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SHIELDED CABLES
WITH OPTIMAL BRAIDED SHIELDS

by

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Original title: Geschirmte Kabel mit optimalen Geflechtschirmen (in German)

Translated from: Nachrichtentechnische Zeitschrift, **1968**, No. 3, 155-61

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1. General

1.1. *Statement of problem*

Braids on high-frequency cables function as not only outer conductors but also shields. A braid is therefore expected to afford good shielding against magnetic fields generated by interference currents. The shielding effectiveness of a cable is measured by the transfer impedance of the outer conductor.

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According to DIN[1] 47250 [1], the transfer impedance is the ratio of the voltage drop along the shield on the interference side (outside) to the interference current on the other side (inside) of the shield. The lower the transfer impedance,[2] the better the shielding action of the braid.

If the transfer impedance increases with increasing frequency, (curves 1a and 1b in Fig. 1), the braid design is poor. Curve 1a represents the typical behavior of a braid with a very high optical density; 1b, for a braid whose optical density is too low. The two curves have been shifted perpendicular to one another by the use of different ohmic resistances (the ohmic resistance is roughly equal to the transfer impedance at 0.1 MHz).

In a good braid (curve 2 in Fig. 1), the transfer impedance as a function of frequency goes through a minimum, whose location depends on the diameter of the wires in the braid and the quality of the braid. If the minimum lies at a fairly high frequency, it is very strongly marked. This implies a substantial increase in transfer impedance at high frequencies. After the minimum, the transfer impedance rises in a linear fashion. The slope is roughly the same for all braids and nearly the same as that of the lines connecting the maximum permissible values from the standards cited.

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[1]German Industry Standard.

[2]Maximum permissible values: 30 mΩ/m at 10 MHz (Marine-Norm VG 88776), 500 mΩ/m at 200 MHz (VDE [German Electrotechnical Standard] 0855 Part 2).

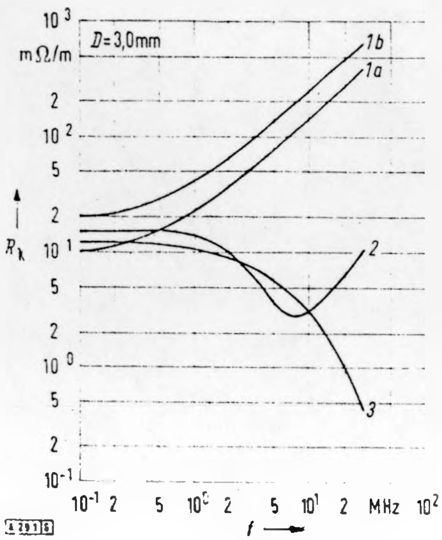


Fig. 1. Transfer impedance versus frequency for various outer conductors. Curves 1a, 1b and 2 measured, 3 calculated.

1a 112 × 0.15, B = 88.2%, α = 45°

1b 64 × 0.15, B = 98%, α = 20°

2 88 × 0.15, B = 79.1%, α = 21°

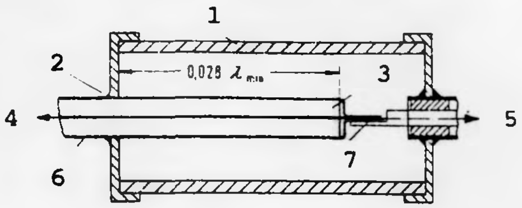
3 Cu tube, 0.15 mm thick, B = optical coverage, see Eq. (3)

There have been a number of studies on the shielding effectiveness of braids, and no doubt remains that the transfer impedance depends on the ohmic resistance, the skin effect and an inductance. Krügel [2] concluded that the inductances of oppositely directed braid elements cancel, so that the increase in transfer impedance must be due solely to stray inductance. Since a closed tube has no stray inductance, the transfer impedance very rapidly approaches zero because of the skin effect (curve 3 in Fig. 1). In order to minimize the stray inductance of braided shields, Krügel recommended the use of designs with an optical coverage of over 90%, braiding machines with the greatest possible number of elements, and heavy-gage braid wires.

For a given wire gage, the transfer impedance necessarily decreases with increasing cable diameter, though at the offsetting cost of more wires. The reason is that the ohmic resistance of the shield becomes smaller. The effect on ohmic resistance due to heavier wires in the braid leads to an improvement in a given frequency range, but the price of the cable goes up rapidly.

This approach would not be attractive unless the required shielding effectiveness could not be provided even given a favorable R_k versus f curve.

The goal of the work reported here was to find laws describing optimal braid designs. The term "optimal" refers to the shape of the curve, not the absolute transfer impedance. VDE 0874/3.59 [5] includes a plot of the quotient transfer impedance/ohmic resistance versus frequency (i.e., standardized curves all with starting value 1, allowing a ready quality comparison).



1 Measuring tube
2 Soldered
3 Test cable
4 Detector
5 Generator
6 Braid
7 Shorted termination soldered

Fig. 2. Measuring setup.

1.2. *Measurement technique*

The method of DIN 47250 [1] was used to measure the transfer impedance at frequencies of 0.1-30 MHz. The length of cable inside the measuring tube was 185 mm, corresponding to $0.028\lambda_{min}$. Since the length was less than $0.05\lambda_{min}$, the terminating impedance could be replaced by a short circuit. The interference current I_{st} and interference voltage U_{st} were measured; the transfer impedance R_k in mΩ/m was determined as

$$R_k = U_{st}/I_{st}l, \qquad (1)$$

where l is the measuring length.

Interchanging the detector and generator connections in the test setup of Fig. 2 led to the same results. The reversal changed the sense of the interaction. This result confirmed that good shielding effectiveness relative to external interference fields also implies low energy release and high crosstalk attenuation.

1.3. *Geometry of a braid*

For reasons of symmetry, a normal shielding braid has the same number and diameter of wires in each helical direction. The wires are grouped in braid elements or "picks," all containing the same number of wires.

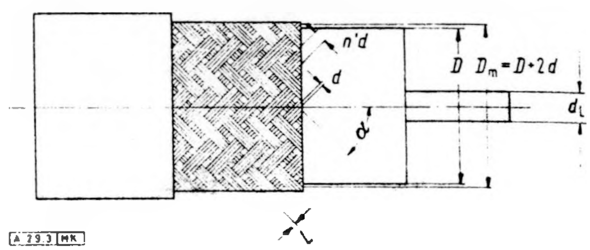


Fig. 3. Geometrical parameters of a braid.

The coverage afforded by the wires going in one helical direction is the braid density (filling factor) G:

$$G = nd/(2\pi D_m \cos \alpha), \tag{2}$$

where n is the number of wires in the braid, d is the wire diameter (mm), D is the inside diameter of the shield (mm),

$D_m = D + 2d$ is the mean braid diameter (mm), and α is the braid angle (°).

The uncovered spaces between the picks in one helical direction are called "gaps" and symbolized by L. The leads in the other helical direction cover a fraction of the gaps equal to the filling factor. The total coverage of a braid is the optical coverage B:

$$B = G + (1 - G)G = G(2 - G). \tag{3}$$

Customers often specify minimum values of the optical coverage. The requirement is formulated in the following way for shipboard cables: "The filling factor shall be so great that the weight of the braid is at least 90% of the weight of a tube that consists of the same metal, has an inside diameter equal to the diameter inside the shield, and has a wall thickness equal to the diameter of a braid wire."

The following relation holds between a given percentage k and the braid density:

$$G = \frac{2k}{\pi} \frac{D + d}{D + 2d}. \tag{4}$$

For approximate calculations, the second fraction in (4) can be neglected, since it approaches unity as the diameter increases.

The simplified formula is

$$G \approx 0.637k. \tag{5}$$

The braid weight P in g/m can be found as

$$P \approx 44GD_m d. \tag{6}$$

The braid angle α is given by

$$\tan \alpha = D_m \pi / s. \tag{7}$$

This is the acute angle between the cable axis and a pick, as defined in [1] and illustrated in Fig. 3.

2. Parameters of the braid

2.1. *Optical coverage*

Of all known braid-shielded coaxial cables, some 50% have an unfavorable transfer impedance versus frequency curve. The design guidelines in force have obviously not been sufficient to define good braids in a reliable way. In a first series of tests, the relationship between the transfer impedance and the optical coverage was investigated.

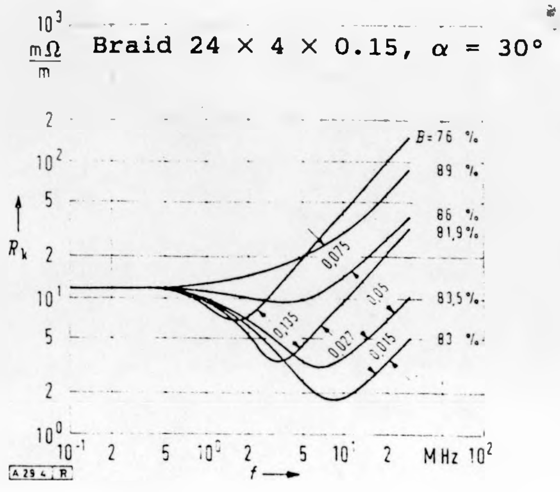


Fig. 4. Effect of optical coverage on transfer impedance for equal copper contents.

The number of wires, wire diameter, number of picks, and braid angle were held constant.

The core diameter and the pitch were varied.

Fig. 4 shows the result of this series. The distinct quality differences between braids can be entirely attributed to differences in the optical coverage. There is a quite definite optical coverage that gives the best curve. All coverages different from this value, no matter whether larger or smaller, give worse curves. The numbers written between the curves represent the increases (in mm) in the gap L between picks from one curve to the next. On the basis of the measured family of curves, the shape of any curve indicates with fair reliability whether a braid can be improved by increasing or decreasing the braid density.

The result shows that, with the constants used, an optimal braid design can be achieved only for a certain narrow range of core diameters.

2.2. *Effect of braid angle*

The best braid designs for various braid angles were found from similar families of curves. For any angle in the usual range of 20-40°, an optimal braid structure exists. There are no quality differences between the optima for various braid angles. All the customary braid angles are equally suitable for the production of a good braid design. Fig. 5 shows the optimal curves for three braid angles. Qualitatively, they are in very good agreement, showing that the coverage giving the best braid design differs from one

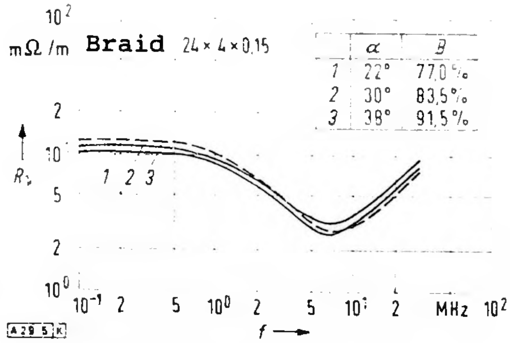


Fig. 5. Transfer impedance versus frequency for optimal braid designs corresponding to various angles α.

braid angle to another. The coverage must be greater for large angles than for small ones. Large-angle braids thus require more copper and cost more to produce (because of the lower plaiting speed) than do those with small angles.

Braids in use up to now have generally been designed with small angles for high plaiting speed and low production cost, but there has been an effort to achieve a high optical coverage such as must be taken at large braid angles according to the present results. This practice, however, gives braids with a very poor transfer impedance.

Fig. 6 presents three curves for distinct braid angles but equal optical coverage. This plot again brings out that there is a best optical coverage for every angle. A coverage of 83.5% is too high for 22° and too low for 38°. Curves 1 and 3 reveal the typical curve shapes for braids

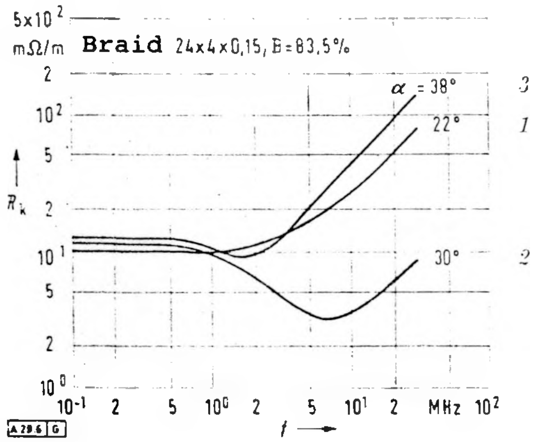


Fig. 6. Transfer impedance versus frequency for equal optical coverage but various braid angles α.

with coverage too high and too low. If the coverage is still further reduced, curve 3 ultimately ceases to display even the minimum that can be seen in Fig. 6 (compare curve 1b in Fig. 1).

2.3. *Effect of element width*

For a given angle, the filling factor for the 24 × 4 × 0.15 braid did not give an optimal structure for the 24 × 5 × 0.15 braid. One possibility was that what has to be reproduced is the gap, not the density. But a test of this hypothesis did not lead to success, so series of tests were needed in order to determine the optimal values for several angles at each element width.

The gap must also grow larger when the braid element increases in width, but the two quantities do not increase in the same proportion. The optical coverage increases with increasing element width. It must be emphasized that the absolute size of the gap does not directly relate to the quality of a braid. The gap or filling factor for the optimal design is a function of the braid angle and the number of wires per pick.

Fig. 7 illustrates these relationships for three element widths. The dependent variable in this plot is the gap divided by the element width, since this choice brings out the differences that exist. The curves have been

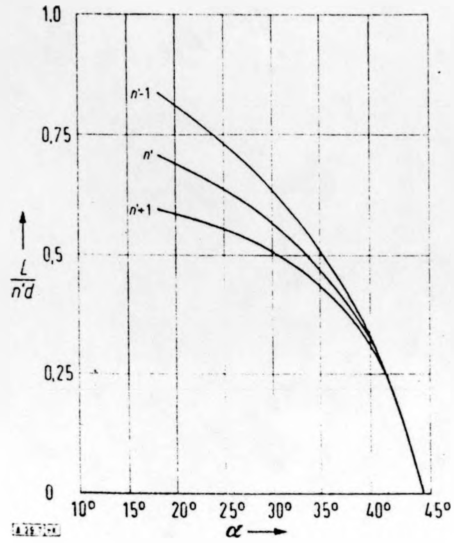


Fig. 7. Ratio L/n'd (L = gap, n'd = element width) versus braid angle.

extrapolated out to an angle of 45°, where they all meet in a point; in this limiting case, the gap takes on a value of L = 0 for all element widths.

2.4. *Effect of the number of picks*

The number of elements used by the plaiting machine has no influence on the quality of the braid, provided the correct coverage has been selected as a function of the braid angle and element width. For example, if a 16 × 6 × 0.15 braid is a good design for a mean diameter of D_m = 4 mm and a given angle, then for D_m = 6 mm and the same braid angle a design of 24 × 6 × 0.15 is also good, since it represents no change in the critical values of braid density, braid angle and element width. If, on the other hand, the diameter inside the braid is held constant and the 24 × 4 × 0.15 braid is taken for comparison, the difference in element width must result in quality differences. In any case, the 24 × 4 × 0.15 braid will be a worse design if 16 × 6 × 0.15 was optimal; the converse also holds, even though the number of wires in the braid is the same in both designs.

2.5. *Effect of wire diameter*

All experimental results reported up to now have been obtained with bright-finished wires 0.15 mm in diameter. Altering the wire diameter did not yield any new knowledge. Any good braid design can be proportionally enlarged. If, for example, a 16 × 7 × 0.1 design is good for a mean braid diameter of 3 mm, the same applies to

$$16 \times 7 \times 0.15,\ D_m = 4.5\ \text{mm}$$

$$16 \times 7 \times 0.2,\ D_m = 6.0\ \text{mm}$$

$$16 \times 7 \times 0.25,\ D_m = 7.5\ \text{mm}$$

Because of the skin effect, however, good designs with unequal wire diameters will differ. If the ohmic resistance is eliminated [5], the effect of the wire diameter on the

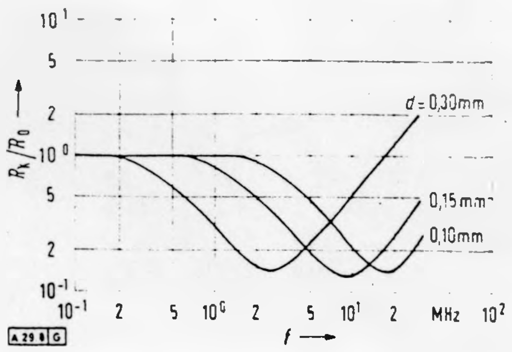


Fig. 8. Standardized curves for optimal braids with various wire gages.

shape of the impedance versus frequency curve is easy to see. The optimal designs for several wires have been plotted in this way in Fig. 8. As the wire diameter increases, the minimum shifts toward lower frequencies. This means that the superiority of heavy-gage wires, with their correspondingly low ohmic resistance, over thinner ones will extend only up to a frequency a little below the minimum-impedance point. In the region where impedance is proportional to frequency, the optimal-braid curves for various wire gages lie so close together that the heavier gages have no discernible advantage.

2.6. *Effect of wire surface*

Silver-plated and tinned copper wires are subject to the design rules stated here, just as are bright copper wires. Any effect on conductance due to these thin metal coatings is overshadowed by the effects of slight changes in braid geometry.

No study has yet been done to determine how great the (usually imperceptible) effect of metal coatings is; it will not be easy to obtain results, for changing a braid-plaiting machine over to a different kind of wire inevitably results in a different braid structure because of the tolerances established for the wires. Any attempt to separate the effects due to these two causes will run into serious difficulties.

Because the use of lacquered copper wires was expected to have a greater influence on the transfer impedance, a number of braids were made from such wires and measured. Fig. 9 presents three curves for braids consisting of lacquered wires. The best of the curves has a markedly good shape, and it is probably possible to obtain a still better-marked minimum by modifying the geometry. But it is not

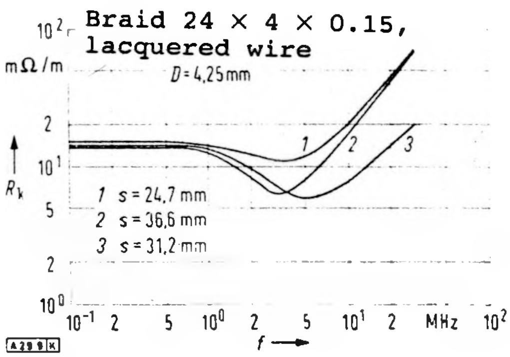


Fig. 9. Transfer impedance versus frequency for lacquered wire braids with various pitches s.

common to plait lacquered wire, so no supplementary trials were run. It can, however, be said with confidence that contacts between the wires and at the crossing points are not important for the transfer impedance, so that lacquered-wire braids will exhibit largely the same behavior as already described.

3. Interpretation of results

3.1. *Selection of cable diameter*

It was found that only the *correct filling factor*, which depends on the braid angle and the element width, leads to an optimal transfer impedance. Eq. (2) contains all the important quantities. The element width is given by the number of wires handled by the plaiting machine. The proper density is found empirically. If the independent variables are separated, for example as

$$\frac{D_m \cos \alpha}{d} = \frac{n}{2\pi G(\alpha, n')} = \frac{n'E}{2\pi G(\alpha, n')} = F, \qquad (8)$$

where n' is the number of wires per pick, E is the number of elements, $n = n'E$ is the total number of wires, the factor F can be plotted versus the angle in two ways. The two families of curves have the diameter D inside the braid and the

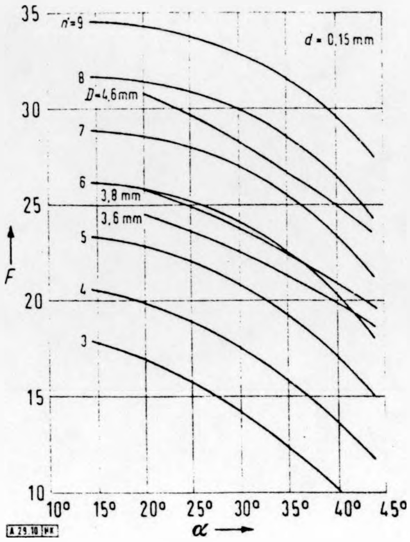


Fig. 10. Diagram for finding optimal braid designs (16 elements, 0.15 mm wire diameter).

number of wires n′ per pick as parameters. Any intersection of the two families satisfies the conditions for a good braid design. Fig. 10 is a plot for three typical diameters. There exist cable diameters for which the 16-pick plaiting machine cannot make a good braid in the range of angles shown. Other diameters--which at, say, 20° lie exactly halfway between two successive element widths--do not have any intersections at angles less than about 40°. The cost of such a braid averages 65% higher than that of a braid that has its best design at 20°. A substantial gain in quality or reduction in cost can be achieved by selecting the best diameter inside the braid.

3.2. *Mixed-element technique*

The optimal braid design represents the best interaction of the relevant braid parameters. The optimum plays off several effects against one another. Departures from the optimum result from different causes in braids whose filling factors are too great and too slight. Because braids made with lacquered wire behaved in the same way as others, the offsetting action must take place in an individual braid wire. For a given diameter and a given angle, then, an appropriate mixture of braid elements (picks) too wide and too narrow for an optimal design might also show such compensation. This assumption has been confirmed: Fig. 11 shows a family of curves from which we can see that an optimum is also found under the "mixed-element" principle. With a normal design it is not possible to make a good or economical braid for an arbitrary cable diameter. If the increment in wire number is equal to the number of picks, this produces a very coarse adjustment to the transfer impedance.

The mixed-element technique offers a fine adjustment, making it much easier to achieve a desired optimum than it would be with a normal braid. A cable of *any* diameter can be provided with an excellent braid having *any* angle. Because the angle can be freely selected, a good braid can always be made in an economical way.

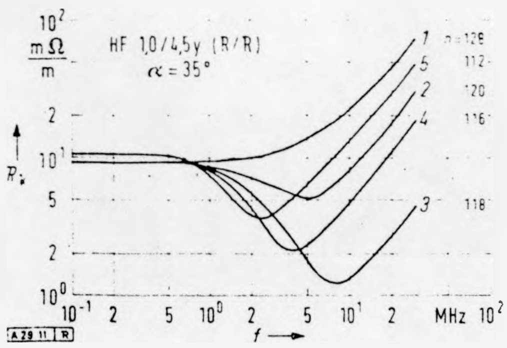


Fig. 11. Optical coverage modified by mixed elements.

1 16 × 8 × 0.15, B = 95.2%

2 (8 × 7 + 8 × 8) × 0.15, B = 92.7%

3 (10 × 7 + 6 × 8)0.15, B = 92.2%

4 (12 × 7 + 4 × 8) × 0.15, B = 91.4%

5 16 × 7 × 0.15, B = 89%

Fig. 12 is a plot for braids with mixed elements. Existing cable diameters were used, and the braid angle was chosen arbitrarily. The design can be determined with a nomograph similar to Fig. 13. These results will soon make ineffective braids a thing of the past.

The interval between the element-width (n) curves in Fig. 13 have been appropriately subdivided in order to simplify the process of determining the proper mixing ratios. The second family of curves, for suitable gear ratios, contributes to the same end. Any mixing ratio can be selected; the correct pitch is then given in terms of the gear ratio. The nomograph has as its parameters the number

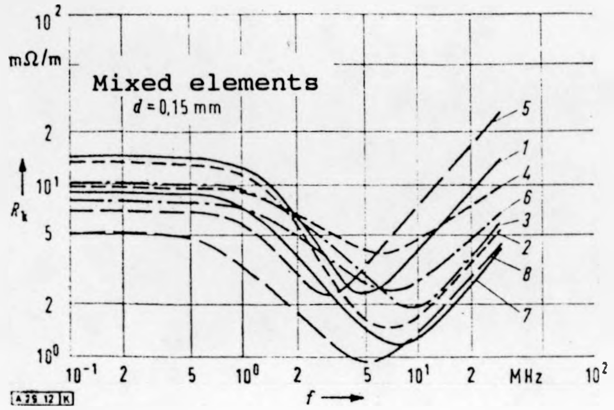


Fig. 12. Mixed-element braids.

Curve	1	2	3	4	5	6	7	8
D, mm	3.2	3.6	4.3	4.5	5.2	5.8	6.3	7.2
α, °	25.2	35	24.9	25.2	29	21.4	39.8	26.7

of elements and the wire diameter, so one nomograph must be prepared for each wire diameter and each plaiting machine in order to select the braid design.

When the mixed-element principle is applied, the braid elements will normally differ from one another by one wire. To establish how larger differences between elements affect braid quality, widths differing by as many as four wires were selected. Fig. 14 shows the result. Even though the number of wires is smaller than in the other braids, curve 2 has the lowest ohmic resistance. The ohmic resistance varies as the cosine of the braid angle. This means that, if the angle is too large, the larger amount of copper used

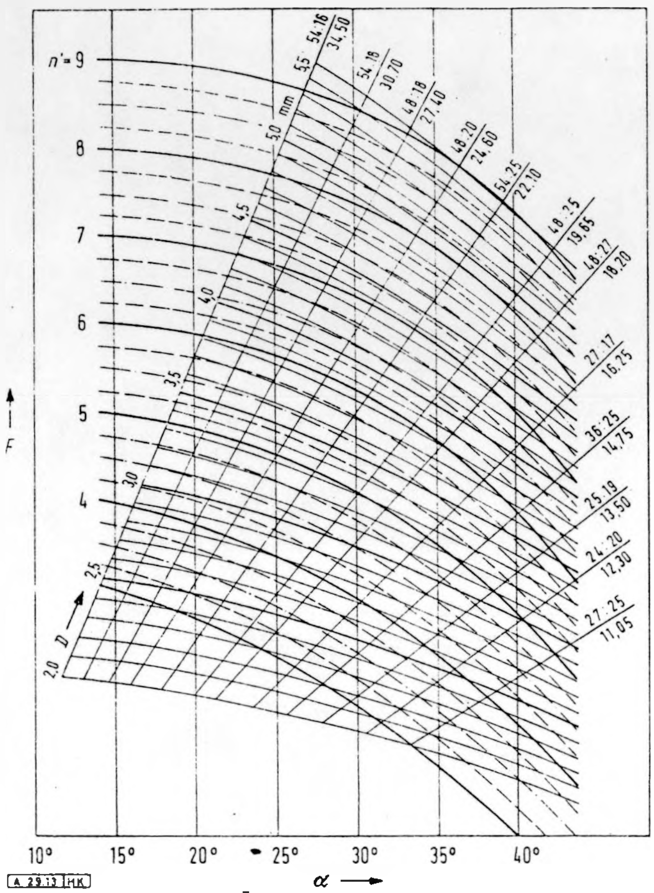


Fig. 13. Nomograph for obtaining design figures (16 elements, wire diameter 0.15 mm).

cannot have a beneficial effect on the ohmic resistance. A braid produced with a small angle on economic grounds thus has no disadvantage, from the electrical standpoint, in comparison with a braid having a higher optical coverage.

Another important advantage to braids with mixed elements is that the design can very easily be adapted to the actual diameter of the cable core.

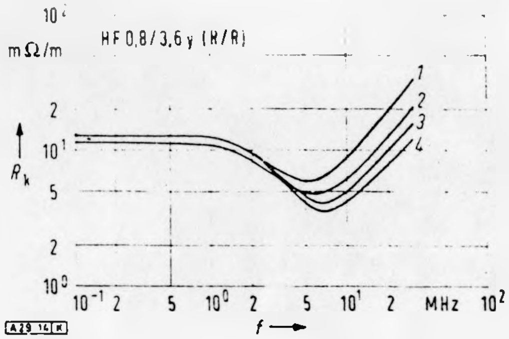


Fig. 14. Mixing of element widths, various increments.

1 16 × 6 × 0.15, B = 94.8%

2 (8 × 5 + 8 × 6) × 0.15, B = 81.8%

3 (8 × 7 + 8 × 5) × 0.15, B = 94.8%

4 (8 × 4 + 8 × 8) × 0.15, B = 94.8%

3.3. *Recommended tolerances*

There is always an optimum if the minimum ohmic resistance is 1/6 to 1/8 times the initial value. In practice, fabrication tolerances will prevent the theoretical optimum being reached except in a very few cases.

Fig. 15 shows the transfer impedance versus the tolerance in the inside shield diameter, measured at 10 MHz. The values come from Figs. 4 and 11. To either side of the minimum, the transfer resistance is proportional to the tolerance. According to Fig. 15a, the transfer impedance of a 24-pick braid at 10 MHz can be held to about 15 mΩ/m if

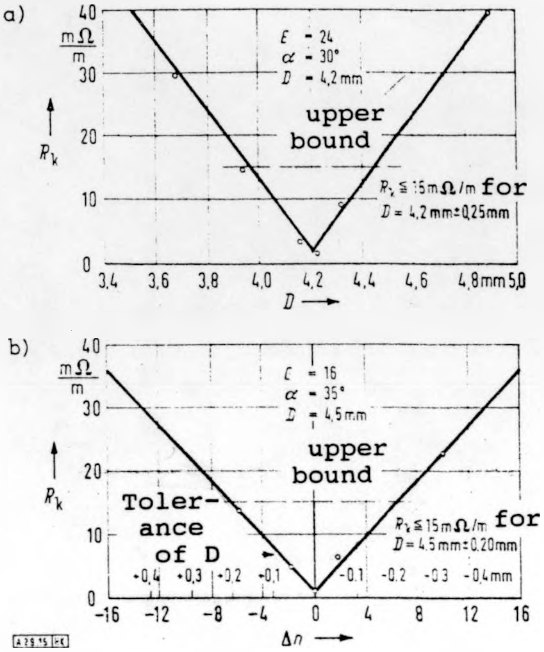


Fig. 15. Transfer impedance versus fabrication tolerance at 10 MHz.

(a) Diameter and pitch varied

(b) Increment Δn in number of wires

the diameter tolerance is ±6%. According to Fig. 15b, the same impedance value can be attained in a 16-pick braid at a tolerance of ±4.4%.

The tolerance range depends to some extent on the braid angle. The tolerances of 24- and 16-pick plaiting machines at a given braid angle would differ by a factor of 1.5. The mean tolerance on the diameter of the braid wires leads, for the same value as above, to the same result. If the tolerances for the core and wire diameters are set at ±3%, no fabrication difficulties occur, and the transfer impedance values are some way below the maximum. In general, the margin will be 50%. The braid design must, however, be optimized as much as possible in planning, so that it will not force wider tolerances. It is easy to meet this requirement with the mixed-element technique.

3.4. *Other Applications*

The rules worked out here for obtaining a good transfer impedance can also be used for assessing the quality of an existing braid by looking at the design. In many cases it will be sufficient to replace time-consuming measurements by a design inspection.

DIN 47250 [1] states the following under 2.12.4: "In some cases, contrary to what was said in Section 2.12.1, the electrical coupling cannot be neglected in comparison with the magnetic coupling, especially in the case of coaxial cables with low filling factors. A suitable measurement method for determining the shielding effectiveness of such braids is in preparation." But the standard did not define more closely *what* a low-filling-factor braid is.

The filling factor of an optimal braid is probably a suitable criterion for low filling factor. If this supposition proves correct, then many braids at present are not being measured by the correct method, because the optical density alone is not enough to indicate that a braid has too low a filling factor from the electrical standpoint.

4. Various shielding designs

It has been stated [2, 3] that braids are less effective shielding structures than double cages. This may be an appropriate conclusion, given that there was no solid knowledge of optimal braid designs when the comparisons were made.

In the future, it will be necessary to weigh the advantages and disadvantages of the two approaches very carefully. Economic considerations will probably work in favor of braids. Calculations have shown that, for a given wire diameter and a given shielding effectivess, a cable with double-cage shielding costs an average of 30% more than the same cable with a braided shield.

A double cage is superior to a braid only when a certain ohmic resistance is required for the shield and this standard can be met only by using wires larger than 0.3 mm in diameter, since 0.3 mm is generally regarded as the upper bound on the diameter of braid wires.

For a concrete example, Fig. 16 shows the relationship between the curves for double cages, single braids and double braids, eaching having the same wire diameter and the

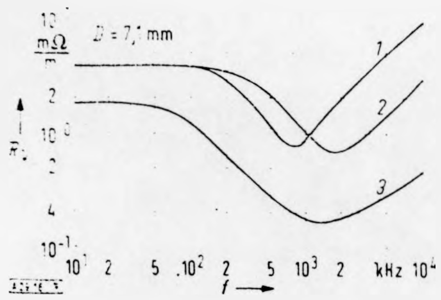


Fig. 16. Transfer impedances compared for various shield structures (g is the amount of copper used in g/m).

	α	d, mm	s, mm	g, g/m
1. Double cage	45°, 49°	0.3	33/38	98.5
2. Single braid 24 × 3 × 0.3	25°	0.3	52	50.2
3. Double braid 24 × 3 × 0.3 with film insulation	25°, 25°	0.3	52/60	100.4

best design for that diameter. Double cages and single braids generally have the same ohmic resistance. Below 1 MHz, the double cage has a better curve; over 1 MHz, the braid.

If, however, the amount of copper g and the production cost are compared (pitch ratio 1:1.6), the small gain from using the double cage instead of the braid at frequencies below 1 MHz is bought at a dear price. Even a double braid is less costly than a double cage, even though it offers a corresponding improvement in transfer impedance.

5. Summary

Extensive tests were done in order to determine what factors govern the design of braids with good shielding effectiveness. The results are purely empirical and relate to the geometrical relationships between the braid parameters.

The influence of various parameters on the shape of the transfer impedance versus frequency curve were investigated step by step. It was found that the optical coverage had been overestimated in the past. Good shielding effectiveness results not from high optical coverage as such, but from the proper type of coverage, which is a function of the braid angle and the element width. These dependences were measured for the ordinary range of braid angles (20-40°). They apply to all plaiting machines and all gages of braid wire. The design rules are largely the same for bright, tinned, silver-plated and even lacquered copper wires.

A new type of braid, which has marked advantages over the conventional design, was proposed. With the "mixed-element" technique, an optimal braid design can be specified on any plaiting machine, for any possible cable diameter, and for any desired angle. This is not possible for the conventional type of braid.

Literature cited

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