission**
- Assessing the quality of the gear train, for example in the case of **tooth profile errors** or **frictional issues**.

The FFT display is therefore an efficient tool for watchmakers to analyse rate variations in a targeted manner and to uncover their mechanical causes.

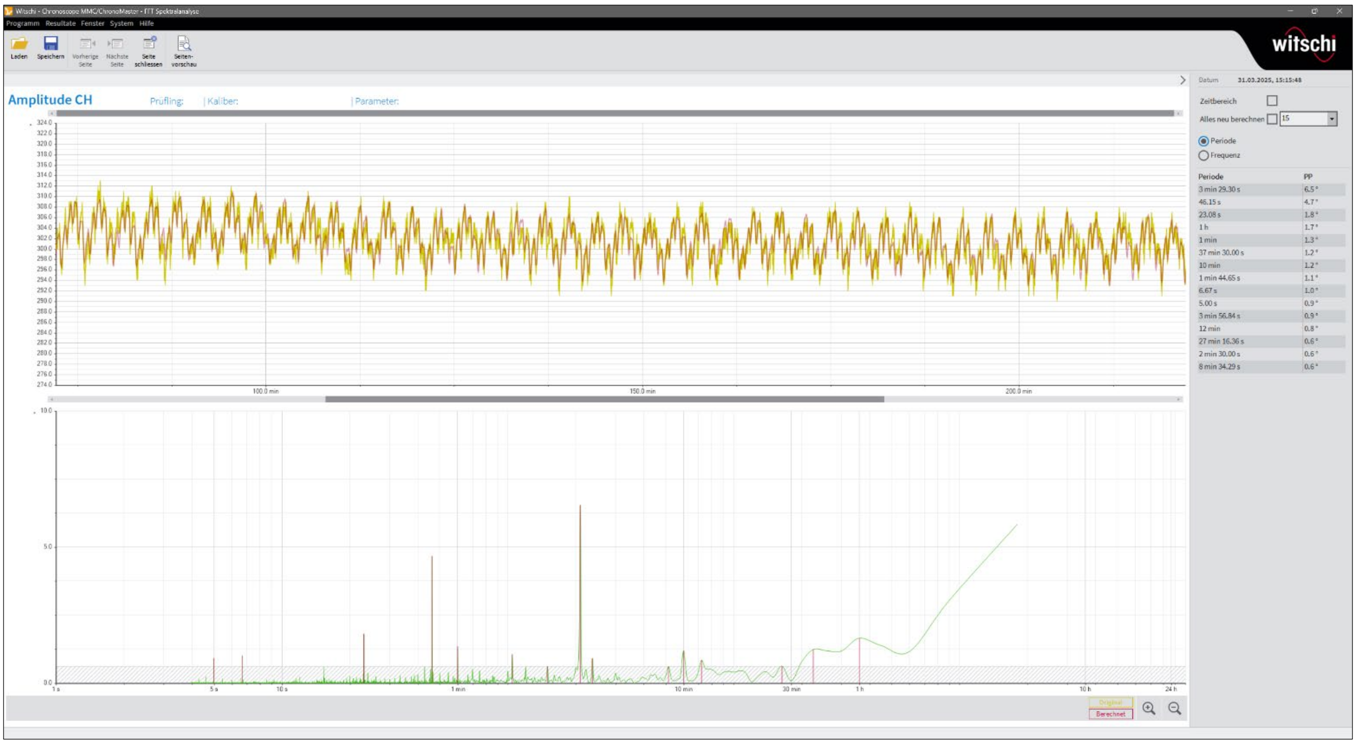

Figure: FFT representation showing 15 periodic components detected during several hours of amplitude measurement in WiCoTRACE 3.

Isochronism (ISO)

The isochronism of an oscillating system consisting of the balance wheel and hairspring refers to the property that the **oscillation period of the balance wheel remains constant, regardless of the amplitude.**

In an **ideal isochronous system**, the balance oscillates with the same period whether the amplitude is large or small.
In practice, however, isochronism is affected by several factors, including:
– the **elasticity** of the hairspring,
– **clearance** in the regulator pins,
– **frictional forces**, and
– **air turbulence** around the oscillating system.

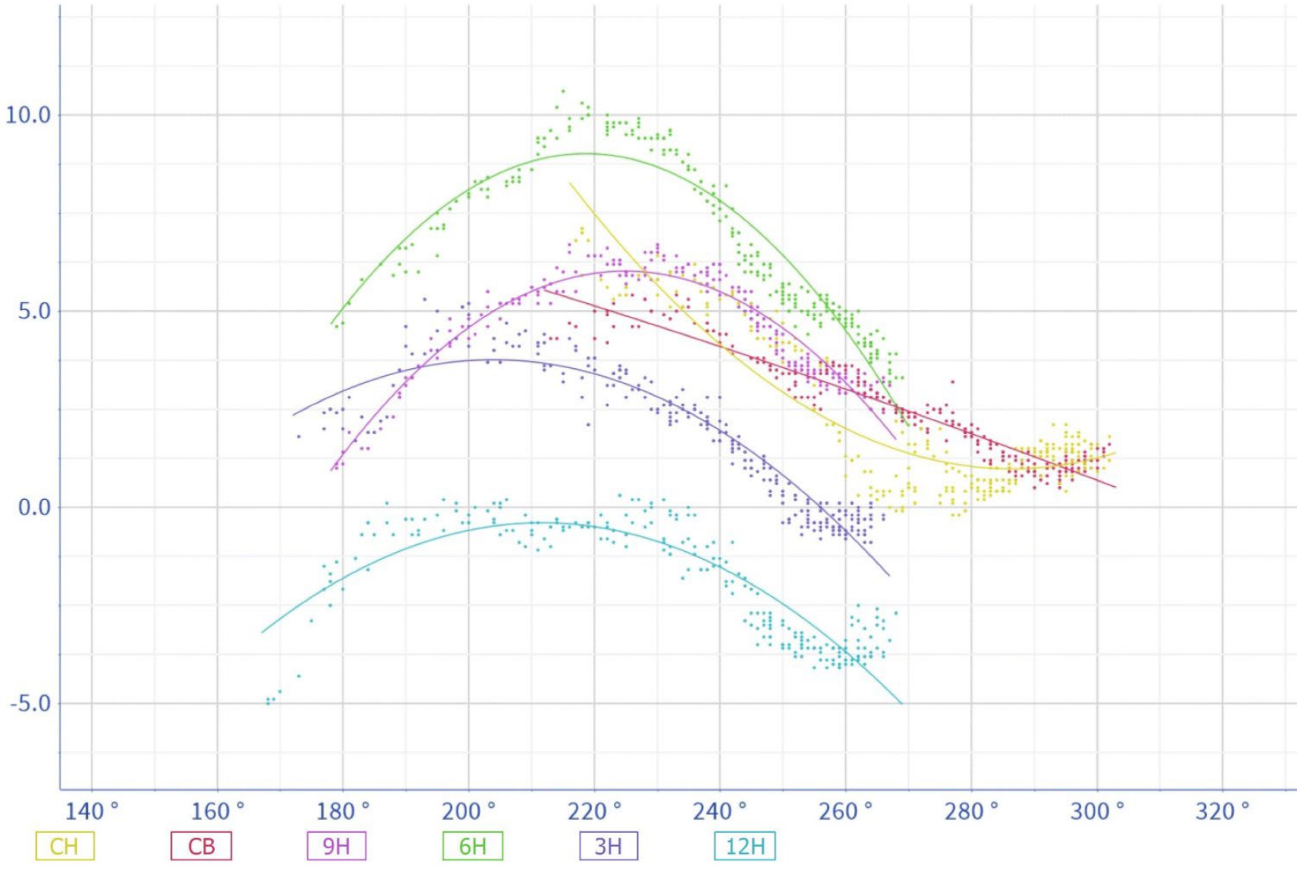

Figure: Isochronism diagram in WiCoTRACE 3

An **isochronism diagram** displays the rate deviation as a function of amplitude and is used to analyse the rate stability across different oscillation amplitudes.
Ideal isochronism is characterised by a constant rate, independent of amplitude changes.

This representation enables a precise evaluation of the isochronal behaviour and helps identify optimisation potential in the regulation and design of the movement.

Calculated Characteristic Values

In addition to various graphical display options, a wide range of **characteristic values** can be calculated from the measurement data. These parameters provide a compact, objective, and comparable assessment of the time- and position-dependent behaviour of a mechanical movement.

The standardisation of these values enables test results to be evaluated efficiently and compared across different watches or test conditions.

To illustrate how these parameters are calculated, a consistent numerical example is used in the following sections. It is assumed that a mechanical watch movement has been measured in **six defined test positions**, both in the fully wound state (0h) and after 24 hours of running (24h). The measurement results include the rate variation (in s/d), the beat error (in ms) and the amplitude (in degrees):

	Results 0h			Results 24h		
Test position	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)
CH (HH)	9.1	0	298	8.6	0.0	298
CB (HB)	10	0.0	294	11.7	0.0	286
9H (VB)	8.3	0.1	287	11.2	0.1	264
6H (VG)	3.2	0.1	283	2.6	0.1	268
3H (VH)	7.2	0.1	287	6.7	0.1	275
12H (VD)	11.2	0.1	278	11.1	0.1	279

This dataset serves as the reference for the definition and calculation of all characteristic values presented in the following sections of this document.

Mean Value (X)

The characteristic value X represents the arithmetic mean of the measured rate values G_i across all test positions, both horizontal and vertical:

(7)

$$X = \frac{1}{N}\sum_{i=1}^{N} G_i$$

	Results 0h			Results 24h		
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)
XH	9.6	0.0	296	10.2	0.0	292
XV	7.5	0.1	284	7.9	0.1	272
X	8.2	0.1	288	8.7	0.1	278

XH: Average value of all horizontal test positions.

XV: Average value of all vertical test positions.

Maximum Difference Between Test Positions (D)

The characteristic value **D** represents the **largest difference** between the measured values across the individual test positions. It provides insight into the positional dependence of the movement.

	Results 0h			Results 24h		
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)
D	8.0	0.1	20	9.1	0.1	34

DV: Maximum difference between all measured vertical test positions.
DH: Maximum difference between all measured horizontal test positions.

Difference Vertical to Horizontal (DVH)

The characteristic value **DVH** describes the **difference between the mean values** of the **vertical** and **horizontal test positions**.

	Results 0h			Results 24h		
Characteristic	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)
XV	7.5	0.1	284	7.9	0.1	272
XH	9.6	0.0	296	10.1	0.0	292
DVH	-2.1	0.1	-12	-2.2	0.1	-20

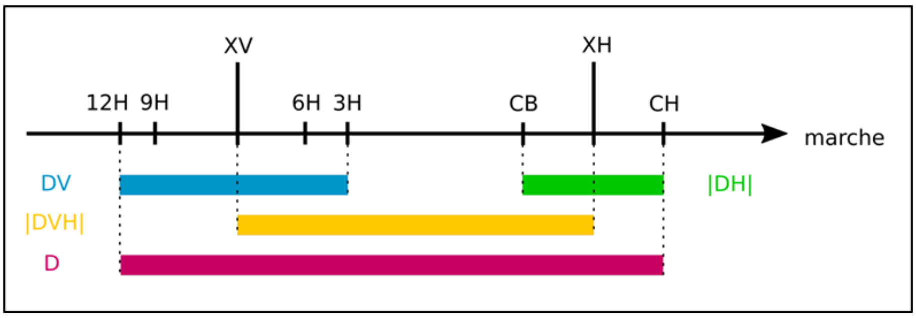

Figure: Visualisation of possible characteristic values XH, HV, DH, DV, DVH and D

Difference Between Test Positions 6H and CH (Di)

The characteristic value **Di** represents the **rate difference** between the test positions **6H** (vertical, crown left) and **CH** (horizontal, dial up). It corresponds to a comparable parameter defined as **criterion D** in the **COSC** standard ISO 3159, but refers to a short-term measurement rather than a multi-day test.

	Results 0h			Results 24h		
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)
Di	-5.9			-6.0		

Isochronism

Isochronism refers to the difference in rate between 0 hours (fully wound) and 24 hours (or after a defined running time *Nh*) in the same test position.
This is a single measured value and must be distinguished from the graphical isochronism representation, in which the rate variation is plotted as a function of amplitude (see, for example, the diagram on page 25).

	Results 0h			Results 24h			
Test position	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)	Isochronism (s/d)
CH (HH)	9.1	0.0	298	8.6	0.0	298	0.5
CB (HB)	10.0	0	294	11.7	0.0	286	-1.7
9H (VB)	8.3	0.1	287	11.2	0.1	264	-2.9
6H (VG)	3.2	0.1	283	2.6	0.1	268	0.6
3H (VH)	7.2	0.1	287	6.7	0.1	275	0.5
12H (VD)	11.2	0.1	278	11.1	0.1	279	0.1
X	8.2	0.1	288	8.7	0.1	278	

Maximum Isochronism Across the Measured Test Positions (Im)

The isochronism characteristic value Im (or $\boldsymbol{I}_{max}$) denotes the **maximum isochronism value**, i.e. the **largest rate difference** between **0 h** and **24 h** observed in any **individual test position**.

	Results 0h			Results 24h			
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)	Isochronism (s/d)
Im							-2.9

Im takes into account the **test positions defined by NIHS 93-10** (excluding **12H**), whereas **Im*** includes **all measured test positions**.

Isochronism Between 0h and 24h (Ie)

The characteristic value **Ie** describes the **stability of the rate** of a watch movement as a function of its **winding state**.
It is calculated as the **absolute difference** between the **mean rate** across all six test positions at **0h (fully wound)** and at **24h**:

(8)
$$Ie = Abs(X0h - X24h)$$

This value (expressed in s/d) indicates how much the rate accuracy changes over time and serves as a measure of the isochronism performance of the movement.

	Results 0h			Results 24h			
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)	Isochronism (s/d)
Ie							0.5

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Difference Between the Mean Values at 0h and 24h (DX)

The characteristic value DX indicates the **difference between the average values** at **0 h** (fully wound) and after **24 hours of running**. It is calculated separately for rate, beat error, and amplitude.

	Results 0h			Results 24h		
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)	rate (s/d)	beat error (ms)	amplitude (°)
X	8.2	0.1	288	8.7	0.1	278
DX				-0.5	0.0	10

The DX value provides information about how the mean rate, beat error, and amplitude of the movement have changed over the course of 24 hours.
In contrast to the isochronism value **Ie**, which uses the **absolute difference**, DX preserves the **direction of change**, making it particularly useful for identifying systematic trends (e.g. gain or loss over time).

Difference Between Complication On and Off (DXC)

The characteristic value DXC indicates the difference between the average values of rate, beat error, and amplitude measured with the complication activated (e.g. chronograph running) and with the complication deactivated.
It provides insight into the influence of additional mechanisms on the performance of the movement.

Maximum Rate Difference Across All Test Positions (Pmax)

Pmax denotes the largest rate difference observed between all measured test positions at 0 h (fully wound).
This characteristic value is functionally equivalent to D at 0 h and provides a measure of the positional sensitivity of the movement at full power reserve.

	Results 0h		
Characteristic value	rate (s/d)	beat error (ms)	amplitude (°)
Pmax	8		

Quality Factor (N)

(Also corresponds to the functional index **Fm** according to standard NIHS 93-10)

The **quality factor N** is a **standardised parameter** for evaluating the **chronometric performance** of a watch movement.
It takes into account deviations in rate, positional behaviour, and isochronism.
The smaller the value of N, the better the overall performance of the movement in terms of precision and positional stability.

(9) $$N = 0.15\,|I_{\max}| + 0.1\,P_{\max} + C$$

C represents the **thermal coefficient** and is determined in test position 6H at a temperature of 38 °C.
If no measured value is available, the maximum thermal coefficient guaranteed by the hairspring manufacturer should be used. For example, for quality grade 1, the standard value is: C = 0.6.

N = 0.15 |-2.9| + 0.1 * 8.0 + 0.6 = 1.8

N takes into account the test positions defined by NIHS 93-10, while N* includes all measured test positions.

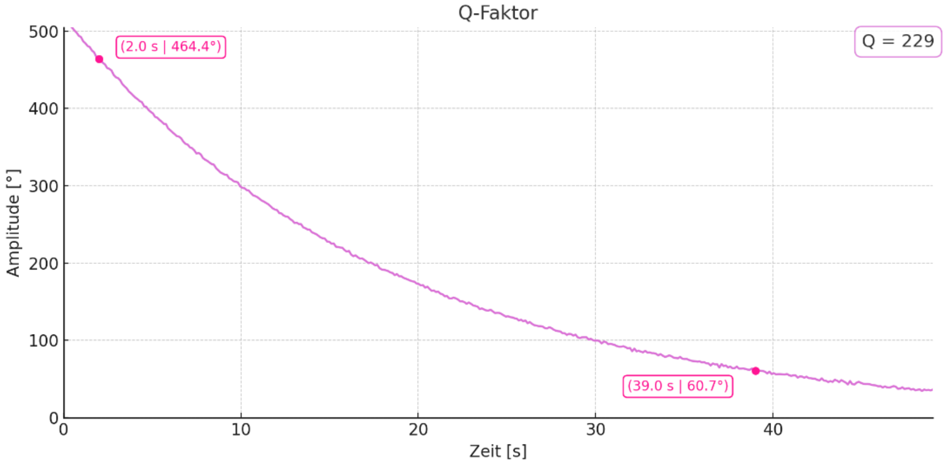
Quality Factor (Q)

The **quality factor (Q factor)** expresses how efficiently a balance with hairspring oscillates. It describes the ratio between stored energy and energy loss per oscillation.
A higher Q factor means that the oscillation is sustained longer, as less energy is dissipated, resulting in a more stable amplitude and improved rate accuracy.

Watchmakers can optimise the Q factor by minimising friction losses or increasing the oscillation frequency.

With **WisioScope Labor**, the Q factor can be measured by recording the amplitude decay over time and analysing the rate of decline.

Q-factor measurement procedure:
- **Remove the pallet fork** and place the watch movement in a stable test position.
- **Manually deflect the balance** and allow it to oscillate freely without impulse
- The **Q factor is calculated** automatically by the software based on the decay rate of the amplitude over time.



Typical **Q factors** for **freely oscillating balance wheels** in mechanical watch movements range from **150 to 300**, depending on factors such as **design**, **bearing quality**, **lubrication**, and **air pressure**.

Typical quality factors are:

Oscillator type	**Q**
Standard mechanical watch	150 ... 300
Very high-quality mechanical watches	300 ... 600
Tuning fork watch	1,000 ... 2,000
Pendulum clock	3,000 ... 15,000
Quartz oscillator TCXO	10^4 ... 10^5
Quartz oscillator OCXO	10^4
Rubidium oscillator	10^7
Cesium beam atomic clock	10^8
Hydrogen maser	10^9
Cesium fountain atomic clock	10^{10}

Centre of Gravity Error (DVm, Φ)

If the **centre of gravity** of the oscillating system (balance and hairspring) does not lie on the axis of rotation, it can have an **accelerating or decelerating effect** on the oscillation frequency. This effect depends on the test position and the amplitude.

By measuring the rate variation in four vertical test positions, it is possible to calculate the centre of gravity error and derive the corresponding corrective measures.

Assuming that the observed differences are caused exclusively by the centre of gravity error, the following formulas can be applied.

First test position:	$\varphi_1 = 0°$	$\mu_1 = \mu_0 + MgaG(\Theta_0)\cos(\phi_0 + \beta)$
Second test position:	$\varphi_2 = 90°$	$\mu_2 = \mu_0 - MgaG(\Theta_0)\sin(\phi_0 + \beta)$
Third test position:	$\varphi_3 = 180°$	$\mu_3 = \mu_0 - MgaG(\Theta_0)\cos(\phi_0 + \beta)$
Fourth test position:	$\varphi_4 = 270°$	$\mu_4 = \mu_0 + MgaG(\Theta_0)\sin(\phi_0 + \beta)$

The amount of material to be removed is

$$Mga = \frac{2}{|G(\Theta_0)|}\sqrt{(\mu_1 - \mu_3)^2 + (\mu_4 - \mu_2)^2}$$

Where

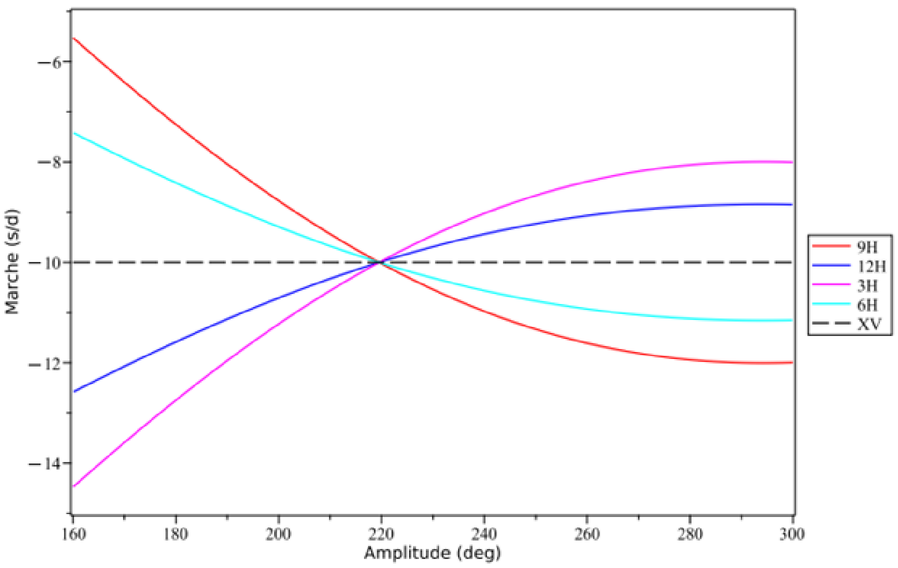
$$G(\Theta_0) = \frac{86\,400}{J_b\omega_0^2}\frac{J_1(\Theta_0)}{\Theta_0}$$

J_b is the moment of inertia of the balance wheel, J_1 is the Bessel function, ω_0 is the angular frequency and Θ_0 is the amplitude of the balance wheel.

The direction of the centre of gravity error relative to the first test position is:

$$\tan(\phi_0 + \beta) = \frac{\mu_4 - \mu_2}{\mu_1 - \mu_3}$$

The influence of a centre of gravity error is greatest at low amplitudes. As the amplitude increases, the effect diminishes and disappears around 220°. At even higher amplitudes, the influence reverses direction, albeit in a weakened form.



If the moment of inertia of the balance wheel is not known, the centre of gravity error can be described by the maximum resulting rate difference, which is referred to as DVm.

DVm represents the **theoretical maximum rate deviation** caused by the centre of gravity error of the balance wheel at an amplitude of **270°** in the vertical positions.

The angle **Phi (Φ)** indicates the rotational position of the winding stem (relative to the 3H position) at which the centre of gravity error reaches its lowest point in the vertical plane.

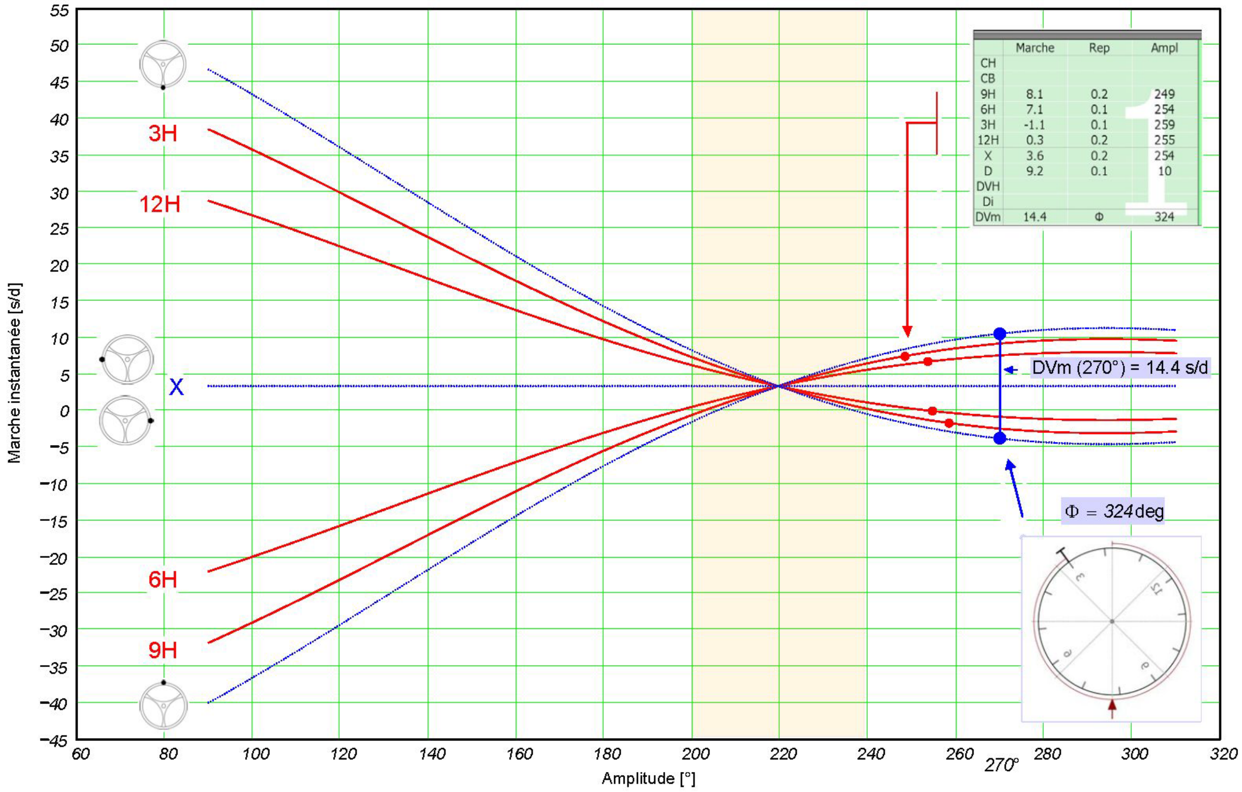


Figure: Example showing how the characteristic values **DVm** and **Phi (Φ)** are determined based on the **rate** and **amplitude** measurements from the four **vertical test positions**..

In **sequence mode** (e.g. on the **Witschi Terminal**), the characteristic values **DVm** and **Phi (Φ)** are automatically calculated from the measured values of the **vertical test positions** and displayed in a **summary table**.

PRÜFLAGE	GANG	REPERE	AMPL	PRÜFLAGE	GANG	REPERE	AMPL
CH	-0.0	0.3	276	X	2.3	0.2	269
CB	7.7	0.2	286	XH	3.8	0.2	281
9H	3.1	0.1	258	XV	1.5	0.2	263
6H	3.2	0.3	268	D	10.4	0.2	32
3H	-2.8	0.3	254	DH	7.7	0.1	10
12H	2.5	0.1	274	DV	5.9	0.2	19
				DVH	-2.3	-0.0	-18
				Di	3.2		
				DVm	7.2	Φ	354

Witschi Measurement Tips

To ensure **precise** and **repeatable** measurement results, certain measurement conditions must be met.
This chapter outlines the recommended **measurement procedures**, explains **factors that influence accuracy**, and summarises the **general influences** on the oscillation period of the balance wheel.

Test Procedure for Accuracy Measurement and Quality Control	Explanations
Check the condition of the watch movement	Ensure cleanliness, evaluate lubrication condition, inspect mechanical components. If necessary: perform a complete service.
Wind the movement	Wind the crown approx. 0 – 30 times to ensure sufficient mainspring tension.
Let the movement run in	Allow approx. 20 minutes of running time before measurement to stabilise the rate. This helps to obtain a regular diagram.
Avoid setting hands near midnight	Date switching may affect measurement accuracy during this time.
Set the crown to the zero position	In the pulled-out position, the movement may be stopped. Always measure with the crown pushed in.
Demagnetise (if required)	Use a suitable device (e.g. *Witschi Teslascope*) to eliminate magnetic interference that can impair rate accuracy.
Set measurement parameters	Per test position: 20 s stabilisation time and ≥40 s measurement time for stable results.
Start in horizontal position (CB)	Perform the first measurement dial-down (CB).
Adjust the movement	Adjust the beat error for symmetrical oscillation; fine-tune the rate for desired accuracy.
Run full measurement sequence	Measure in all six positions: Horizontal (CH, CB), then vertical (9H, 6H, 3H, 12H). Start with horizontal to reduce stabilisation time.
Readjust if necessary	Make corrections based on sequence results to optimise rate accuracy.
Check calendar and hands	Functional test of date change and correct hand setting.
Test automatic winding / wear simulation	Use wear simulator (e.g. *Cyclomat*) for automatics; wind manual watches manually.
Final 24h check	After 24 h: verify rate, time and date display, and perform final function check.
(Optional) Power reserve check	Note the start time, allow the watch to run until it stops, and measure the elapsed time.

Standard Tolerances

The following table shows **typical measurement ranges** for **well-functioning, fully wound** mechanical watch movements. Please note that these values may **vary depending on the manufacturer** and movement design.

Watch Category	Rate [s/d]	Amplitude (H)	Amplitude (V)	Beat Error
Women's watch (small diameter)	-5 ... +25	260° ... 320°	240° ... 280°	< 0.5 ms
Men's watch	-5 ... +15	"	"	"
COSC chronometer (< 20 mm diameter)	-5 ... +8	"	"	"
COSC chronometer (> 20 mm diameter)	–4 ... +6	"	"	"
METAS-certified chronometer	0 ... +5	"	"	"

Typical Values of the Power Reserve

Watches Category	Power Reserve
Standard watches (single barrel)	38 – 48 hours
High-quality manufacture movements	60 – 75 hours
Extended power reserve (e.g. optimised or double barrel)	5 – 8 days

Factors Influencing the Oscillation Period of the Balance Wheel

Factor	Influence
Friction	Bearing friction, air resistance, condition and ageing of lubricants
Escapement	Impulse efficiency, escapement error
Vibrations	Shocks, impacts, external mechanical vibrations
Imbalance of the balance wheel	Uneven mass distribution, geometric asymmetries
Imbalance of the pallet fork	Manufacturing tolerances, uneven weight distribution
Imbalance of the hairspring	Spiral asymmetries or eccentricity
Play between regulator pins	Asymmetrical limitation of hairspring deflection
Elasticity variation in the hairspring	Due to material ageing or temperature-dependent changes
Temperature fluctuations	Affect spring elasticity and oil viscosity
Centrifugal forces	Due to strong wrist movements
Inertia of the hairspring	Dynamic deformation effects at high frequencies
Air pressure fluctuations	Affect air resistance on the balance
Magnetic fields	Magnetisation of components, especially hairspring
Electrostatic fields	Interaction with non-conductive materials (e.g. plastic holders)

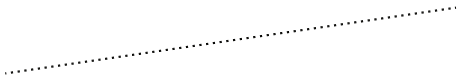
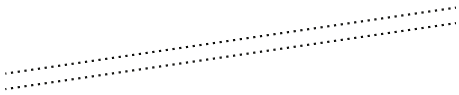
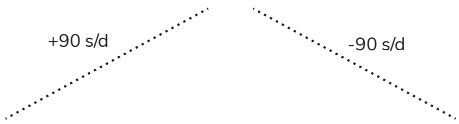
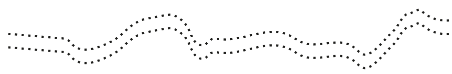
Note: This list is not exhaustive and serves as a general overview of the most relevant factors affecting the oscillation period of the balance wheel.

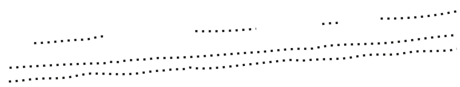
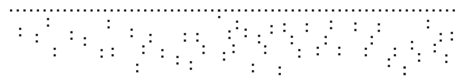
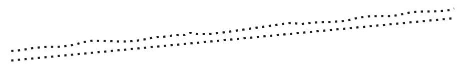
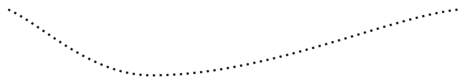
Fault Detection

The **graphical representation of the beat noises** enables detailed analysis of the **escapement condition**.
The unlocking behaviour and its timing can be visualised using the **diagram**, while the shape of an individual beat noise is displayed in the **scope**.
The following section explains how to interpret these displays and outlines possible causes of irregularities.
Note: The listed examples are not exhaustive. Similar or identical display patterns can result from a wide range of mechanical issues.

Fault Finding with Diagram

Signal amplification setting: Default value is **2**.
If no clear diagram appears, the **signal gain** on the measuring instrument must be **increased or reduced**, depending on the signal strength of the watch.

Fault	Description	Image
Watch movement in good condition	No action required.	
Beat error too large (approx. 3 ms)	First check the amplification setting on the measuring instrument. If no effect is visible, adjust the watch: correct the beat error (repère) first, then adjust the rate.	
Rate deviation – adjustment required	Watch movement on the left: strong gain; on the right: strong loss. Adjust the rate to the desired target value, e.g. +0 to +10 s/d.	
Large positional deviations between vertical positions	Centre the hairspring, poise the balance wheel, or replace the regulating organ.	
Deviations between vertical and horizontal positions	Adjust the position of the hairspring between the regulator pins. If the DVH value is negative, reduce the clearance (close the pins). If the DVH value is positive, increase the clearance (open the pins).	
Large but regular rate variations	Fault in the gear train. Overhaul and, if necessary, replace parts of the gear train.	
Very irregular rate and functional faults	Typically caused by insufficient amplitude. The movement requires servicing.	

Balance wheel "knocks" intermittently (overbanking)	Amplitude is too high (> 330°). Double "tick-tock" is audible in the loudspeaker. Mainspring, pallet fork and/or escape wheel must be replaced.	
Balance wheel "knocks" continuously	Same as above: amplitude too high (> 330°). Permanent double beat indicates severe overbanking – replace mainspring, pallet fork and/or escape wheel.	
Escape wheel is out of round	Replace the escape wheel. A full revolution corresponds to 15–21 teeth.	
Pallet fork poorly fitted or "dry" (gummed)	Clean the escapement or replace the escape wheel.	
Hairspring is rubbing	Often due to contact between the hairspring and regulator pins or stud. Listen for noise. Centre the hairspring and adjust the rate.	
Slow oscillation after position change	Poor lubrication in balance or gear train bearings. Clean, oil and overhaul if needed.	

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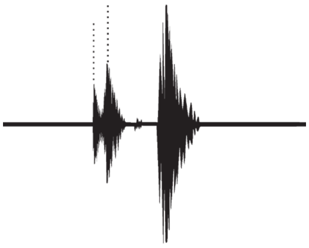
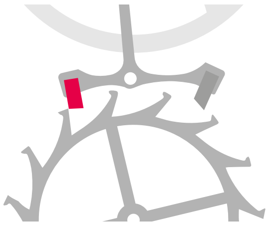
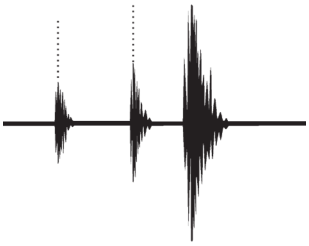
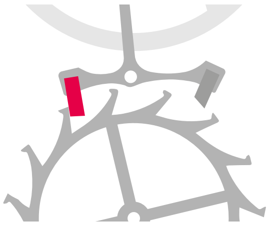
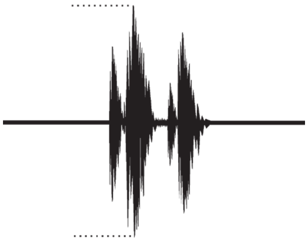
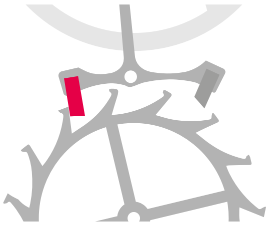
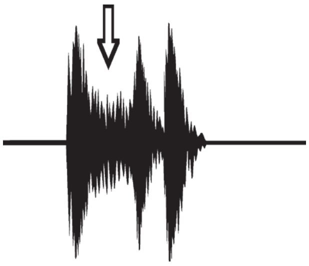
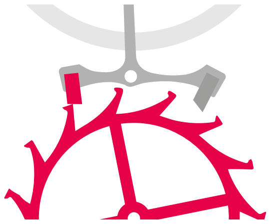
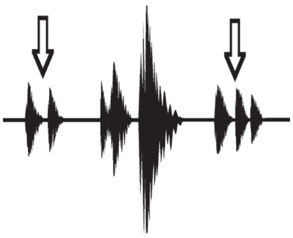
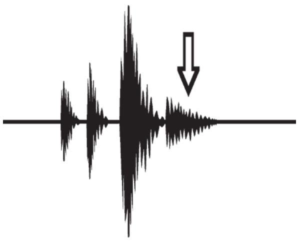
Fault Finding with Scope

Fault	Description Action	Image
Escapement fitting weak		
Escapement fitting strong		
Unlocking too strong		
Additional friction in the escapement		
Safety pin (Dart) touching the roller		
Not enough clearance between the slot and impulse pin		

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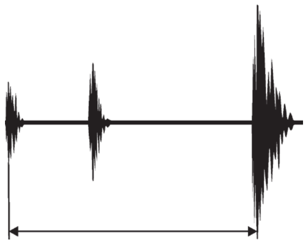
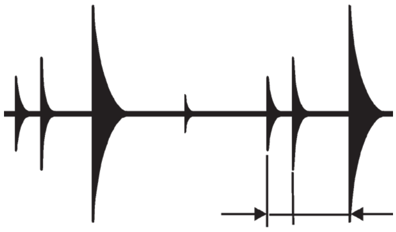
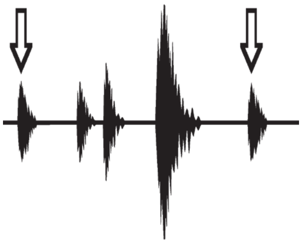
Weak amplitude



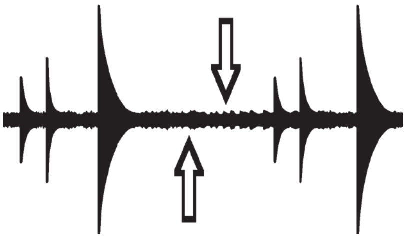
Too much axial end shake in the pivot of the balance



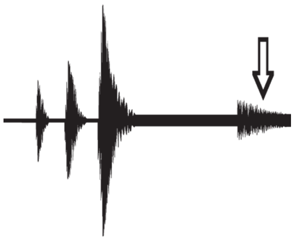
Impulse pin touches the fork horn (knocking)

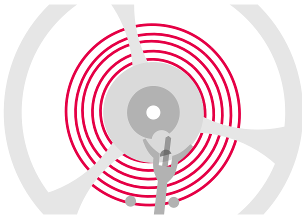


Damaged (or worn) balance staff pivot

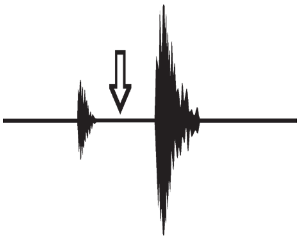


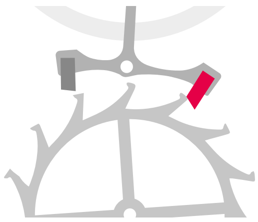
Grazing balance wheel / hair spring





A Tooth of the escape wheel hits directly into the impulse plane





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