3.3.4 Measurements with the yoke

Putting together a string-ring wound with two coils is highly time-consuming. For any investigations into the market, simpler measurement approaches would thus be desirable. In the following, the **test-bench utilizing a yoke** will be introduced: it employs a ring-shaped electromagnet with an air gap. The string to be measured is inserted into the latter.

To measure magnet parameters, advantage is taken of the **continuity conditions** that appear at boundaries as the field permeates them [e.g. 7]. At the string/air-boundary, the tangential component of the field strength H is continuous. Therefore, if the axis of the string is directed in parallel with the field lines within the air gab, the field strength H_i internal to the string corresponds to the field strength H_L within the adjacent air layer. The field strength in the interior of the string can therefore be determined without having to actually enter the string. To **measure** H_L, two coils of different diameter are wound around the string: a tightly fitting inner coil with the diameter D_1, and coaxially a second coil with the diameter $D_2 > D_1$. As a sinusoidal AC-flux Φ flows through the string, induction voltages are generated in both coils. These voltages depend on Φ, on the frequency f, and on the turns-numbers. If both coils feature the same number of turns N, opposite-phase connection makes it possible to compensate for and cancel out the part of the voltage that results from the magnetic flux flowing through the inner coil. As a consequence, the combination of the two coils measures only the magnetic flux in the *ring-shaped range* between the two coil surfaces. Using this approach, the field strength H_L in air can be determined via μ_0 (the known permeability of air). H_L corresponds to the axial field strength in the string (provided there is homogeneity).

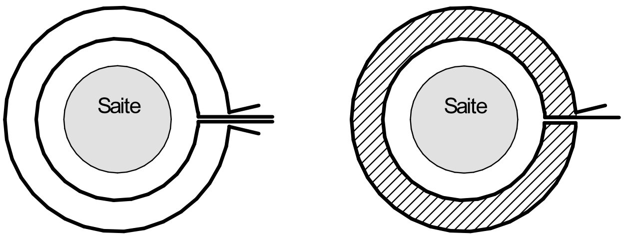

Fig. 3.9: Coaxial annular coil.
Left: two windings with 1 turn each.
Right: ring-winding for measuring H.

Fig. 3.9 presents a cross-section of the measurement setup. The magnetic field generated by an electromagnet (not shown in the figure) is directed perpendicularly to the viewing-plane. It runs in parallel to the string axis and permeates two coil-windings concentrically surrounding the string. The overall cross-sectional area is designated S_S, the cross-sectional area of the inner winding is S_1, and that of the outer winding is S_2. For reasons of clarity, each winding consist of merely one turn in the figure; in practice about 100 turns each yields a good compromise between sensitivity and (small) size. The number of turns of the two coils should be exactly the same♣; they are connected in opposite phase. Given this setup, only the magnetic field flowing between the two windings into the ring-surface forms a contribution to the induced voltage. In the right-hand part of Fig. 3.9, two ends of the windings are connected such that a winding W_H encompassing the ring surface ($S_2 - S_1$) results. The voltage induced in W_H depends, according to the law of induction, on the turns number N, and on the temporal change of the magnetic flux Φ_{Ring} permeating the ring surface. This flux is again a product of ring surface, magnetic field strength H, and the permeability of air μ_0.

♣ If both coil-voltages are recorded separately, correction can also be achieved via post-processing.

From the ring induction voltage U_H, the **field strength at the ring surface** H can be calculated:

$$U_1 = N \cdot d\Phi_1 / dt; \qquad U_2 = N \cdot d\Phi_2 / dt; \qquad U_H = U_2 - U_1 = N \cdot d\Phi_{Ring} / dt$$

$$\boxed{H = \int \frac{U_H}{N \cdot \mu_0 \cdot (S_2 - S_1)} dt}$$

$S_2 - S_1$ = ring surface, $\mu_0 = 4\pi \cdot 10^{-7}$ Vs/Am

Prerequisite for exact measurements is a homogenous H-field; with pole shoes of high magnetic conductance this can be generated with sufficient accuracy. The measuring coils can be wound with very thin wire, making small dimensions possible. About 100 turns will generate induction voltages in the range of 10 – 100 µV, which is comfortably measurable with a low-noise amplifier. Highly significant is avoiding measurement of external interfering fields (connecting lines, shielding, grounding!). In case not the voltage of the ring winding is recorded, but rather the individual voltages of the two coaxial coils, particularly high precision is required: the ring-voltage U_H results from the difference of two voltages that may potentially differ by a factor of 100. Any imbalance between the measurement channels (even as small as in the ‰-range) may lead to unacceptable errors.

On top of the **field strength at the ring surface** H (that approximately corresponds to the axial field strength of the string), the axial **flux density of the string** needs to be measured as the second field quantity. Magnetic flux in the string Φ and flux density in the string can be determined via the voltage U_1 induced in the inner coil. However, this involves a systematic error because the inner coil will not directly touch the string in a test-bench suitable for various string diameters. Instead of measuring only the part of the flux that flows through the string, a part of the flux that flows through the surrounding air is measured in addition. Given high permeability of the string, this error would possibly be negligible – but in the saturation range the string-permeability is precisely NOT high anymore, and the error would be inacceptable. Still, there is an elegant way to directly measure the magnetic **polarization** J of the string. J may be imagined as "material-bound part of the flux density". Given imprinted field strength H, the flux density $B_0 = \mu_0 \cdot H$ results in air. Introducing ferromagnetic material into this H-field will increase the flux density to $B = \mu_r \cdot B_0$. This is transformed to:

$$B = (\mu_r - 1) \cdot B_0 + B_0 = J + B_0 \qquad J = B - B_0$$

J = magnetic polarization

Thus J is the share by which the flux density increases (from B_0 to B), depending on the given material. Now the voltages induced into the windings W_1 and W_2 can be rearranged into:

$$U_1 = S_1 \cdot N \cdot \dot{B}_0 + S_S \cdot N \cdot \dot{J} \qquad U_2 = S_2 \cdot N \cdot \dot{B}_0 + S_S \cdot N \cdot \dot{J}$$

$S_1 \cdot N \cdot \dot{B}_0$ is the part of the voltage that would be induced into the inner coil if there were no string present. The part of the voltage delivered by the string is added as the second summand $S_S \cdot N \cdot \dot{J}$. In both voltage equations, $\dot{B}_0$ may be eliminated, and J can be calculated♣:

$$\boxed{J = \int \frac{U_2 - kU_1}{(k-1) \cdot N \cdot S_{\text{string}}} dt} \qquad k = S_2 / S_1$$

Given known geometry of the coils, the field strength and the polarization in the string can now be determined from the two coil-voltages U_1 und U_2.

♣ The letter J is – loco citato – also used for the electrical current density!

The accuracy for the *H*-measurement is determined by the ring voltage U_H and the area of the ring. The potential problems with forming the difference have already been noted. The ring area should be very small in order to capture exclusively the field in the air directly next to the string; this makes the precise determination of area difficult, though. A solution is the use of Helmholtz-coil enabling us to generate a highly accurate magnetic field and to calibrate the *H*-measurement that way. For establishing the value of *J*, especially the area-ratio $k = S_2 / S_1$ needs to be precisely known. Calibration is done without string: the value of *k* is corrected as necessary until *J* reaches zero. For the integration (which advantageously is performed with digitized signals in a simple manner), attention needs to be paid to extremely precise offset-compensation. If errors occur here, the hysteresis curve fail to close in the case of multiple revolutions; it will rather diverge, or be represented with the wrong width.

Fig. 3.10 shows measurement results of a “no-name” string that were gathered with the measurement setup as described above. The *H*/*J*-relation is typical for metals that are magnetically hard to a lesser degree. We obtain $_JH_C$ = 1,6 kA/m for the **coercitivity**, and we get J_R = 1,4 Tesla for the **remanence**. A comparison with “name products” (**Fig. 3.11**) indicates small differences regarding the magnetic parameters. The sources of these differences cannot be clarified unequivocally – it may be assumed, though, that the tolerances due to the test bench are in a similar order of magnitude. Let us therefore remind ourselves that measuring magnetic parameters requires much effort, and despite this effort they can only achieve a modest accuracy.

This figure is reserved for the print version of this book

This figure is reserved for the print version of this book

Fig. 3.10: Hysteresis-loops measured on the yoke-test-bench for a “no-name” string (∅ = 0,43mm, plain). The measurement frequency (2 Hz) is sufficiently low for individual strings.

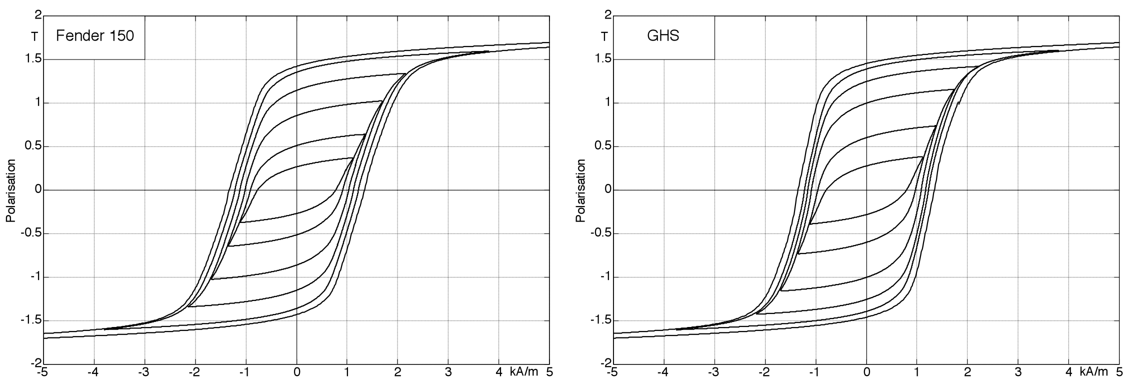

Fig. 3.11: Hysteresis-loops measured on the yoke-test-bench for “name” strings (∅ = 0,43mm, plain).

