Magnetische Präzisionsmessung von elektromagnetischen Aktoren
Magnetic Precision Measurement for Electromagnetic Actuators

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Kurzfassung

Die Innovation magnetischer Messung besteht darin, dass ein beliebiger handelsüblicher Elektromagnet nicht nur als Aktor, sondern auch als Sensor verwendet wird. Diese Tatsache bietet zahlreiche Möglichkeiten bei der zerstörungsfreien Prüfung bzw. Zustandsüberwachung von elektromagnetischen Systemen sowohl während der industriellen Fertigung als auch bei der Anwendung. Alle Elektromagnete vom kleinsten Relais über schnellwirkende Einspritzventile bis zu großen Bremsmagneten können gleichzeitig als Sensoren für mechanische, elektrische und magnetische Größen betrieben werden. Die dabei gewonnenen Signale können z.B. für die Fehlererkennung verwendet werden, wobei nicht nur interne mechanische Defekte in Elektromagneten, sondern auch die externen Defekte in der angeschlossenen Last des Elektromagneten erkannt werden können.

Abstract

The presented innovative magnetic testing method utilises the fact, that each commercially available electromagnet can not only be used as an actuator, but also comprises internal sensor functions. This allows a huge application variety in the fields of non-destructive testing and condition monitoring of electromagnetic systems during production and within the application in the field. Each electromagnet, from the smallest relay to very fast acting injection valves and large electromagnetic brakes, can be employed as sensor for mechanic, electric and magnetic quantities. The obtained signals can be used e.g. for error detection, not only for internal mechanical issues inside of the electromagnet, but also for external errors occurring at the connected load.

1 Introduction

Magnetism was mentioned for the first time by William Gilbert in 1600 in his publication „On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth". In 1824, the English engineer William Sturgeon developed the first electromagnet. During the 20th century, magnetic actuators have seen a rapid evolution through the means of mass production with a multitude of applications. A comparison of a passenger car from 1960 and today illustrates this development: While in former times only about 10 electromagnetic relays were installed, today more than a hundred electromagnetic actuators are part of a modern vehicle.

In parallel to the extending application of electromagnets, electronic devices for measuring magnetic fields in air and in ferromagnetic materials were developed. This development was historically detached from application and development of the electromagnets themselves. Thus, a high innovation potential can be found in the combination of these two branches by applying magnetic measurement to electromagnetic actuators. This trend has started and can be seen at different manufacturers of electromagnets.

The innovation in this case is considering a common electromagnet not only as actuator but also as sensor.

The basic concept sees any electromagnet as object to be measured or tested non-destructively and without additional sensors with the accuracy of electric measurement and to be analysed magnetically. Thus, a magnetisation characteristic $\Psi(i,\delta)$ is obtained as a global characteristic of the overall system, comprising a multitude of state and functional variables. This includes not only magnetic but also mechanic behaviour of the electromagnet and its load. The $\Psi(i,\delta)$ characteristic can be drawn as a diagram with three axes, where Ψ represents the magnetic flux linkage, i the current and δ the air gap (**Fig. 2**).

As a potential object to be analysed, any electromagnetic system is possible, comprising:
- at least one coil,
- fixed and moving parts made of ferromagnetic materials,
- at least one air gap.

Typical examples are all systems based on the reluctance principle: electromagnets, magnetic actuators, magnetic valves, relays, reluctance motors and so on.

For operating these systems as sensors, they need to be characterised accordingly. By interpreting $\Psi(i,\delta)$ characteristic, the concrete benefits and value of magnetic measurements for the specific test object can be obtained. This can be insight into the following properties and parameters, which is gained by measuring, comparing and evaluating only one characteristic within a few (milli-) seconds [1]:
- actuation times and currents,
- armature motion and position,
- friction within the overall system,
- contamination,
- spring forces or other counter forces,
- dynamic magnetic forces,
- production errors and quality issues.

With the possibility to evaluate, visualise and record the $\Psi(i,\delta)$ characteristic automatically, a 100% in-line or endof-line testing of electromagnets can be realised also for short cycle times, not only detecting errors themselves but also their causes.

Electromagnetic systems are used as micro or macro systems in literally all branches of technology: starting from small reed contacts, relays, chokes and inductors up to large electromagnetic brakes or clamps with high power [2]. Electromagnetic valves are a particular group of actuators with a large industrial or automotive field of application. They are usually fully integrated into a higher-level system, making conventional testing and error detection more difficult. Despite the variety of electromagnets differing in various criteria, such as

- functional: switching or continuous/proportional,
- excitation: DC-/AC-current, PWM,
- system design: neutral, polarised (with permanent magnets),

all these types of actuators can be analysed with the described method [3]. Without loss of generality the following sections will focus on DC solenoids.

2 Limitations of the conventional testing of electromagnets

The main function of every electromagnet is the conversion of supplied electrical energy into mechanical work, while the required force is exerted along a certain stroke. Thus, the mechanical force-stroke measurement has established itself as conventional testing method for quality control of electromagnets.

If the electromagnet in its application is integrated into a higher-level system, only the respective main function of the complete system is tested; if the electromagnet is e.g. actuating a pneumatic or hydraulic valve, function and quality of the complete magnetic valve are determined by evaluating pneumatic or hydraulic characteristics. If considering an injection valve, the injected fuel amount is the quality criterion; for a magnetic brake, the torque or braking energy are most relevant and so on.

For complex systems with a higher grade of integration the practical every-day challenge is to handle this complexity with the available testing methods in order to guarantee the quality of the products. With increasing complexity of the actuators themselves and a higher level of integration, limits of conventional testing methods are often reached or exceeded; hence testing methods are tend to become very time-consuming and cost-inefficient.

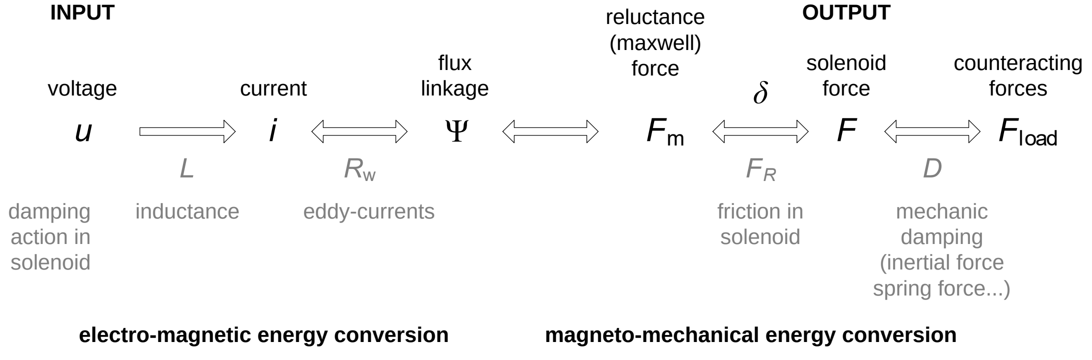

Fig. 1 Energy conversion in solenoid

In case of detected errors or deviations from the target characteristic in the behaviour of the whole system it is often very difficult or even impossible to identify the real error source. These difficulties come from the complex interdependence of all components within the system – although the overall system can be tested and analysed, the components or subsystems remain black boxes for the observer.

If the measured hydraulic characteristic of a hydraulic magnetic valve is not coinciding with the target characteristic, it is mostly difficult to determine whether this is caused by the magnetic or valve part.

Especially for complex testing tasks, the magnetic measurement can be applied advantageously, as it discovers some additional information on the real behaviour of the electromagnet (also with load), that cannot be gained with conventional methods.

This can be achieved with the so-called single-coil measurement method, where the excitation coil of the actuator is mutually used as measuring coil. For this non-invasive measurement, only the existing terminals of the electromagnet need to be contacted.

3 The coil – inherent part of the electromagnet

The excitation coil is an inherent part of every electromagnet, with the designated function to generate a magnetic field and thus a magnetic force. In the field of magnetic measurements, similar measurement coils are used as sensors for magnetic fields. The single-coil measurement method is based on the known mechatronic principle of functional integration.

The existing excitation coil within an electromagnet is used as measurement coil at the same time. The measurement method allows to excite an electromagnet during the measurement and to determine its real behaviour at the same time without additional sensors.

The electro-magneto-mechanical energy conversion of an electromagnet can be described in a simplified way as follows (**Fig. 1**):

- Input parameter is the electric voltage that is applied to the coil terminals.

- This results in an electric current through the coil that is delayed by the inductance of the coil.
- The current in the coil generates a magnetomotive force that results in a magnetic flux (linkage), that is delayed again by eddy current effects.
- The magnetic flux through the air gap leads to a reluctance (or Maxwell) force onto the armature, resulting in motion. Armature motion is often accompanied by mechanical friction; hense there is a difference is differentiated between reluctance and magnetic force. The magnetic force is considered as the resulting force, measured with a force-stroke testing device and seen as output of the electromagnet.
- The electromagnet can be coupled to a load (e.g. a valve) with additional forces exerted onto the armature like spring forces, friction, pressure forces etc. that are influencing the armature motion and with that the overall system behaviour.

The philosophy of modern magnetic measurement [4, 5] of electromagnetic systems is based on the following principles:

- voltage, induced voltage and current are closed-loop-controlled and measured with high resolution and accuracy,
- magnetic flux linkage is computed,
- the obtained $\Psi(i,\delta)$ characteristic is analysed, interpreted and utilised as testing/verification function of an electromagnet

The analysis of the $\Psi(i,\delta)$ characteristic represents a new approach to analysing electromagnets, where the complete electro-magneto-mechanical energy conversion is considered with this global characteristic. Every point of this characteristic can be considered as vector parameter consisting of several significant main parameters and derived instantaneous values:

$$p = f(u, i, \Theta, u_{ind}, t, R, T, \Phi, \Psi, L, L_d, \delta, F, v, a, W)$$

The instantaneous values here are voltage, current, magnetomotive force, induced voltage, time, ohmic resistance, temperature of the coil, magnetic flux, magnetic flux linkage, inductance, differential inductance, air gap, magnetic force, armature velocity, armature acceleration, magnetic energy.

The area between the $\Psi(i,\delta)$ characteristic and Ψ-axis represents magnetic energy. The characteristic contains information of energy and armature position. With these quantities, the resulting magnetic force can be calculated, especially if it cannot be determined by other means, for example in enclosed solenoids without access to the armature or where preparation with additional sensors would heavily influence the quantities to be analysed.

4 Quasi-static measurement

The quasi-static measurement is a known method in magnetic measurement technology, employed for automated B(H) material characteristics measurement. The speciality is a preferably slow change in magnetisation of the measured object in order to make dynamic effects negligible. This measurement method does generally not emulate real operation conditions of an electromagnet, but allows highly accurate quality control of magnetic actuators. The high sensitivity of the method also enables detection of tiny mechanical changes in the system.

The quasi-static measurement uses a closed-loop controlled slow current feed to the coil with an accordingly slow change in the magnetisation of the system. This results in an artificial behaviour significantly reducing all dynamically delaying effects: the magnetic subsystem is able to directly follow the electrical excitation and the mechanical subsystem follows the magnetic excitation almost without delays, respectively. Eddy currents, flux leakage and skin effect, inertia and dampening become negligible. It is only as much electrical energy supplied to the system as is required for the static mechanical work to be done (displacing the armature through the complete stroke by the magnetic force). The motion or respectively the displacement of the armature is significantly slower than during a normal switch operation, because the instantaneous magnetic force values are only just exceeding the counter forces. This represents a measurement method with minimised dynamic mechanical work (DIN VDE 0580), that is especially suited for the analysis of the mechanical subsystem. Many mechanical defects are detected with higher sensitivity.

The parameterisation of the appropriate measuring rate by defining the set point of the induced voltage is a knowledge and experience-based iterative process depending on inductance, size and temperature sensitivity of the system to be tested. The maximum sensitivity is reached with an optimal setting of the flux change rate or induced voltage. Therefor, two requirements have to be considered:

- Minimizing temperature change of the coil during the measurement (increasing u_{ind} for eliminating the most significant disturbance quantity – temperature change ΔT)
- Minimizing the dynamic mechanical work (decreasing u_{ind} for assuring the quasi-static behaviour of the mechanical subsystem)

The magnetic behaviour of the core material or respectively of the magnetic circuit is showing a high reproducibility for equal excitation parameters and remains constant over the solenoid´s lifetime. Only changes in the electric or mechanical subsystem are influencing the magnetic behaviour of the overall system.

This stability in the behaviour of the magnetic subsystem also allows an innovative and reliable condition monitoring of magnetic systems.

5 Interpretation of characteristic curves

The real value of magnetic measurements is created only by correct interpretation of measured magnetisation characteristics.

Due to the slow excitation the mechanical subsystem of the electromagnet is able to follow the electromagnetic subsystems. It is only as much energy supplied to the system as needed for the displacement. The influence of eddy currents and inertia of the magnet’s behaviour is minimised.

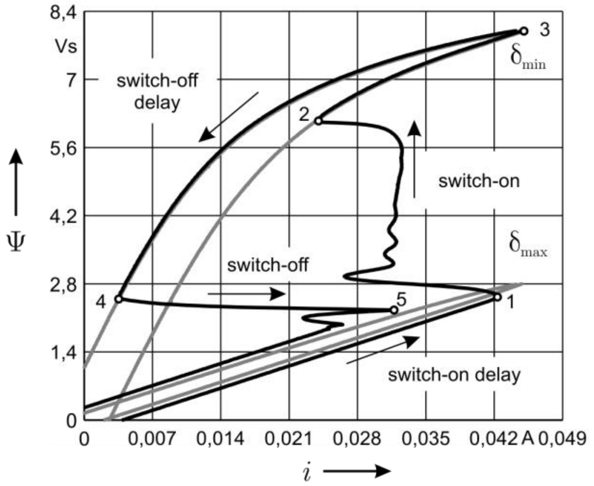

Fig. 2 Operation cycle (activation/deactivation operation) of an electromagnet with cycle direction

0 – 1 – 2 – 3: pull-in operation

0 – 1: Pull-in delay (t_{11}) – Induction effect in a coil during activation of an electromagnet. The armature is located in its starting position δ_{max}. A magnetic field is generated and the supplied electric energy is converted into magnetic energy and electric power losses. Because of the large air gap in the open magnetic circuit, the $\Psi(i,\delta)$ characteristic is strongly sheared and almost linear. The pull-in delay is caused by the counter forces and the inductive effects of the coil.

1: At operating point 1 the magnetic force (as a function of time) overcomes all counter-forces (spring preload, static friction, weight of the armature). Armature motion starts.

1 – 2: Pull-in motion (travel time t_{12}) – Induction effect in the coil caused by armature motion. The electro-magnet is conducting its actual task. The energy conversion is electro-magneto-mechanic.

$$u = iR + \frac{d\Psi(i,\delta)}{dt} = iR + \left(\frac{\partial\Psi(i,\delta)}{\partial\delta}\frac{d\delta}{dt} + \frac{\partial\Psi(i,\delta)}{\partial i}\frac{di}{dt}\right)$$

with $\frac{\partial\Psi(i,\delta)}{\partial i}\frac{di}{dt}$ – „magnetic“ part of the induction by current change (self-induction), $\frac{\partial\Psi(i,\delta)}{\partial\delta}\frac{d\delta}{dt}$ – „mechanical“ part of the induction by armature motion (motion induction)

The armature moves along the stroke from δ_{max} towards δ_{min}. The armature motion causes a change in the magnetic flux linkage. According to Faraday’s induction law this causes an induced voltage. With a constant voltage applied to the terminals of the magnet, this leads to a decrease in current during the motion.

2: Armature reaches its final position δ_{min} (Pull-in time $t_1=t_{11}+t_{12}$)

2 – 3: Magnetisation rise in pulled-in position. Current reaches its final value

3 – 4 – 5 – 0: drop-out operation

3 – 4: drop-out delay (t_{21}) the electromagnet is being demagnetised (exponential current decrease). The drop-out delay is caused by the required time for the collapsing field (eddy currents) and counter forces; decrease of magnetic force

4: The return motion of the armature starts. Return forces (spring tension at δ_{min} and weight of the armature) overcome the remaining magnetic force and the static friction.

4 – 5: drop-out motion (reverse travel time t_{22}) the mechanical return forces move the armature against remaining magnetic forces from δ_{min} into the initial position δ_{max}.

Every transient characteristic can be divided into static and dynamic parts according to the armature motion.

Static parts (no armature motion):

0 – 1 Armature in initial position before begin of motion

2 – 3 – 4 Armature in final pulled-in position

5 – 0 – Armature in initial position after return motion

Dynamic Parts (moving armature):

1 – 2 Pull-in motion

4 – 5 drop-out motion

Because of the higher counter-forces, jamming or short stopping during the motion phases can occur. Reasons therefor are huge differences in the load characteristics (e.g. parallel spring arrangements with different spring rates), pressure peaks, friction and stick-slip effects. These phenomena can be detected with the measurement method. As long as no electric or mechanical defects are occurring, the static parts of the characteristic 0 – 1 and 2 – 3 – 4 remain constant.

Influences on the behaviour of the electromagnet can be classified as internal or external effects. The internal effects do also occur without load present under normal conditions. They can support or oppose the magnetic force and are detected in the dynamic parts of the characteristic. Examples are friction and wear, eddy currents (material properties) and inertia (spatial distribution, spring force and pretension, viscous damping)

The external effects are all kinds of purposefully made or disregarded changes affecting the load characteristic of the electromagnet, e.g. fluidic forces, temperature, pressure or vibration effects. The magnetisation characteristic is the graphical representation of an energy-based analysis approach of an electromagnet. It shows the interaction of the magnetic force of the electromagnet and all internal and external influences and thus allows to detect all respective effects involved [6, 7].

6 Accuracy

The magnetic energy that is represented by the $\Psi(i,\delta)$ characteristic usually is only a small fraction of the overall supplied electric energy (approx. 5% for conventional electromagnetic systems). The utilised energy for mechanical work in turn is only a small fraction of the magnetic energy and is about 1% of the supplied electric energy. The single coil measurement method requires a constant ohmic resistance of the coil during the measurement itself. In reality, most energy losses in an electromagnet are thermal losses that can influence temperature and respectively resistance of the coil. Thus, the necessary assumption of a constant resistance requires a careful and correct parameterisation of the measurement. An optimal parameter set must be found as compromise between preferably fast (less energy losses) and sufficiently slow measurement to keep eddy current effects negligible and avoid signal rounding. This becomes especially important for measured objects with small ohmic resistances and small thermal time constants.

Mathematical approaches and measurement modes to consider potential changes in resistance are currently subject of further research work [8]. First results show a promising repeatability increase in the measurement of thermally critical objects. The magnetic measurement of electromagnets is very sensitive in detecting smallest changes of the system, resulting in a resolution in the range of micrometers or respectively micronewtons. **Figures 3** and **4** show sample measurements of a solenoid actuator.

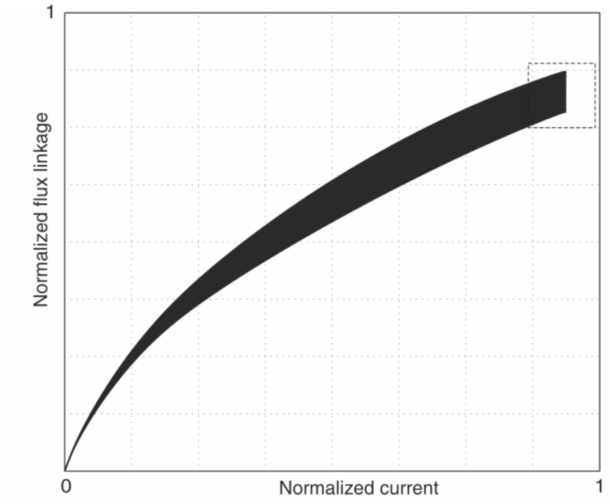

Fig. 3 Ψ(i, δ) family of characteristics of a solenoid with fix armature positions in 2 µm steps

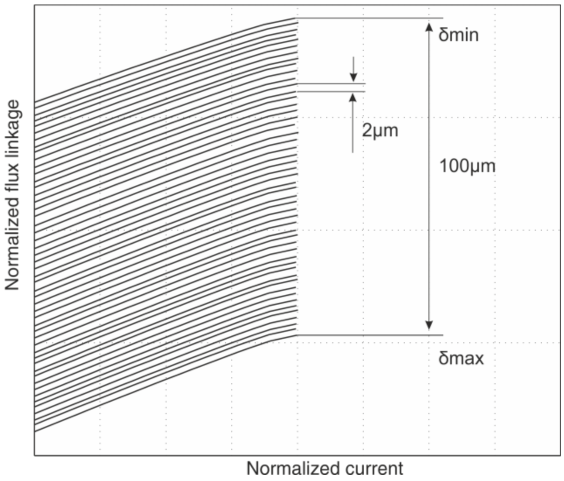

Fig. 4 Detail of the Ψ(i, δ) characteristics in Fig. 3

The resolution is sufficient to detect the armature position sensorless with an accuracy of 2 micrometers.

For achieving this level of precision in the analysis of the mechanical subsystem, the measurement device has to meet high demands on the accuracy of the electrical measurement and the control system, thermal stability and also on the sensitivity and resolution for setting the measurement parameters.

This article can only show a few examples to point out the error detection capabilities for magnetic systems.

The following figures show the analysis of a safety-relevant magnetic valve for pneumatic applications, consisting of a coil, magnetic yoke, flat armature, membrane spring, inlet and outlet ports and a rubber sealing.

The black-coloured characteristic is representing a reference or respectively target characteristic of a good part.

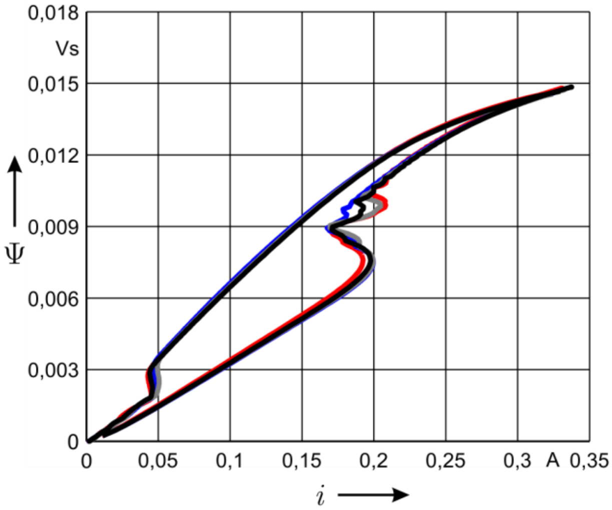

Fig. 5 Four good magnetic valves without errors. Small deviations through the production process are visible

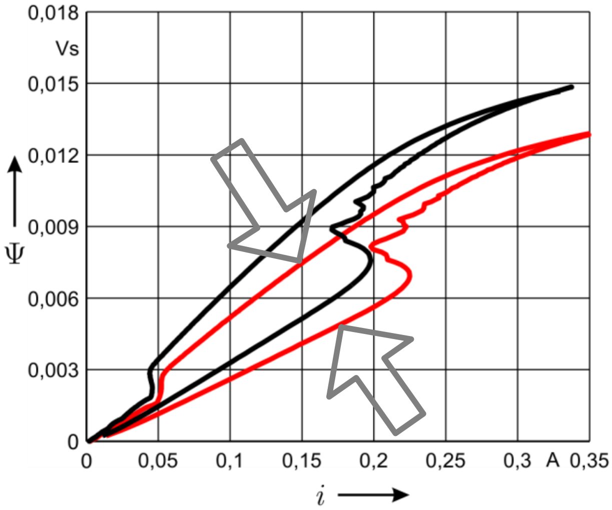

Fig. 6 Short-circuit between turns of the coil with 10% reduced active winding

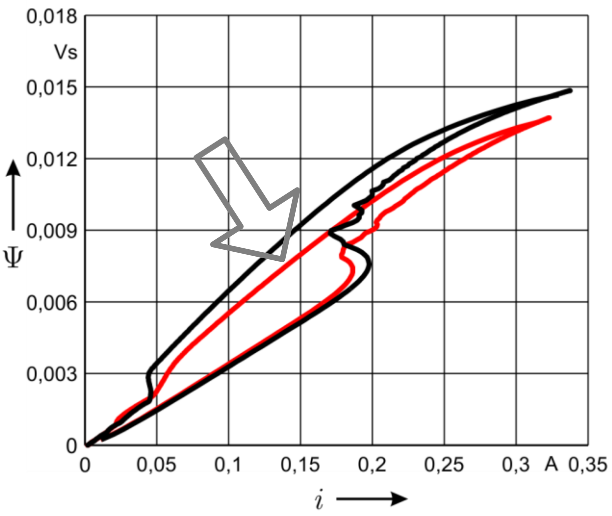

Fig. 7 Contamination on the upper armature side

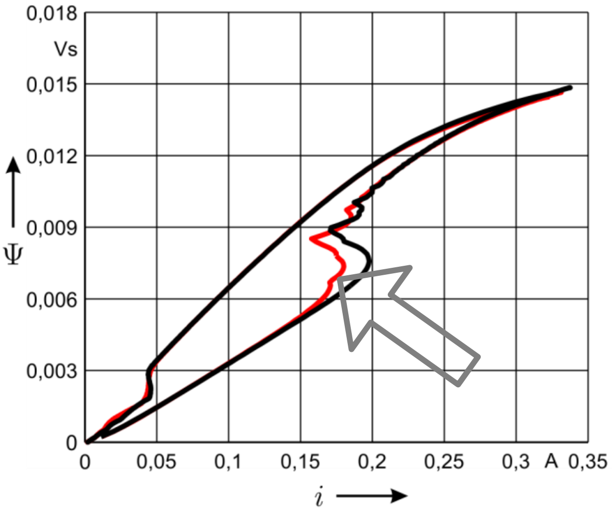

Fig. 8 Broken leg of the membrane spring

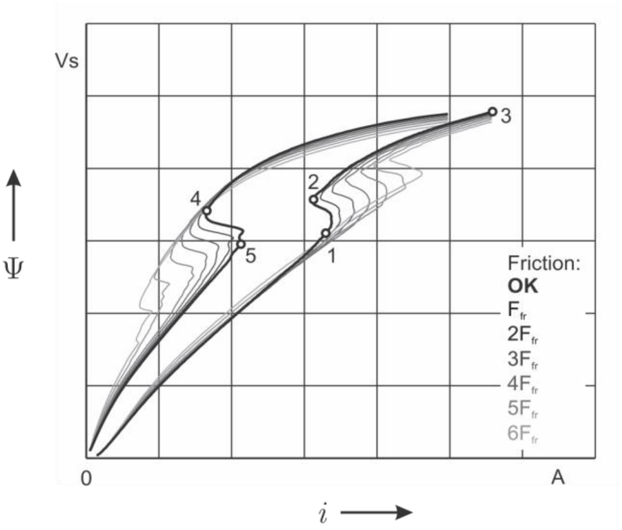

Fig. 9 Endurance testing with several million cycles and increased friction due to wear

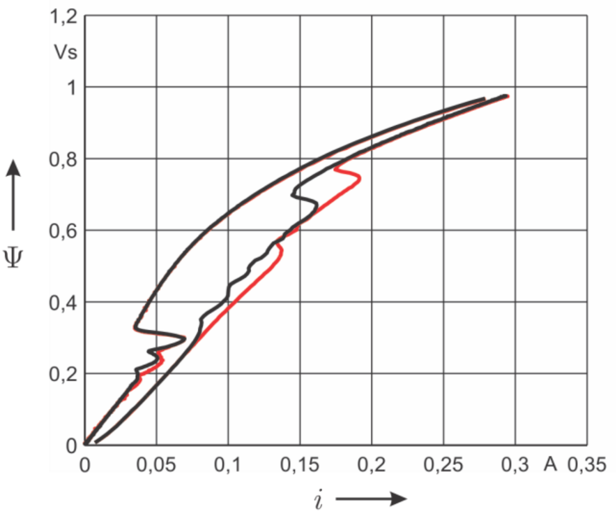

Fig. 10 Measurement under pressure shows influence of counter forces

7 References

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