High resolution magnetic induction wire rope test

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There are two possible ways to improve the knowledge of reading the test results obtained by the „High Resolution Magnetic Rope Testing Method“:

- testing damaged rope samples
- calculating the magnetic scatterfields of broken wires.

The basic knowledge about scatterfields of broken wires will be discussed. Possible calculation methods are presented and about an unique calculation method (CCM) will be reported.

With the CCM the scatterfields of two brocken wires -side by side- were calculated and limits of distinction of each individual broken wire will be defined.

A measuring, made with the „STUTTGART High Resolution Magnetic Rope Testing Method“ is compared with the calculated result of the CCM.

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Part 2: Detection of broken wires in wire ropes by analysis of the scatterfield

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As **Haller 1995** pointed out, the "Imaging Method" or „High Resolution Wire Rope Testing" is a significant improvement of the well known electromagnetic wire rope inspection. We have obtained more information about the scatterfield with it, but up to now we only know little about the corellation between the broken wires and their magnetic scatterfields.

The electromagnetic wire rope inspection has been world wide known for many decades and a lot of experts are working employing this method (and there fore countiniously evaluating their diagnostic skills, **Mueller 1952, Mueller 1957, Rieger 1983, Beck 1998**). But the „Imaging Method" was developed making use of discarded rope samples. The number of samples is limited and all damages acurred accidentally. Ex: it is very difficult to analyse clusters of brocken wires, because one wirebreak with a large gap causes almost a similar scatterfield as two wirebreaks side by side with small gaps.

There are two possibilities to improve the knowledge:

First: Continuing the strategy, to test damaged wire ropes to discover broken wires. There fore a radiographic testing (X-Ray) is necessary. As **Haller 1995** mentioned, 10% to 30% of the broken wires (in clusters) are not detectable. But these „hidden" wire breaks very often are generating magnetic scatterfields.

In practice it is sometimes almost impossible to maintain constant testing conditions in multiple tests, e.g. working on a 210 feet tower in windy, rainy weather.

Second: Learning by calculation. The correlation of broken wires (reason) and magnetic scatterfields (consequence) is evaluated theoretically. The reason is well known (airgap, position inside the rope, number of wirebreaks in clusters, etc.). And contrary to the finite number of samples employed by the „Imaging Method", the examination by a calculation method offers the possibility of considering an unlimited number of samples.

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Calculation methods

What do we need: A mathematical modell of a wire rope with internal broken wires has to be developed. The method should be as simple as possible.

To decide, which parameters or elements are important, three items should be discussed:
- radiation of the scatterfield in the near surrounding of the wirebreak
- shielding by unbroken wires
- congruence.

Scatterfield

Local damages are radiating a magnetic scatterfield, Figure 1. The rope has to be magnetically saturated, the B-H-diagram in Figure 2 shows the range of magnetization in ropes from a practical point of view (DC or permanentmagnet test devices). The abrupt change of magnetic permeability (μ) at the gap of the local damages causes a scatterfield. Up to now there is only a very general information in the specialized literature which can be considered relevant, **Meyer 1973**.

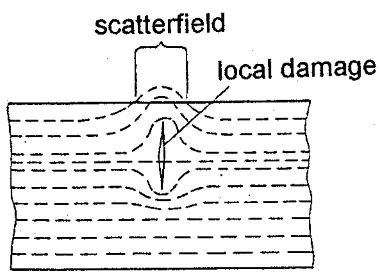

Figure 1. Magnetic scatterfield , **Heptner 1969**

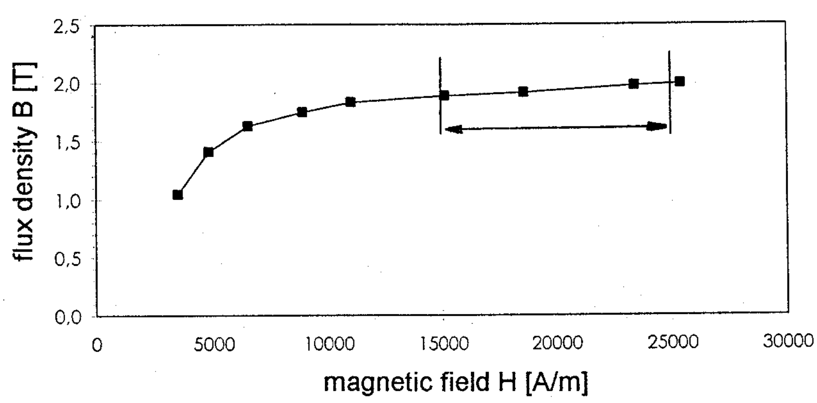

Figure 2. B-H-Diagram of wire ropes

In order to know more about it, we measured the magnetic flux density (B) in a scale-modell, that is an only one isolated wirebreak. The scale-modell consists of two segments and a space between them (gap). The proportion between the length of the segment and the diameter is 100:1. The complete set was placed in a homogenious magnetic field (field parallel to wire axis). A small induction coil was moved along the wirebreak-modell. The registered data is the magnetic flux (and there fore the flux density) which is a function of the distance from the gap. Figure 3 shows a test result, the x-axis represents the relative distance from the seperation. The y-axis displays the B-value inside the wire. It is really surprising, that the flux density inside a broken wire remains at the normal level and drops sharply as it moves closer to the zone of the wire break. All the tests (with various gaps) were processed with a mathematical method to find a universal equation for this phenomenon.

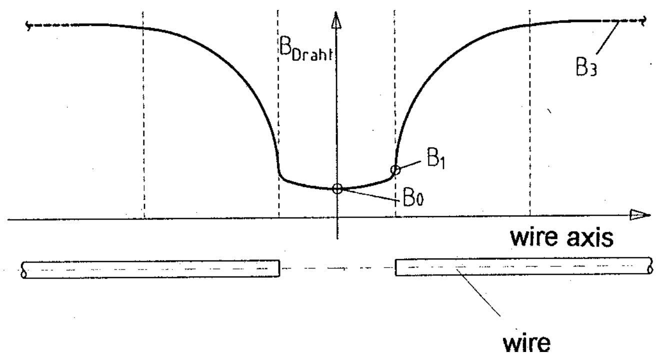

Figure 3. Flux density inside a broken wire

<u>Shielding of unbroken wires</u>

As a result of the long lasting experience in electromagnetic testing of wire ropes we found a very little influence of shielding. Broken wires in the center of the rope and broken wires near the internal surface of the rope have almost similar results.The explanation for this phenomenon are two factors. First, the very poor magnetization of wires cross the main-axis (factor of geometrie, **Kneller 1962**), depending on the wire´s shape (z-wires or round wires) the transversal permeability is $\mu = 2 \div 3$. Compared with the permeability of air ($\mu \approx 1$) it is very low.

Second, the direction of the fluxlines in the near surrounding of the separation. The longitudinal permeability of the magnetically saturated wire (or rope) is, in the case of electromagnetic wire rope inspection, about $\mu = 40 \div 60$ (according to Figure 2). Similarly to the refraction of a light beam in the optics, a flux line will be refracted. All the flux lines are leaving the wire in a transversal direction, Figure 4. And as formerly mentioned, transversal fluxlines are not shielded by the other unbroken wires.

As a consequence of this, it is possible to ignore all unbroken wires when calculating the magnetic scatterfield. The modell can be reduced to a pair of wire pieces with an airgap.

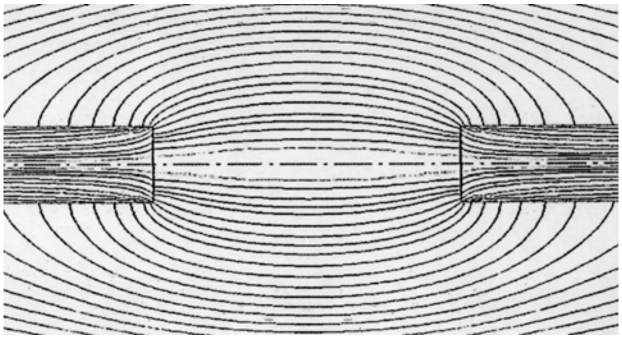
Figure 4. Flux lines at a broken wire

Congruence

One of the most interesting question in science is the universality of results. Similarly to Reynold`s Number in aerodynamics, for electromagnetic testing of wire ropes a geometric congruence exists already. We found this by analysing all factors, sizes, scientific numbers, etc., which are relevant for electromagnetic testing. They were processed using a mathematical method (called „π-Theorem“, **Dubbel 1987**). The practical consequence of this knowledge is, that a test device can be simply scaled up or down, and that all the knowledge about it is universal.

Calculation method for magnetic scatterfields of broken wires in ropes

The FEM is used traditionally for all calculations with nonlinear material constants. Magnetic calculations can be done easily using FEM, when the environment is two-dimensional. Up to now three-dimensional FEM is not easy to handle, modelling and meshing are not really comfortable. But the three-dimensional analysis of scatterfields is essential for clusters of wirebreaks.

Solution: A individual calculation method for magnetic scatterfields in ropes has to be developed. There are some basic principles. First, a static magnetic field calculation is similar to an electrical circuit. All parts of the magnetic arrangement (wires, separation, surroundings) can be modelled employing equivalent electrical resistors. The magnetic field of the test head is represented by an electrical voltage source, altogether are arranged in a mesh. The electrical current in each element can be calculated, it is an equivalent to the magnetic flux density. This method is limited to two-dimensional modells (as the FEM).

The second possible calculation method is based on the formal analogy between electrostatic and magnetostatic fields. The ends of the magnetized broken wires are represented by a pair of electrostatic charges. Coulomb`s Law is the basic formula for this method. This method fits very well to practical needs, in comparison with the corresponding measurements, **Meyer 1973, Martyna 1981**. But in theory there is a discrepance between an electrical and a magnetic field. A magnetic field hasn`t sources and, similar to stream linies in aerodynamics, all flux lines are closed lines (vortex), **Lehner 1996**.

To overcome this disadvantage, we developed an unique calculation method. Basically these are the measurements of Figure 3. The method is named „Circular Current Method“, CCM. As shown in Figure 5, at the ends of the broken wire, the flux density is reduced by ∆B. There fore ∆B variies depending to the distance between the wire ends. The whole wire is devided in an infinite number of short wire elements with the length ∆l. Each wire element is equipped with a imaginary solenoid with one single winding. The imaginary solenoid is feed by a current I, Figure 6. The current is set as high as its own electromagnetic field reaches the amount of ∆B. On the other hand this electromagnetic field is penetrating the surrounding space outside the wire. The superposition of all these external fields corresponding to all infinite wire elements results in the expected magnetic scatterfield around a broken wire.

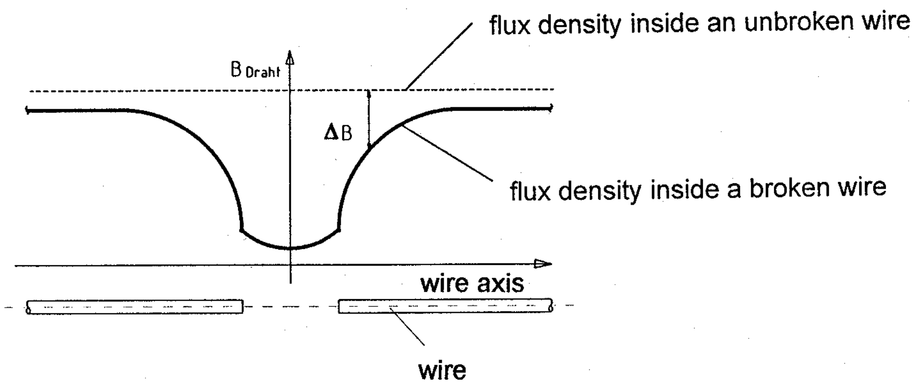

Figure 5. Flux difference ∆B in a broken wire

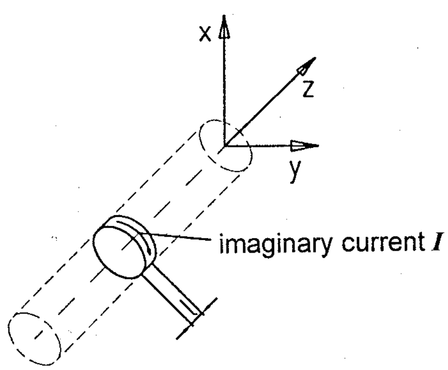

Figure 6. Infinite wire element with an imaginary current and solenoid

Calculation program

To keep things simple, all the necessary equations are omitted in this paper. To operate the program, the only necessary input is the geometrie of the broken wire. For a single wirebreak:
- position in the rope (radius from center)
- gap
- radius or diameter of the „search-coil".

In order to calculate the scatterfield of two or more wirebreaks the method of superposition is used.

Visualisation of results

A nice way to visualize the calculated scatterfields is a isometric surface image. The circumference of the rope is unrolled and is used as a base, Figure 7. The radial component of the field for a single broken wire is shown in Figure 8, the axial component in Figure 9.

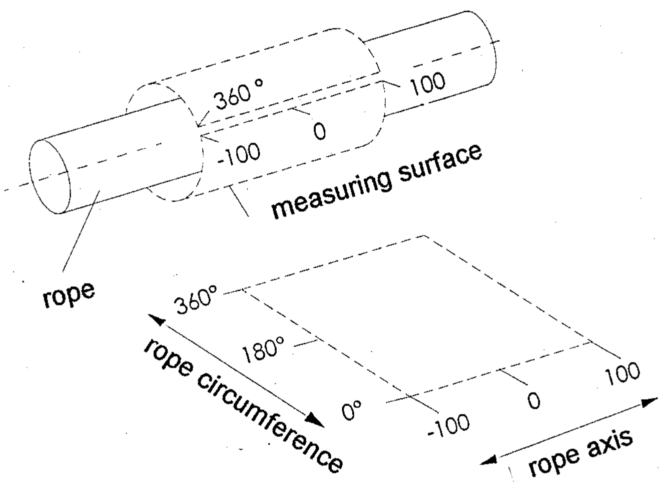

Figure 7. Unrolled measuring surface

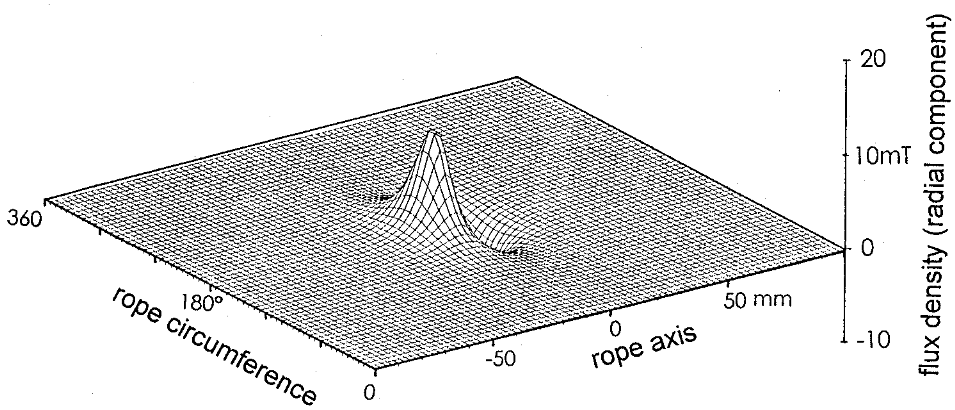

Figure 8. Radial component of scatterfield

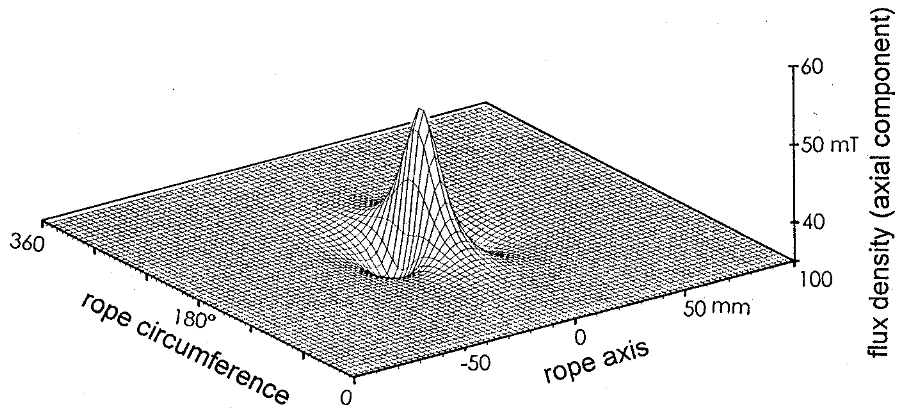

Figure 9. Axial component of scatterfield

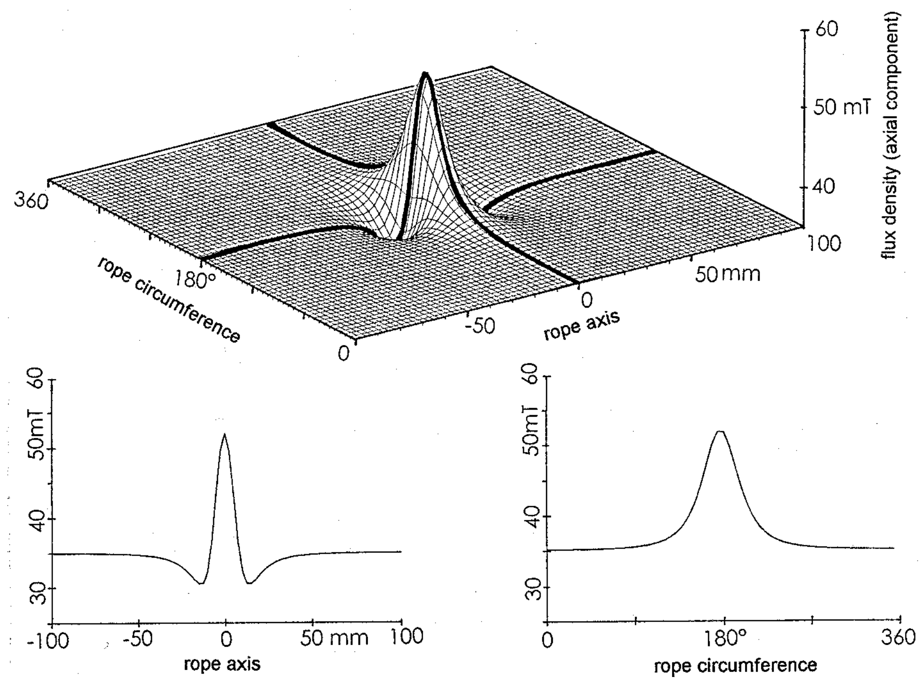

Figure 10. Intersections

For the interpretation of more complex fields, a longitudinal or transversal intersection through the surface can be very helpful. Figure 10 shows these intersections for the axial component of a scatterfield.

Detection of broken wires in clusters

For a typical track rope of an aerial tramway (first and secound layer made of z-wires) the scatterfields of broken wires in the second layer (from outside) are calculated. Why the second layer? In practice it is well known, that almost all broken wires are occuring in the second layer of modern track rope constructions. **Wang 1990** analysed the phenomenon and proved this hypothesis.

Longitudinally spaced wirebreaks: The signals (longitudinal intersection of the axial component of the scatterfield) for three different spacings Δz are shown from Figure 11 through Figure 13. In Figure 11 only one signal occures. With increasing spacing Δz (Figure 12 and Figure 13) two individual peaks are visible. The total separation of each individual wirebreak signal is shown in Figure 13. The spacing Δz is scaled in multiples of the rope diameter. With the help of the geometric congruence these results are universal, because the track rope designs are almost identically. Refering to Figure 12 and Figure 13 a definition for the limit of distinction has to be defined.

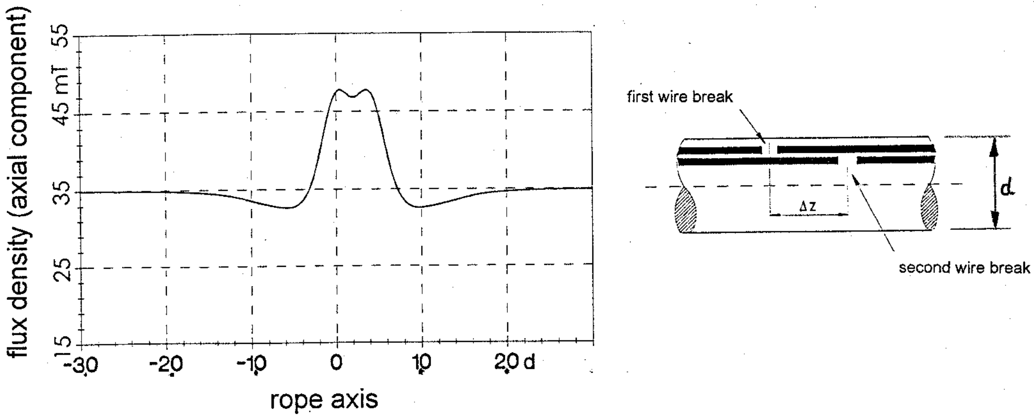

Figure 11. Two wire breaks, spacing Δz = 0.4 x d

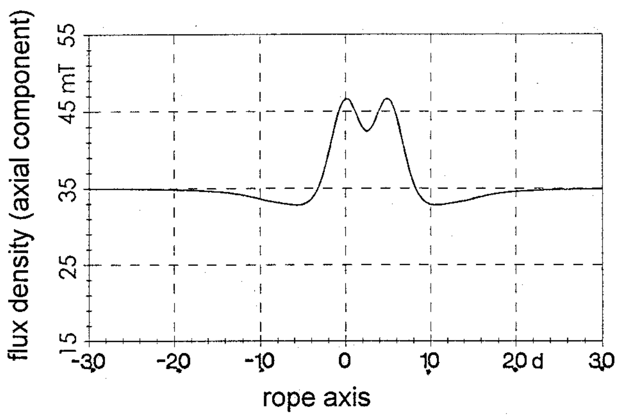

Figure 12. Two wire breaks, spacing Δz = 0.5 x d

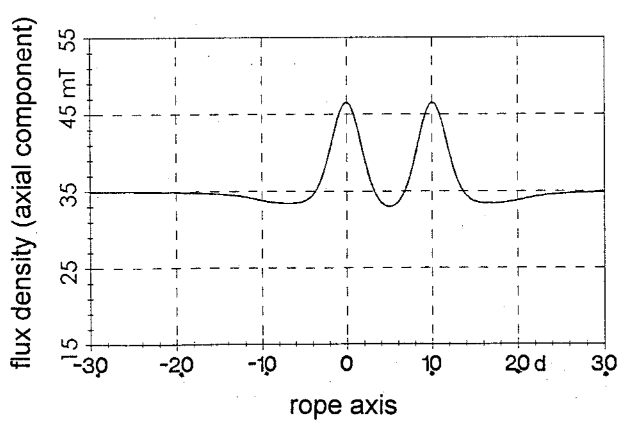

Figure 13. Two wire breaks, spacing Δz = 1 x d

From a practical point of view a drop of the signal between both peaks to the „zero line" is defined as the limit of reliable distinction of each individual broken wire. According to this definition, the smallest spacing Δz is 0.9 x d, e.g. for a
2 inch trackrope the minimum spacing Δz is 1.8 inches.

Circular spaced wirebreaks: The signals (transversal intersection of the axial component of the scatterfield) for three different angles δ are shown from Figure 14 through Figure 16.

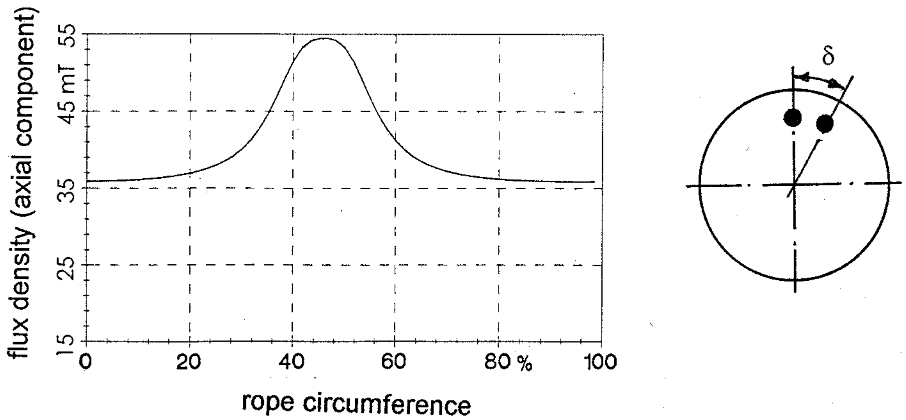

Figure 14. Two wire breaks, angle δ = 30°

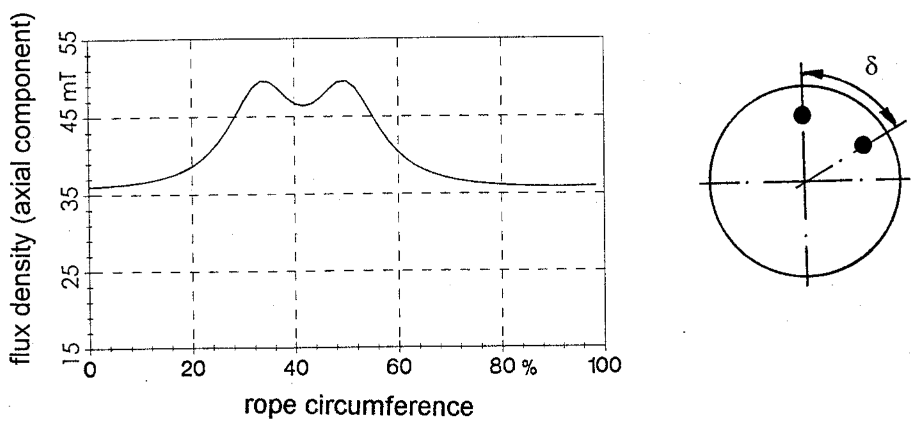

Figure 15. Two wire breaks, angle δ = 60°

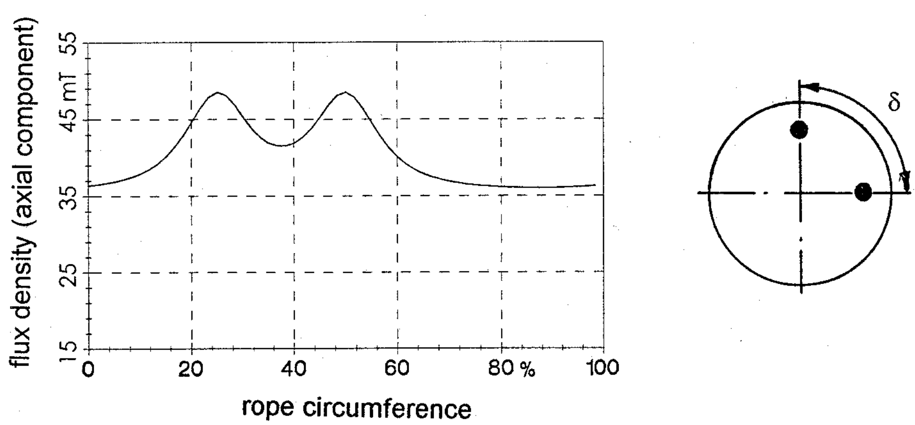

Figure 16. Two wire breaks, angle δ = 90°

Very similarly to the topics discussed above, with increasing angle δ two individual peaks in the signal are visible. The definition for the limit of distinction is a 20% drop of the magnitude between the two peaks. We examined an angle $\delta > 60°$.

For stranded ropes, e.g. 6x19 Seale + FC, the limits of distinction of two broken wires (actually no longitudinal spacing Δz) are shown in Figure 17. Two broken corewires are individual distinguishable in the case of two strands side by side, Figure 17b. The Seale wires are only distinguishable, if one strand is laying between the damaged strands, Figure 17c and Figure 17d.

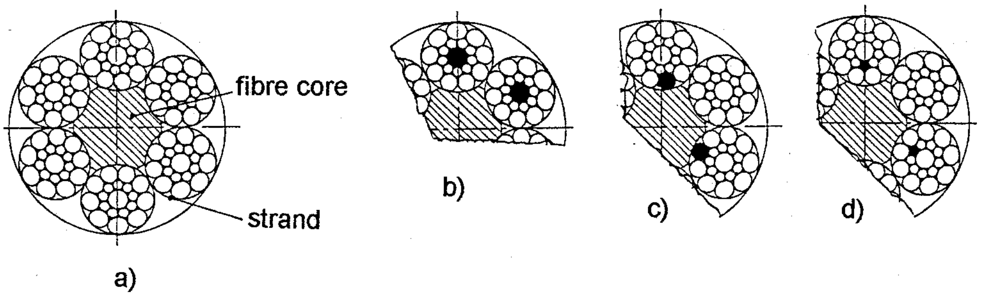

Figure 17. Distinguishable wirebreaks in a stranded rope

Comparison of measuring and calculation

The comparison between a measuring carried out by our institute in 1994 on the basis of the „High Resulution Wire Rope Testing“ (and as published by **Haller 1995**) and a calculation with the CCM is shown from Figure 18 through Figure 20. The tested rope was used in a bicable aerial tramway as a track rope. The rope diameter is 1¾ inches with two layers of z-wires. In a electromagnetic inspection done periodically, a „suspicious“ part was detected. This part of the rope was examined with the „STUTTGART High Resolution Wire Rope Testing Method“, our test result is shown in Figure 18. There are 13 individual wirebreak signals („hills“ in the surface image) recognizable. This rope has to be discarded.

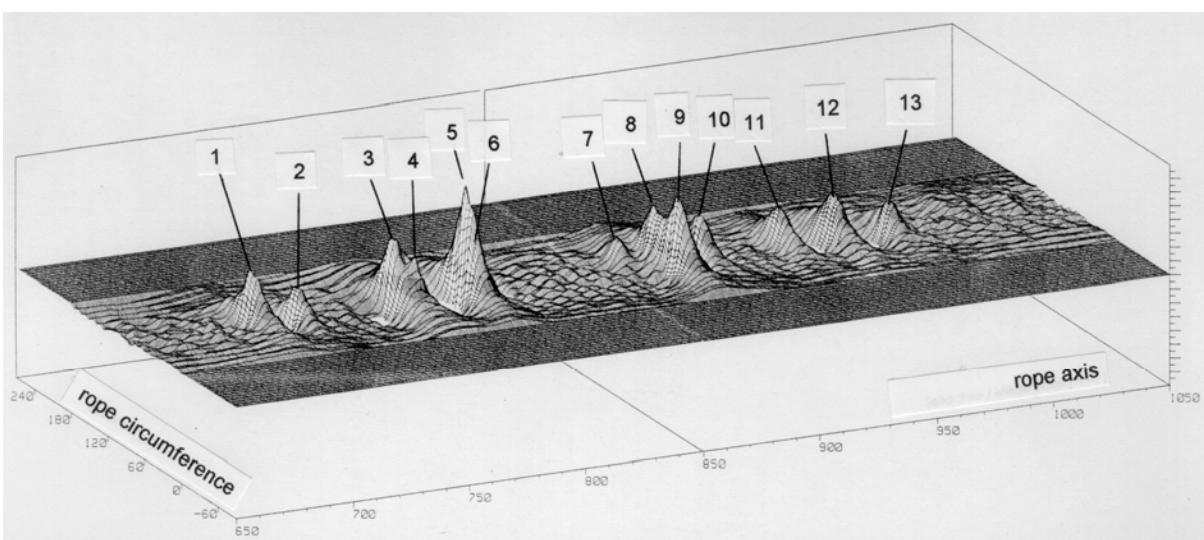

Figure 18. Measured scatterfield of the rope with the „Stuttgart High Resolution Wire

Rope Testing Method“

After replacing the damaged rope, the concerning part of the rope was sent to our institute. We removed the first layer of z-wires. The actuall damage was absolutely identical to our diagnosis, each of the 13 broken wires was found at the forecasted position, Figure 19.

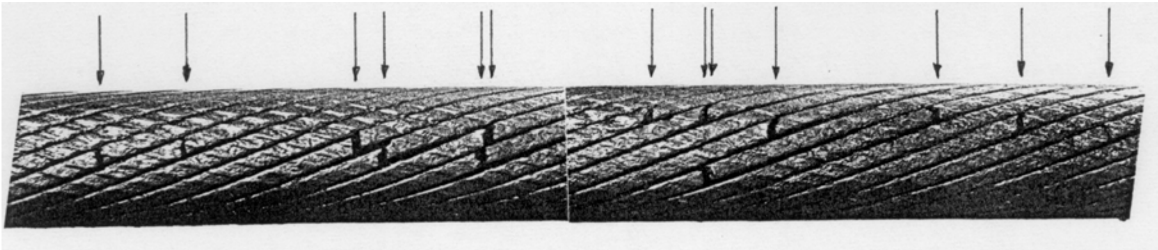

Figure 19. Actual damages at the secound wire layer

To verify our calculation method CCM, we entered the data of the actual wirebreaks into our program and calculated the scatterfield.

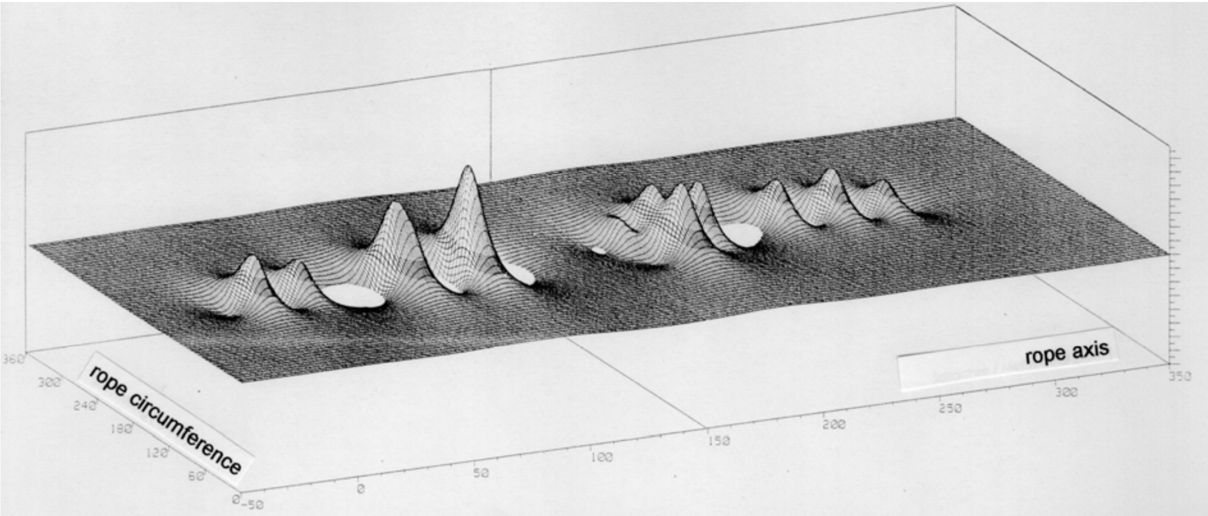

Figure 20. Calculated scatterfield of the rope damage with CCM

The calculated result is printed in Figure 20. Broken wires with small gaps are causing „small hills“ and vice versa. The comparison between Figure 18 and Figure 20 proves the quality of the CCM calculation method.

<u>Summary</u>

There are two possible ways to improve the knowledge of reading the test results obtained by the „High Resolution Magnetic Rope Testing Method“:

- testing damaged rope samples
- calculating the magnetic scatterfields of broken wires.

The basic knowledge about scatterfields of broken wires was discussed. Possible calculation methods were presented. A unique calculation method (CCM) was developed. With the CCM the scatterfields of two brocken wires -side by side- were calculated and limits of distinction of each individual broken wire were defined. A measuring, made with the „STUTTGART High Resolution Magnetic Rope Testing Method“ was compared with the calculated result of the CCM.

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