Development of a Multifactorial Method for Condition Monitoring of Fiber Ropes for Cranes

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A measuring system to determine the rope condition and time of discard of fiber ropes used on cranes is being developed. It consists of two electrical conductors integrated into the fiber rope core with electronic components connected to them at regular intervals. These electronics must be protected from the mechanical loads in the rope. The compressive forces and their distribution are determined to design the necessary cylindrical protective covers. Furthermore, various materials are tested for their suitability as electrical conductors in the rope, which mainly depends on their elastic elongation behavior and electrical resistance.

Keywords: *fiber rope, condition monitoring, measurement, pressure load, electrical conductors.*

1. INTRODUCTION

High-strength fiber ropes offer some significant advantages over steel ropes when used on cranes. However, this comparable new technology lacks a safe and automated method for condition monitoring. Many different approaches for monitoring fiber ropes based on different measurement methods and rope properties exist.

This project aims to develop a technically feasible automatic measurement system for condition monitoring of fiber ropes on cranes by combining known measurement methods. A technical-economical evaluation of different measuring methods for various rope characteristics and possible combinations thereof led to the measuring system which is briefly described in chapter 2. This paper focuses on two issues in the development process, the forces acting inside the rope and the selection of a suitable conductor material.

2. MULTIFACTORIAL MEASUREMENT SYSTEM

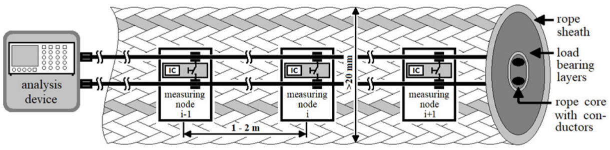

Figure 1. Sketch of the measuring system in a fiber rope [1]

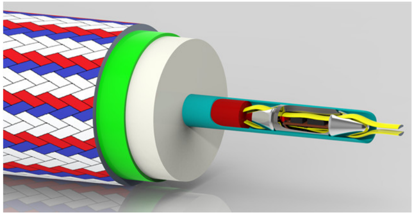

Figure 2. A sectional view of the electrical conductors embedded in the rope core with a measuring node [1]

In the measuring system shown in Figures 1 and 2, electronic measuring nodes are inserted into the rope core at regular intervals. These nodes are connected by two continuous electrical conductors which extend over the entire rope length and are connected to the analysis device at one end of the rope. This device contains evaluation electronics as well as a data analysis and storage unit. Operating data of the crane, for example current rope position and load, is provided for the analysis. The specially equipped rope, access to one end of this rope, and an interface to the crane's operating data are required for the measuring process. Additional sensors on the crane are not necessary, but are possible.

The measuring nodes contain a microcontroller that enables digital communication with the analyzer. The distance between two nodes is between one to two meters. This enables a section-by-section measurement of various rope properties, such as elongation, stiffness, electrical resistance of the conductors and temperature over the entire rope length. [1]

2.1 Chronological steps in the measurement process

To determine the rope characteristics of a rope section with the proposed measuring system, several steps are necessary. The data captured by the analyzer contains:

- crane data (load, rope position, temperature, ...)
- temperature in the rope
- electrical resistance of the conductors in the section (of which elongation or damage can be derived)
- signal propagation time in the section (of which elongation and longitudinal stiffness are derived)

These steps take place within a few milliseconds each. The analyzer supplies the energy for the measuring nodes and transmits the targeted measuring node ID to all measuring nodes via the two conductors. The nodes then switch themselves off, except for the selected measuring node with the right ID. This node determines the temperature and transmits it digitally to the analyzer. It then closes a MOSFET switch between the two conductors to connect them at its location in the rope. The analyzer then

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performs the resistance and signal propagation time measurements in the resulting conductor loop. When reversing the polarity of the conductors, the switch reopens and the conductors are isolated again. The supply voltage is applied and the process starts with the next ID. [1]

3. COMPONENTS OF THE MEASUREMENT SYSTEM

The measurement system can be divided into three components (as shown in Figure 1):

- analysis device
- measuring node electronics with its protective cover
- electrical conductors

These components are first designed and simulated theoretically, then prototypes are made for functional tests of each of them individually. The conditions when using these components in a fiber rope must be considered, for example available space and forces in the rope or the electrical resistance of the long conductors. [1]

3.1 Analysis device

The analyzer is located outside of the rope, so there are only a few boundary conditions to consider. It consists of a computer and memory unit and a measuring unit with two fast analog inputs and outputs. These are connected to the two electrical conductors in the rope and enable power supply and communication with the measuring nodes. In addition, they are used to measure the resistance and the signal propagation time in the active conductor loop to derive its length. Since the analyzer unit is not part of the rope, it does not have to be changed with the worn-off rope, instead it can be used permanently on one crane for several ropes. [1]

3.2 Measuring node electronics and protective cover

Figure 3 shows a measuring node consisting of the circuit board and the protective cover through which the two electrical conductors are passed and connected to the circuit. The board electronics can electrically connect or disconnect the conductors, measure the temperature, and communicate with the analyzer via the two conductors.

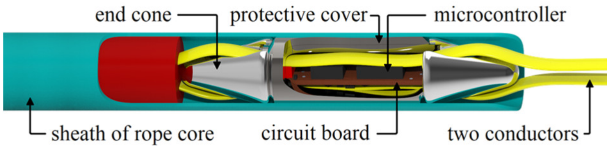

Figure 3. A sectional view of the measuring node with its protective cover and electrical conductors [1]

The main component on the circuit board is a simple, energy-efficient microcontroller with an analog-to-digital converter, a timer, I/O pins and a temperature sensor. Other required components are a broadband voltage converter, MOSFETs, diodes, capacitors and resistors. The components are arranged on both sides of the 2.1 mm by 8 mm sized circuit board.

The contact points to the two electrical conductors are on opposite sides of the board, preventing mutual contact between them. The protective cover encloses and protects the electronics. It needs an inner diameter of 2.25 mm, the necessary outer diameter will be specified after determining the acting forces depending on the respective fiber rope and application (see chapter 4). [1]

3.3 Electrical conductors

The cable core consisting of the two insulated conductors and the measuring nodes with their protective cover are shown in Figures 2 and 3. The electrical conductors form the connection between the analyzer and the measuring nodes. They consist of two continuous wires through the whole rope, there are no interruptions at the measuring nodes. As a result, the failure of one contact point on a measuring node only leads to its own malfunction, while the others remain operational.

The electrical voltage between the two conductors decreases with the distance from the analyzer. To provide sufficient supply voltage even at the most distant measuring nodes, the conductance of the material should have a maximum electrical resistance of 10 Ohms per meter. The resistance can be adjusted by the conductor cross-section, which is required to be 1 mm^2 or less. [1]

3.4 Research questions

Two questions that arose during the development of these components are:

- What mechanical loads are required for the design of the cylindrical protective covers enclosing the measurement node electronics?
- Which materials are suitable for the electrical conductors, especially regarding electrical conductivity and elastic ductility?

These research questions are discussed in the following chapters 4 and 5, respectively.

4. PRESSURE ON THE PROTECTIVE COVER

To properly design the protective cover for the measuring node electronics, the loads acting on it have to be estimated first. The protective cover is a hollow cylinder made of metal or a fiber composite material. There must be an inner diameter of 2.25 mm for the measuring electronics, and the outer diameter should be as small as possible, at a maximum of about 8 mm. The load and load distribution to be identified provide the basis for the choice of the cover material and the determination of the required wall thickness.

The use of a single-layer winch system is assumed. In the case of multiple layers on the winch, higher compressive loads in the rope are expected in this area.

The two methods used for determining these loads in the rope are:

- simplified analytical approach,
- measurement with pressure-sensitive foil.

Two cases of different rope applications were analyzed and compared with each method:

- rope straight under pure tensile load,
- rope bent over a sheave with tensile load.

4.1 Analytical approach

With some assumptions, the complex rope structure can be simplified to such an extent that an analytical consideration of the compressive forces inside the rope becomes possible. The results allow an estimation of the effects on the loads in the rope when changing, for example, the core diameter or the lay length.

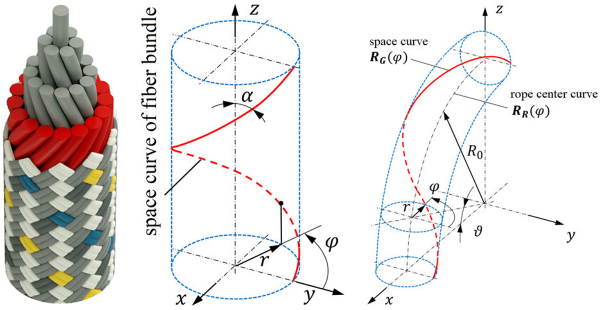

Figure 4. Spiral fiber bundles in a rope and their geometrical description in a straight and a curved rope section [4]

In the first step, a simplified fiber rope subjected purely to tensile stress is investigated. The rope is described by fiber bundles which are considered to be homogeneous. These are wound around the core in several layers with pitch α and lay length l at different radii r (Figure 4) [4]. A fiber bundle itself can be a spiral strand or simply consist of parallel fibers.

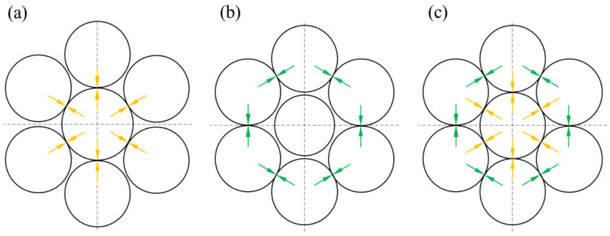

Figure 5. Forces between rope core and 6 strands [3]

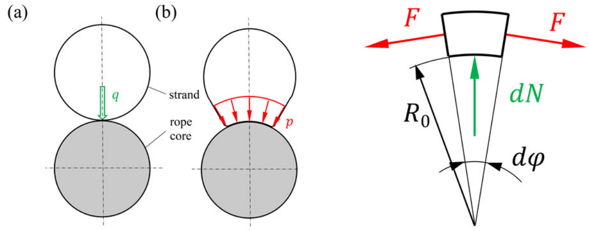

Figure 6. Adaption of fiber bundle shape to the rigid core; forces acting on a bent fiber bundle segment [4]

Depending on the geometric conditions, the support forces between the rope components differ (Figure 5) [3]. In contrast to steel wires, the mutual support of the rope elements in one layer is hardly present due to the low transverse stiffness of the fiber bundles. For the same reason, there is no single point or line contact between the core body and the surrounding fiber bundles. The fiber bundle takes the shape of the comparatively rigid body in the rope core and encloses it. The pressure distribution is assumed to be constant in the area between a fiber bundle and the core, as shown in Figure 6 (b) [4].

The calculation of the forces as a function of the rope tensile force S and the geometric conditions is carried out starting from the force equilibrium shown in the right part of Figure 6. With the strand force in the fiber bundle ($F_i = \frac{S_i}{\cos\alpha}$), the radial force dN for small angles dφ is calculated as follows: $dN = 2 \cdot F \cdot \sin\frac{d\varphi}{2} \approx F \cdot d\varphi$ [4].

Further calculations with these assumptions result in a contact pressure p on the core body, valid for a straight rope with the same lay length of all rope layers. It is evenly distributed at the circumference of the core and has a linear relation with the rope tensile force S:

$$p = \frac{\pi \cdot S \cdot (d_A + d)}{d_A \cdot l^2 \cdot \sqrt{\frac{\pi^2 \cdot (d_A + d)^2}{4 \cdot l^2} + 1}} \qquad (1)$$

It is not possible to find a similar general solution for the pressure on the rope core in a part of the rope that is bent over a sheave. The geometrical description is shown in Figure 4 on the right side. An additional distributed force is acting between the rope surface and the sheave groove. This and the smaller bending radius of the outermost fiber bundles lead to higher pressure zones on the side of the sheave and the opposite side of the rope. The pressure can be calculated numerically. [2]

An exemplary solution for both cases is described in chapter 4.3 and shown in Figure 11.

4.2 Measurements with pressure-sensitive foil

Meaningful results were obtained by measuring the compressive forces in a real rope. Different cylindrical aluminum test specimens (Ø 6 mm and Ø 8 mm) were equipped with pressure measuring foils. The foil was wrapped around the circumference of the cylinders or placed between two half-cylinders. These test specimens were inserted into a braided fiber rope on a testing machine and statically loaded with different rope tensile forces for two minutes each. [2]

The measurement was carried out in two positions of the rope: in the straight rope area (Figure 7 A), and the area on the sheave for the curved rope (Figure 7 B).

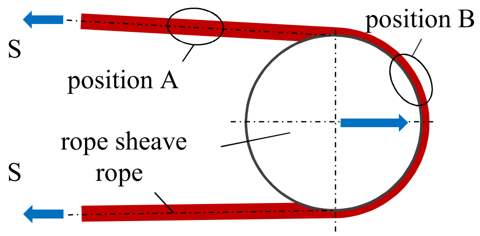

Figure 7. Positions A and B of test specimens in the rope

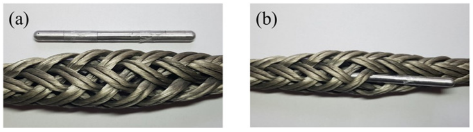

Figure 8. Loosening of the unloaded rope (a) and insertion of the test specimen with pressure measuring foil (b) [2]

The rope used for these tests is a braided UHMWPE rope with 12-strand construction, 18 mm outer diameter and 160 mm lay length. A braided rope has the advantage that the different test specimens can be easily inserted into and removed from the rope after load testing by basket formation. This operation is shown in Figure 8. [2]

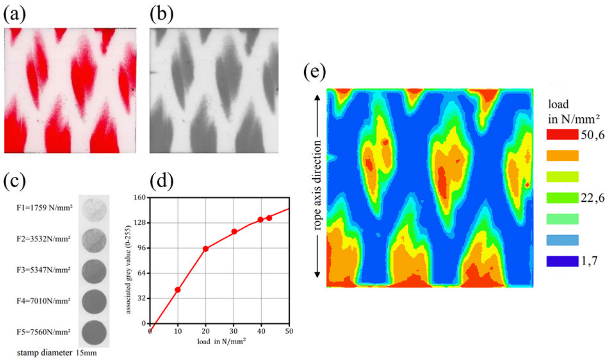

Figure 9. Evaluation steps of pressure measurement foil [2]

The pressure measuring foils obtain a red discoloration depending on the maximum occurred local pressure, which is analyzed afterward. Figure 9 shows the evaluation steps for an example scan (a) with calibration points (c), calibration curve (d) and result (e). Since each foil covers only a certain pressure range (less pressure and it remains white, higher pressure and it is saturated red), the appropriate foil must be chosen either by trial and error or by an already made estimation of the expected pressure. This estimation was made in advance using the analytical calculation results. [2]

4.3 Results of the pressure on the rope core

The results of a fiber rope with diameter d = 22.2 mm, lay angle α = 14° or lay length l = 165 mm with an inserted core body with d_A = 8 mm are shown in Figure 11. The rope is loaded with S = 73 kN for (a) and (b), the sheave used for the calculation as well as for the measurements has a radius of 222 mm with a rope groove diameter of 22.5 mm and a groove opening angle of 70°. The braided rope for the measurement with pressure measurement foils has a diameter without an inserted measuring body of 18 mm. With the measuring body inserted in the core, the rope diameter is also about 22 to 23 mm.

Figure 11 (a) and (b) visualize the calculated and measured contact pressure on the measuring body in the straight rope and in the rope on a sheave. The large variations in the experimental observation are due to the fiber bundles in the braided rope, as they cannot fully adapt their shape to the measuring body (also seen in Figure 9).

Figure 11 (c) shows the increase in mean pressure in the straight rope when the rope tensile force is increased. The linear increase and the magnitude of the contact force between rope and measuring body calculated with equation (1) were closely reproduced in the experiment. [2]

5. COMPARISON OF CONDUCTOR MATERIALS

The electrical conductors are used for power supply and communication with the measuring nodes in the rope. They also serve as measuring lines for resistance and signal running time measurements. Therefore, certain properties are required from the conductor material:

- compatibility with other rope materials (chemically stable, no abrasive rub-off, …)
- elastic reversible elongation equals or exceeds the elongation behavior of the fiber rope.
- electrical conductivity as high as possible

These properties are to be determined in tensile tests. After a pre-selection, various materials that could meet the requirements (listed in Table 1) were examined.

The materials to be compared in the tensile test can be divided into three groups: metallic conductors, fibers coated with conductive particles and elastomer extrudes with conductive filler (as seen in Table 1).

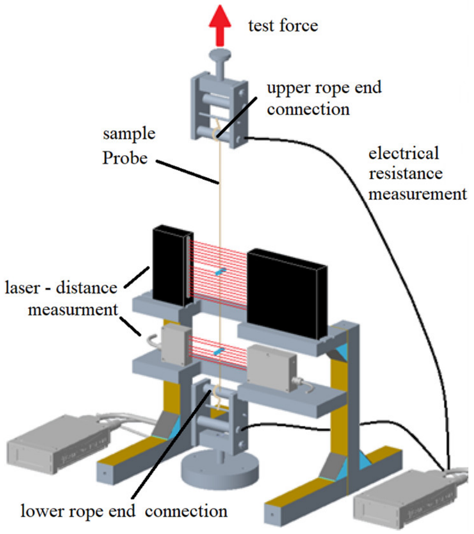

Figure 10. Setup for testing the wires/threads

The measurements are performed on a Zwick AllroundLine Z250 tensile-compression universal testing machine. Different load cycles with different elongations, partly up to the failure of the sample, were applied. In addition to the tensile force and elongation measurement data recorded by the testing machine, the electrical resistance between the two wire/thread end attachments was measured. These end attachments consist of three wraps of the test material on an aluminum cylinder with Ø 20 mm. To absorb the residual force, the remaining piece of wire is bent around a rod, respectively the remaining thread is tied to it. Figure 10 shows this setup.

Some of the measurement results are summarized in Table 1. The electrical resistance was determined for a single wire or thread, it is possible to lower it by using the material several times in parallel in the rope if its cross-section is small enough to stay below 1 mm^2.

In the elongation cycle tests, the development of the resistance over time was examined. It can remain constant (Figure 12) or increase (Figure 13). Both progressive and degressive increases were observed. One sample showed stepwise increases from time to time when one of the few integrated conductive wires broke.

5.1 Results of metallic conductor materials

The various metallic conductors, which consist either of a single metal wire or thin metal wires with plastic fibers, were particularly convincing in terms of very good conductivity. The purely metallic wires have an electrical resistance of less than 1 Ω/m. If the elongation remains low enough (e.g. Steeltech 100, 200 cycles at 1% elongation, see Figure 12), no significant change in resistance occurs. A disadvantage is the limited elastic ductility, in some cases well below 1%, which eliminates these materials for this application.

Tests carried out with wires in fiber ropes resulted in the formation of loops when the load was removed [5]. A possible solution for metallic conductors can be found in measuring systems for fiber ropes based on integrated glass fibers [6]. In this case, the insufficiently stretchable elements are arranged in a spiral in the core, resulting in a significantly higher effort in design and production.

5.2 Results of fibers coated with conductive particles

This group of materials is similar to the load-bearing parts of the fiber rope. Thus, the elastic elongations occurring during regular rope use can be endured without problems. The electrical resistance however is high compared to purely metallic conductors, ranging from a few Ohms per meter up to several 100 Ohms per meter.

The ongoing increase in electrical resistance under cyclic loading varies, but is present throughout this group. Some materials show a degressive increase per cycle. Thus, even at very high cycle numbers, the resistance approaches a limit value and does not continue to increase uncontrollably (for example Figure 13 right).

The thread Shieldex® 235/36 HCB x6 (Figure 13) has the lowest resistance of this group and approximately doubles its initial resistance after 400 cycles with about 5% elongation each. The strongest increase occurs within the first few cycles, after which the increase in resistance is much slower. If this increase continues alike, the resistance rises into the range of 50 to 60 Ω/m after 10000 cycles. The thread can be used 6 times in parallel to be able to still achieve the desired 10 Ω/m. The conductor cross-section would be about 1 mm^2 then.

5.3 Results of conductive particles in extrude

The elastomer extrudes have very high ductility. However, the electrical conductivity is far below the required limits. In addition, unlike the other, thinner materials, these extrudes already fill the available conductor cross-section individually and therefore cannot be used several times in parallel to lower their resistance

6. SUMMARY

The mechanical loads on the protective covers of the measuring node electronics in the rope core can be estimated analytically. These calculations were verified with pressure-measuring foils. For the rope tested, the average pressure at the ropes nominal load is around 50 MPa. The pressure distribution in the straight rope is uniform around the circumference. In the bent rope section on the sheave, the highest compressive forces occur on the outside and inside of the bend. This critical case will be used for the mechanical design of the protective cover.

According to initial estimates, a cover made from stainless steel with the required 2.25 mm inner diameter and an outer diameter of about 5 to 6 mm can permanently withstand the observed loads. This diameter is within the acceptable range for use in the rope core.

Various materials were investigated for the use as electrical conductors in the rope. The most suitable materials turned out to be fiber materials coated with silver particles, in particular Shieldex® 235/36 HCB x6. These threads have sufficiently high elongation capacity, the electrical resistance is at the upper limit of the target value and increases with elongation cycles. This requires the electronics in the rope to be as energy efficient as possible to work properly and/or limits their quantity.

7. OUTLOOK

The protective cover will be designed for the determined loads and can then be tested for sufficient strength in a test rope. The conductivity of the conductor material is sufficient for the first prototype and can possibly be increased later by additional coating with conductive paint or similar measures.

The next steps in the development process should lead to a prototype of the measurement system in which all components are used and tested together. If the tests of the prototype are successful, the measuring system can be installed into a fiber rope. Then it will be further tested and improved on a test rig under conditions closer to the intended use of the fiber rope on a crane.

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NOMENCLATURE

p	surface pressure on measuring element in rope core
S	rope tensile force
S_i	proportionate rope tensile force of a fiber bundle
F_i	tensile force in the fiber bundle
d_A	outer diameter of measuring body in rope core
d	rope diameter
l	lay length
α	pitch (0° corresponds to parallel elements)
r	distance between rope center and fiber bundle
R_0	sheave radius
ID	unique identification number of each measuring node

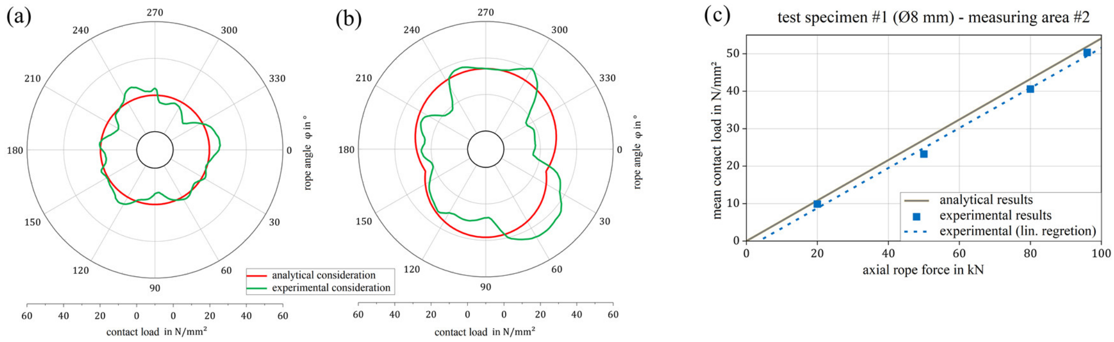

Figure 11. Comparison of results from analytical calculation and tests with pressure measurement foils: pressure distribution at the circumference in the straight rope (a), in the curved rope (b), and mean pressure as a function of rope tensile force (c)

Table 1. Conductive materials tested with selected characteristic values determined.

material	composition or filler material	fracture strain (%)	resistance (Ω/m)	elongation in cycle test (%)	development of resistance-
metallic conductors:					
aluminum	-	21	0,5	-	-
AMANN Steeltech 100	polyester - stainless steel	15	50	2	constant/in steps
spring steel	-	3	0,8	1	constant
copper	-	11	0,7	-	-
silver	-	29	0,4	2	constant
fibers coated with conductive particles:					
AMANN Silvertech	polyamide/polyester-silver	23	80	8	degressive
Shieldex® 400 µ Monofil	polyamide/nylon - silver	24	250	-	-
Shieldex® 117/17 HCB	polyamide/nylon - silver	25	120	5	degressive
Shieldex® 117/17 HCB x2	polyamide/nylon - silver	25	80	5	degressive
Shieldex® 235/36 HCB x2	polyamide/nylon - silver	26	30	7	degressive
Shieldex® 235/36 HCB x4	polyamide/nylon - silver	27	20	6	degressive
Shieldex® 235/36 HCB x6	polyamide/nylon - silver	28	10	5	degressive
conductive particles in elastomer-extrude:					
MTC AGAL elastomer	silver-plated aluminum	>100	-	-	-
MTC AGCU elastomer	silver-plated copper	>100	-	-	-
MTC AGGL elastomer	silver-plated glass	>100	-	-	-
MTC AGNIC elastomer	nickel-plated graphite	>100	250	6	progressive

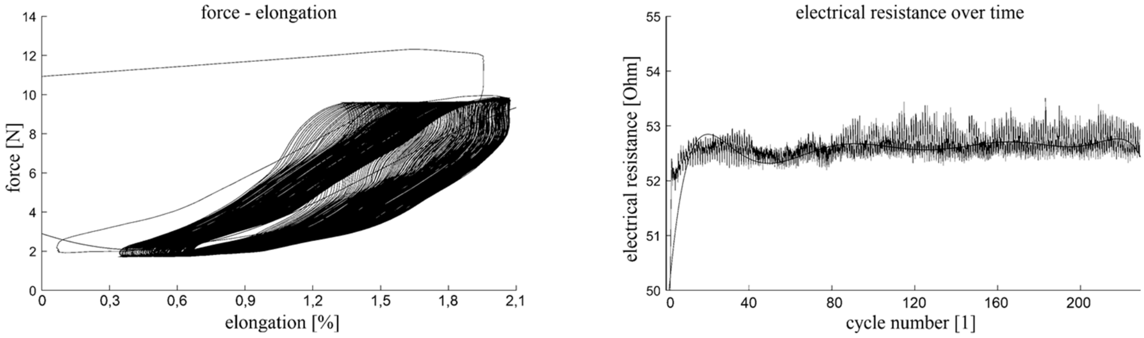

Figure 12. 200 cycles with 2% elongation for fiber material with thin stainless steel wire: constant electrical resistance

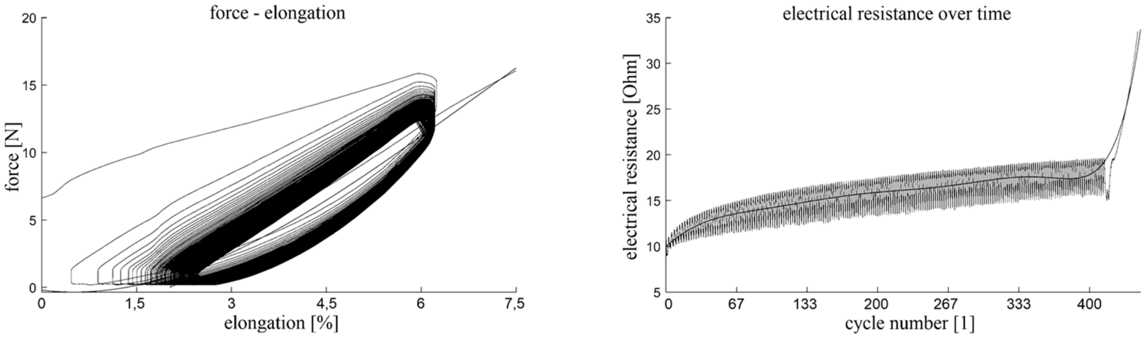

Figure 13. 400 cycles with 5% elongation for fiber material with conductive particles: sufficiently high elastic elongation, but (degressive) increase of the electrical resistance with each cycle