An Investigation of Magnetic Spectra of Solid Solutions of Some NiZn-Ferrites in the Radiofrequency Range

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Results are presented of the investigations of magnetic spectra of NiZn ferrites with initial permeabilities $\mu_a \approx 200$, 400, and 2000 gauss/oersted in the range of 0.2-60 megacycles/sec. An examination is made of the method of measuring the spectra and of eliminating possible inaccuracies in the results. Samples have been studied in the state of complete demagnetization, in a state of residual magnetization, and at various values of a constant magnetizing field. It is shown that the spectra of ferrites have a resonance or a relaxation character, are practically independent of core dimensions, and can be interpreted in terms of the dispersion of the ferromagnetic substance which, for ferrites with $\mu_a \approx 2000$ gauss/oersted, is apparently due principally to the inertia of the effective mass of the boundaries, and for ferrites with $\mu_a \approx 200$ gauss/oersted is due to the precessional motion of the magnetization vector in the effective field of the anisotropy of the substance of the ferrite.

1. IN magnetic spectra* of continuous polycrystalline ferrites, at least five regions of dispersion have been recognized: a) the low-frequency region, characterized by an insignificant decrease in the permeability μ in the range 0-0.2 mc.[2] b) the "infraradiofrequency" range characterized by a sharp resonance peak in μ_1 at $f \sim 0.1$ mc due to magnetomechanical effects[2-4]; c) the radiofrequency range, characterized by a rapid falling off of the real component of the complex magnetic permeability of the ferrites, and by a clearly pronounced absorption peak in the range ~ 1-200 megacycles [2,5-12]; d) the ultrahigh-frequency range, characterized by the phenomenon of natural ferromagnetic resonance, usually observed at frequencies of 10^3-10^4 mc, which is due to the precession of the electron spin in the effective field of the anisotropy of the substance of the ferrite[13,14]; e) the "infrared" region. According to calculations, since the "natural exchange resonance" in the field of exchange interaction has not yet been experimentally observed by anyone, this region should be characterized by a small resonance change of the curves of dispersion and absorption at frequencies $\sim 10^7$ mc[15]. The main decrease in the permeabilities μ and μ_1 of ferrites is observed in the radiofrequency range, as a result of which the investigation of dispersion at radiofrequencies has the greatest practical significance.

For a bicomplex medium, i.e., (according to Arkad'ev) for a medium with complex magnetic permeability and dielectric permittivity $\epsilon' = \epsilon - j\sigma'$ the phenomena of radio-frequency dispersion and absorption are ascribed in the literature to the following three causes: a) the dispersion of the ferrite substance, which may be due, in accordance with the theories of Landau and Lifshitz[16], and of Döring[17] to the inertia of the effective mass of the

* According to Arkad'ev[1] the name magnetic spectrum is given in the general case to dispersion curves $\mu_1(f)$ and absorption curves $\mu_2(f)$ or dispersion curves $\mu(f)$ and absorption curves $\rho'(f)$ where μ_1 and μ_2 are the real and imaginary parts of the complex magnetic permeability of a ferromagnetic body ($\bar{\mu} = \mu_1 - j\mu_2$), while μ and ρ' are the elastic and the viscous components of the complex magnetic permeability of a ferromagnetic substance $\mu' = \mu - j\rho'$; here f is the frequency.

1 V.K.Arkad'ev. Collection of articles entitled *Problems of ferromagnetism and magnetodynamics*. Published by the Academy of Sciences of the USSR Moscow-Leningrad, 1946.

2 R. Feldtkeller and O. Kolb, Z. angew. Physik. 4,448, (1952).

3 A, Weis, Electrotechnik 5, (1951).

4 A.A.Shvarts, Jour .Tech. Phys. (USSR) 3, 413(1953).

5 D. Polder, Proc. Inst. Elec. Engrs. 2, 97, 246(1950).

6 A. L. Fomenko, J. Exper. Theoret. Phys. USSR 21, 1201(1951); 24, 365(1953); 25, 107(1953).

7 D. Vent and E. Gorter, Collection of Articles entitled *Problems in the technology of radiolocation* IIL, Moscow 1, (1953) (Russian translation).

8 H.P.J.Wijn, M.Gevers and C.M.van der Burgt, Revs. Mod. Phys. 25, 91, (1953).

9 R.E.Alley and F.J.Schnether, J. Appl. Phys. 24, 1524(1953).

10 J.P.Blewett, M.H.Blewett and M.Plotkin, Rev. Sci. Instr. 24, 800(1953).

11 I. Lucas, Z. angew. Physik 6, 127,(1954).

12 N.G.Katkov, Thesis summary. MEI, Moscow(1954).

13 A. Welch, P.Nicks,A.Fairweather and F.Roberts, Collection of articles entitled *Ferromagnetic Resonance*, IIL, Moscow(1952), p. 154.(Russian translation).

14 G.T.Rado, Rev. Mod. Phys. 25, 81(1953).

15 J. Kaplan and C. Kittel, Collection of articles entitled *Problems of modern physics* 6, 50(1954)(Russian translation).

16 L.D.Landau and E.M.Lifshitz, Z. Physik Sovjetunion 8, 157(1935).

17 V. Döring, Collection of articles entitled *Ferromagnetic Resonance* IIL, Moscow(1952) p.312(Russian translation).

boundaries, and according to Landau and Lifshitz[16] and Snoek[18] may be due to the precession of the magnetization vector in the effective field of the anisotropy of the substance of the ferrite; b) to the dispersion caused, in accordance with Ref. 12, by the specific structural peculiarities of the material; c) to the dispersion of the permeabilities of the body of the ferromagnetic, which is due to dimensional effects: a surface effect and a volume resonance*, and which was first discovered in MnZn-ferrites by Brockman, Dowling, and Steneck[19].

As has been noted by Polivanov[20] the phenomena indicated above can, as a result of superposition, lead to quite complicated dispersion curves which differ in their appearance from the simplest types of magnetic spectra dealt with in Arkadiev's theory of magnetic viscous spectra.

Investigations (which have been largely carried out by Rado and collaborators[14]) using certain ferrites have shown that in the general case, under the condition that dimensional effects have been eliminated, magnetic spectra of the ferrite substance in the ranges of radiofrequencies and ultra high frequencies have two pronounced dispersion regions, one of which, the radio frequency one, is interpreted in terms of the inertia of the effective mass of the boundaries, and the other one, the ultra high frequency one, in terms of gyromagnetic resonance. Moreover, as a result of investigations by a number of authors[8,14] the existence of another, more numerous group of ferrites has been discovered, to which in particular, the NiZn-ferrites are found to belong, the magnetic spectra of which show a single pronounced dispersion region within the range of radio and ultra high frequencies. This region has been interpreted by the majority of investigators[5,7,8,11,18] from the point of view of rotational processes.

The study of radio frequency magnetic spectra of ferrites (with one exception[21]) has been carried out for the state of complete demagnetization of the material. The object of the present work is the investigation of magnetic spectra of several types of NiZn ferrites in the demagnetized state, as well as in a state of residual magnetization, and also at various values of the intensity of the constant magnetizing field.

2. Investigations were carried out using toroidal samples of Ni-Zn ferrite of the oxyfer types 0-2000-I, 0-400 and 0-200[22] with an ambient temperature of 25°. The values of saturation intensity of magnetization I_s, of the coercive force H_c, and of the initial permeability μ_a are given in the table. By definition, μ_a was taken to be the high-frequency permeability of samples measured in very weak fields at a frequency of f=0.25 mc.

By means of a high-frequency bridge, and also by means of Q-meters of types KV-1 and UK-1 the dependence of ϵ (f) and σ' (f) on f was measured for the various samples. For measurements made with the aid of the high-frequency bridge, the quantities ϵ and σ' were calculated from the data on effective series impedances X_c and R_c of an experimental condenser:

$$\varepsilon - j\sigma' = \frac{1{,}8\cdot10^{12}b}{fS_\kappa}\left(\frac{X_c}{R_c^2+X_c^2} - j\frac{R_c}{R_c^2+X_c^2}\right), \quad (1)$$

where S_k is the area of the ring of the side surface of the toroid which was coated with soft graphite and then metallized; f is the frequency in cycles/sec, and b is the axial thickness of the toroid in centimeters.

For samples 0-200 and 0-400 in the frequency range 0.15-60 mc, the permittivity ϵ showed little dependence on the frequency (Fig. 1), while the permittivity σ' was, as a rule, much smaller than ϵ. For samples of 0-2000-I, the frequency dependence of ϵ and σ' is shown in Figure 2.

The magnitudes of the permeabilities of ferrites at different frequencies were determined from the results of investigating the frequency dependence of the values of the effective inductance L_x and the effective resistance R_x of toroidal coils wound on the core being investigated. The measurements of the coil parameters were carried out by means of a high-frequency bridge.

3. A simplified circuit diagram of the bridge is given in Fig. 3. The main idea of the method of measurement consisted of the following: For each frequency used, the bridge circuit was first

* The volume resonance arises when the wavelength penetrating into the core is close to twice the dimensions of its cross section; standing waves are set up in the core, as a result of which the values of the magnetic flux and of the scattered power increase[20].

[18] J. Snoek, *Investigations in the field of new ferromagnetic materials* IIL, Moscow(1949)p.162(Russian translation).

[19] F.G. Brockman, P.H.Dowling, and W.G.Steneck, Phys. Rev. 77, 85 (1950).

[20] K.M.Polivanov, Proceedings of M.E.I., 14, G.E.I., Moscow- Leningrad(1953).

[21] D. Rado, R. Wright, and V. Emerson. Collection of articles *Ferromagnetic Resonance, IIL*, Moscow, 1952, p. 284, (Russian translation).

[22] N.N.Shol'ts and K.A.Piskarev, Izv. Akad. Nauk SSSR,Ser. Fiz.16, 6 (1952).

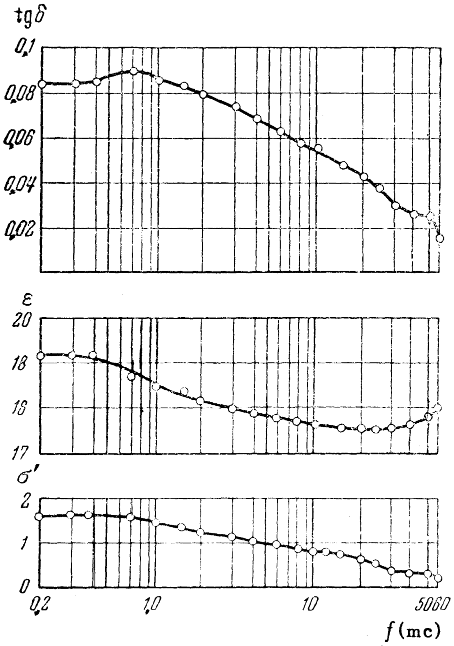

FIG. 1. Frequency dependence of the dielectric permittivities ϵ and σ' and of the tangent of the phase angle due to dielectric losses tan $\delta = \sigma'/\epsilon$ for sample 6 of 0-400.

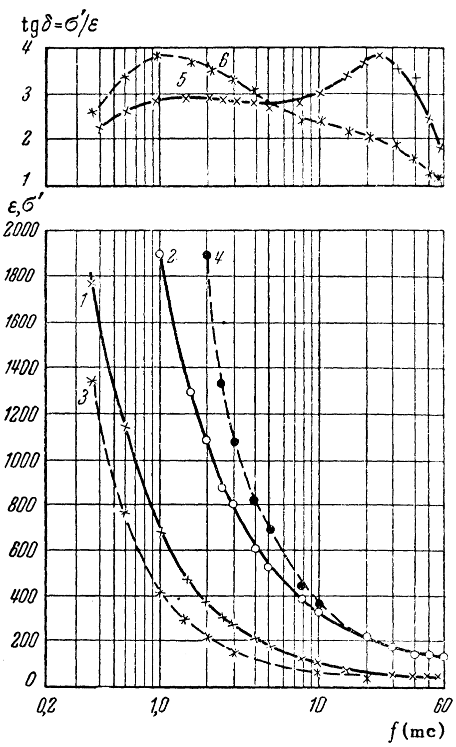

FIG. 2. Frequency dependence of ϵ, σ' and tan δ for 0-200-I: 1,2 and 5—sample 8; 3,4 and 6—sample 9(curve 6 corresponds to tan $\delta/2$).

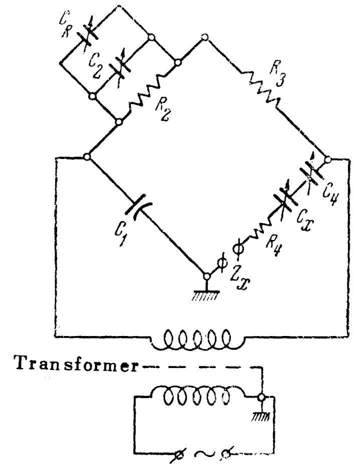

FIG. 3. Simplified circuit diagram of the high-frequency bridge.

balanced by means of C_2 and C_4, with Z_x shorted out. After the coil to be measured had been connected to the terminals Z_x the circuit was balanced again, but this time by means of condensers C_R and C_x. The equations for the preliminary (2) and final (3) balance are given below:

$$C_2 = \frac{R_4}{R_3} C_1 - C_{R\,\min}; \tag{2}$$

$$C_4 = \frac{R_2 C_1 C_{x\,\max}}{C_{x\,\max} R_3 + C_{x\,\max}\,\omega^2 C_1 L_4 R_2 - R_2 C_1};$$

$$R_x = R_3\,(\Delta C_R / C_1); \tag{3}$$

$$X_x = \omega L_x = \frac{1}{\omega}\,\frac{\Delta C_x}{C_{x\,\max}\,(C_{x\,\max} - \Delta C_x)}.$$

Consequently, the increment in the capacitance C_R is proportional to the value of R_x and does not depend on the frequency; the increment in the capacitance C_x is a function of the quantity L_x and of $\omega^2 = (2\pi f)^2$.

A block diagram of the measuring apparatus in which the high-frequency bridge was utilized is given in Fig. 4. The use of sensitive null indicators allowed the reduction, without a loss in the precision of measurement, of the high-frequency voltage supplying the bridge down to a value of 0.1-0.5 v, which insured the possibility of measuring cores at very weak variable magnetic fields $H < 1$ milli-oersted. The possibility of using sensitive null indicators was in turn insured by suitable screening of the apparatus and by filtering its supply circuits. For the measurement of the inductance L_x the error in the measurement, as follows from equation (3), depends on the accuracy of determining the frequency; therefore the frequencies of the generators supplying the bridge were controlled by means of a heterodyne wavemeter, which in turn was checked against a quartz calibrator. Results of measurements of special selected points of the curves $\mu(f)$ and $\rho'(f)$ were in addition checked by a comparison method.

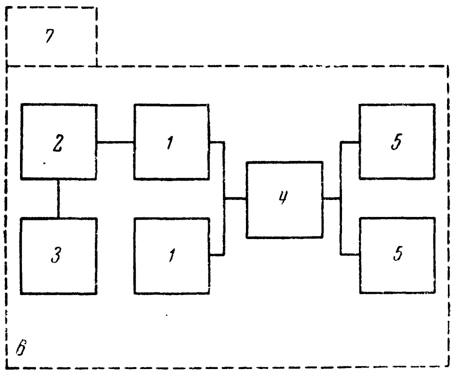

FIG. 4. Skeleton diagram of the measuring apparatus: *1*-high-frequency generators; *2*-heterodyne wavemeter; *3*-quartz calibrator; *4*-high-frequency bridge; *5*-null indicators which consist of superheterodyne receivers provided with input voltage dividers and output vacuum tube voltmeters with a maximum sensitivity with respect to the input high-frequency voltage of the order of $1\mu V$; *6*-shielding chamber; *7*-high-frequency interference-suppressing filter connected into the 50 cycle mains supplying power to the installation.

The total experimental error in the main part of the frequency range investigated is estimated to be less than ±6%. The influence of accidental error in the course of measurement was excluded by taking each measurement at least three times. With the same end in view, a large number (50-100) of experimental points were taken within the frequency range, and only a part of them is shown on the graphs.

When spectra of ferrite samples in a magnetized state were being obtained, the direct current which magnetized the core was introduced into the toroidal winding through special separating chokes characterized by low self-capacitance. Moreover, the choice of the number of turns of the toroidal winding, and the choice of the type of the separating choke, was made in such a way that, in control experiments without the magnetizing current, the influence of the introduction of the separating chokes on the results of measurement was quite negligible. In addition to the method described above, measurements were made in which the separating choke was replaced by a second ferrite toroid which carried a winding identical with the winding of the first toroid. The toroids were chosen in such a way that their magnetic spectra in the demagnetized state would be the same. In this case the magnetic spectrum of the samples was determined as a certain mean spectrum--from the results of measuring the effective inductances and resistance of the toroid windings connected in parallel (through a 1 mfd. blocking condenser).

4. During the investigation of magnetic spectra, the toroidal cores of Ni-Zn ferrites were placed inside electrical (open-circuited) screens made from soft aluminum foil of 0.08 mm thickness, which were then covered by winding them with insulating tape made of styroflex, the total thickness of the insulating layer being 1-1.5mm. The cores which had been screened and insulated in this manner were then wound with a single layer of windings which had small thicknesses, and which, insofar as it was possible, were uniformly distributed along the whole length of the core. In order to compare results, additional measurements were made with identical windings wound without the preliminary introduction of a screen either directly on the core, or on the core with an insulating layer.

The main idea in using electric screening consisted first of all in the simplicity of determining in this case the distributed capacity** C_0 of the windings, and second, in eliminating the uncertainty in that part of the losses which must be ascribed to the capacitative branch of the coil in the case of an unscreened core, when the influence of dielectric losses in the latter is unavoidable (but which, however, turned out to be insignificant).

In the case of an unscreened core and with a small number of turns in the winding, the estimate of the value of C_0 was carried out in an indirect way; for this purpose X_x and R_x were measured over the frequency range for coils wound on the same ferrite core both with and without screens. The thicknesses of the insulating layers between the winding and the screen were so chosen, that measurements of X_x and R_x of coils with unscreened and screened cores would give, in the frequency range in question, approximately the same results,

** C_0 was determined by a graphical method by means of plotting the experimental points, obtained with the aid of Q-meters, for the dependence of $C = \phi(1/f^2$ with a subsequent extrapolation of the straight lines so obtained until they intersect the capacitance axis. During measurements, the ferrite toroid was replaced by a polystyrol one with identical screening, insulation, and winding.

which allowed one to consider the values of C_0 for both types of coil to be the same. For coils with a large number of turns, the values of C were measured in the region μ=const, and in this case, therefore, the cores were not replaced by polystyrol ones.

Windings with different numbers of turns were used. Each of the experimental points obtained for one winding was duplicated by a measurement on the other winding. The number of turns on the windings was so chosen that their resonance frequencies would be considerably higher than the frequency at which measurements were made, but that the reading of condenser C_x would not lie at the beginning of its scale. Moreover, at high frequencies, measurements were made with the aid of a shorted section of coaxial line into which the toroid under investigation was placed.

5. The values of L_x and R_x obtained as a result of such measurements were recalculated to the true values ++ of L and R by means of the following formulas which take into account the influence of the capacitance C_0 and the parasitic capacitance C' of the measuring circuit, with $C' = C_0 + C_0'$:

$$L = q_L L_x, \quad R = q_R R_x, \tag{4}$$

where

$$q_L = \frac{1 + \beta^2 + \xi^2}{(1+\beta^2)^2 + (\beta\xi)^2}; \quad q_R = \frac{1}{(1+\beta^2)^2 + (\beta\xi)^2}; \tag{4a}$$

$$\beta = \omega / p; \; \xi = R / K; \; p = (L_x C')^{-1/2};$$

$$K = (L_x / C')^{1/2}.$$

In order to reduce the recalculation to the true values of L and R according to Eq (4) the graph shown in Fig. 5 was constructed.

The values of R_c and L_c were obtained from L and R. These new values depend only on the properties of the cores used. The quantity R_c was found by measuring the actual resistance R_w of windings wound on a polystyrol toroid of dimensions identical with the ferrite core, and then taking the difference $R_c = R - R_w$. The value of L_c was determined by taking into account the corrections for leakage flux, which were estimated by means of measurements (these being significant only for low values of $\mu < 100$ gauss/oersted. The permeabilities μ_1 and μ_2 of the body of the core were computed with the aid of typical formulas (cf., for example, Eqs. (1) and (2) of Ref. 6 or page 183 of Ref. 23).

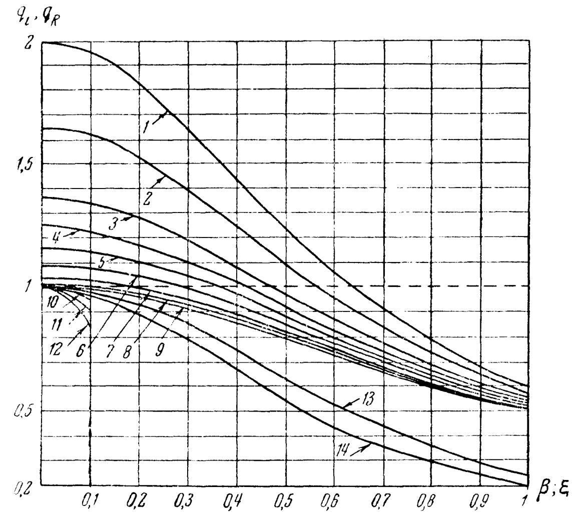

FIG. 5. dependence of the coefficients q_L and q_R on the quantities β and ξ : q_L =curves 1—9; q_R = curves 10-14; ξ has the values: 1=1.0; 2=0.8; 3=0.6; 4=0.5; 5=0.4; 6=0.3; 7=0.2; 8=0.1; 9=0; 10=2.0; 11=3.0; 12=4.0; 13=0. 14=1.0.

6. The subsequent transition from the quantities μ_1 and μ_2 to the values directly of interest to us of the elastic (non-dissipative) permeability μ and the viscous(dissipative) permeability ρ' of the substance of the ferrite can be carried out for a given ϵ and σ' by means of eliminating (by calculation) the effect on the permeability of the surface effect and of the volume resonance in the ferromagnetic substance. In particular, the solution of this problem makes possible the method of two experiments which was suggested by Polivanov[24].

According to Polivanov[20], the condition for the ocurrence of volume resonance in a bicomplex medium can be written in the following form:

$$\mathrm{Re}\,(j\omega\mu'\mu_0\gamma - \omega^2\varepsilon'\varepsilon_0\mu'\mu_0) \tag{4b}$$

$$= -(m^2/a^2 + n^2/b^2)\pi^2,$$

where m, n are odd integers which determine the order of the resonance; a, b are the sides of the cross section of the core; $\epsilon_0\mu_0 = c^{-2} = (3.10^{10})^{-2}$ (cm/sec)$^{-1}$; γ is the conductivity of the material of the core.

++ The equivalent circuit of the coil is referred to here in which R has been ascribed to the inductive branch.

23 L.I.Rabkin and N.N.Shol'ts, *Magnetodielectrics and ferro-coils*, GEI, Moscow-Leningrad, (1948).

24 K.M.Polivanov, Elektrichestvo 3, 19(1954).

Assuming that the dielectric losses in ferrites at high frequencies considerably exceed losses due to conductivity currents, we shall rewrite the given expression for the resonance of the first order ($m=n=1$) in the case of a core of square cross section $a=b$ in the form $\mathrm{Re}\,(-\omega^2 \epsilon' \mu' /c^2) = -2\pi^2/a^2$ or, taking the real part of the left hand term, we get

$$a = \lambda_B / \sqrt{2(\varepsilon\mu - \sigma'\rho')}, \qquad (5)$$

where λ_B is the wavelength of electromagnetic waves in vacuo. Consequently, if

$$\lambda_B \gg a\sqrt{2(\varepsilon\mu - \sigma'\rho')} \approx a\sqrt{2\varepsilon\mu}, \qquad (6)$$

then volume resonance cannot occur in the ferrite core.

The influence of the surface effect is described by the expression for the equivalent penetration depth δ_E for the electromagnetic field into a bicomplex medium (cf. Eqs. (89)-(93) of Ref. 1)

$$\delta_E = (\lambda_B/\pi)\,[2(|\mu'||\varepsilon'| - \mu\varepsilon + \rho'\sigma')]^{-1/2}. \qquad (7)$$

Under the condition that $\delta_E \gg a$, i.e.,

$$\lambda_B \gg a\pi\,[2(|\mu'||\varepsilon'| - \mu\varepsilon + \rho'\sigma')]^{1/2} \qquad (8)$$

$$\approx a\pi\,(2|\mu'||\varepsilon'|)^{1/2},$$

the surface effect will not be present in the ferrite core.

Calculations show that inequalities (6) and (8) are fully satisfied for ferrites 0-200 and 0-400, and are approximately satisfied for 0-2000-I. Therefore, for the whole frequency range we assume that approximately*

$$\mu_1 = \mu, \ \mu_2 = \rho' \qquad (9)$$

7. Results of the investigation of frequency dependence of the permeabilities μ and ρ' of samples of NiZn-ferrites are shown in the graphs of Figs. 6-11. An examination of curves 1 of Figs. 6-11 of the completely demagnetized state of the ferrite samples shows that the dependence $\mu(f)$ of

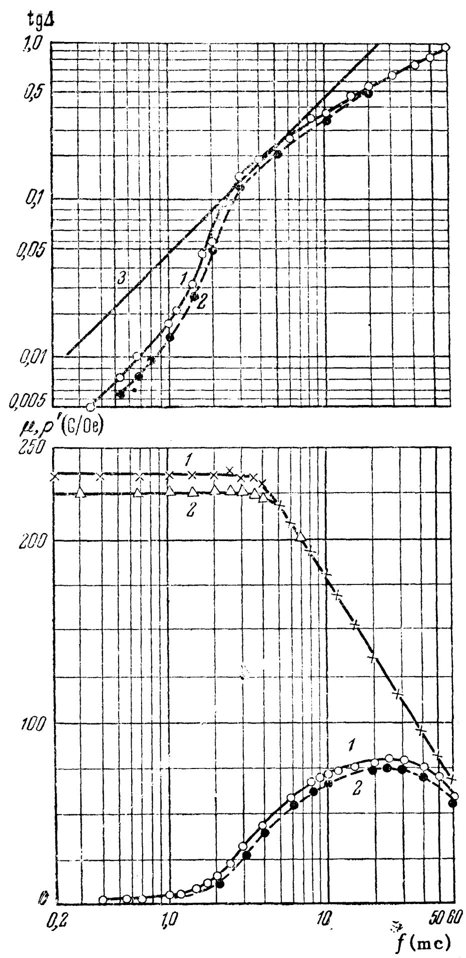

FIG.6. Magnetic spectra of sample 2 of 0-200: *1*-totally demagnetized state of the substance; *2*-state of residual magnetization; *3*-values of tan Δ calculated by formula (13) for the totally demagnetized state of the sample.

0-200 and 0-2000-I has a relaxation character, while that of 0-400 has a resonance character, which does not depend on any accidental factors such as: choice of the number of turns of the winding (Fig. 12a, b,c), or volume resonance whose frequency (according to Ref. 20) should have become displaced when the sides of the toroidal core are metallized, an event which was not observed (Fig. 12d) in our case. From a comparison of the curves 1 of the above graphs it follows, moreover, that for samples of NiZn-ferrite of the same composition and of the same technology of manufacture, the magnetic spectra differ but little from sample to sample. In particular, this conclusion is supported also by the investigation of spectra of samples 4 and 5 of 0-400, whose dimensions are significantly larger than those of samples 3 and 7 (Figs. 9 and 11), and of sample 8 of 0-2000-I whose $\mu(f)$ and $\rho'(f)$

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* A certain indeterminacy is introduced into this conclusion only by the possible dependence of ϵ and σ' on the intensity of the electric field, which will be different when electric and when magnetic measurements are made. However, measurements of ϵ and σ' at various electric field intensities did not demonstrate any noticeable change in them.

curves are close to curves 1 of Figs. 7 and 10 in spite of a noticeable difference in their dielectric

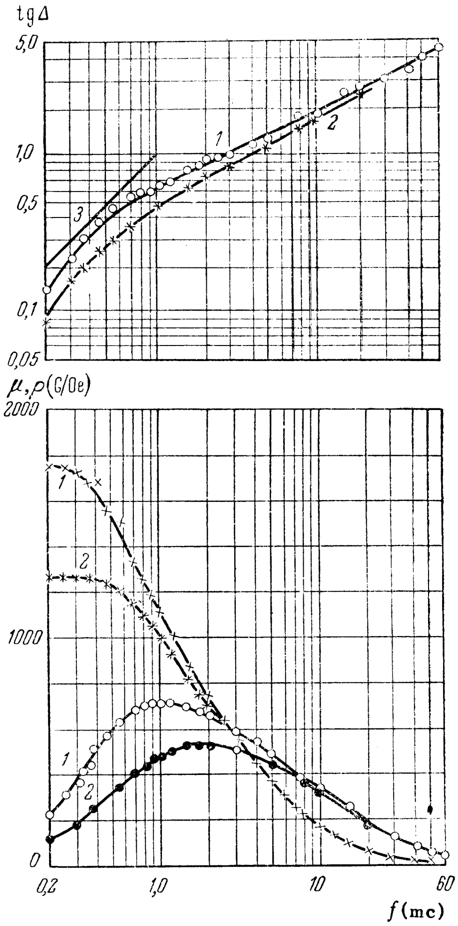

FIG. 7. Magnetic spectra of sample 9 of 0-2000-I(the labels are the same as in Fig. 6.)

permittivities (Fig. 2); apparently these data once again point to the independence from dimensional (volume resonance and surface effect) effects of the dispersion μ and absorption ρ' observed by us.

The independence of the observed dispersion of the permeability of the material of the ferrite from the surface effect follows, moreover, from the measurements on the spectra of sample 7 of Fig.11, which was hand ground with abrasives in order to avoid any appreciable heating in the course of grinding. The ground sample had, in comparison with the whole sample of lower μ_a, a higher f_u (in contrast to the data of Ref. 9), whose shift is approximately given by Eq. 10, a flatter maximum in the curve $\rho'(f)$, a larger slope of the curve $\mu(f)$, and also a smaller value ρ' max $=0.39\,\mu_a$, as against ρ' max $= 0.43\,\mu_a$ for the whole sample, which points to the broadening of the band of frequencies of relaxation and of resonance for samples of smaller axial thickness. The observed character of dependence of f_u on the thickness of the sample most likely is a consequence of its macroscopic inhomogeneity, as the character of the shape of the curves $\rho'(f)$ of the ground and of the whole samples in the region of high frequencies excludes the possibility of explaining the appearance of the dispersion curves through a surface effect. However, the possibility is not excluded that the effective anisotropy constant is altered in the course of grinding, because of the increase in the demagnetizing factor of the body of the toroid, and also because of the change in the dimensions d of ferromagnetic regions [25] (page 257) which may lead to a change in the frequency f_u.

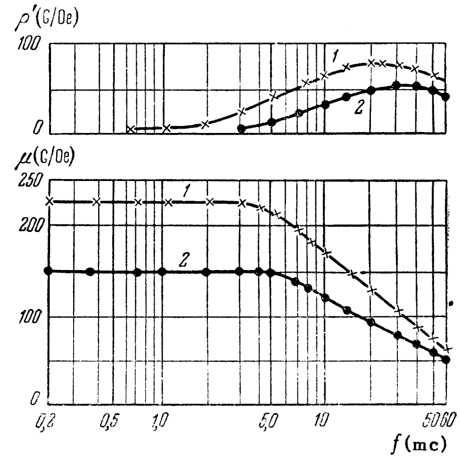

FIG. 8. Magnetic spectra of sample 1 of 0-200 for different values of the intensity of the constant magnetizing field: *1-H*=0; *2-H*=4 oersteds.

8. The values of the frequencies of absorption maxima f_u of the ferrites investigated, which are approximately (up to a factor of the order of two, since in the case of relaxation spectra the damping is apparently close to critical) equal to the average resonance frequencies of their material, are given by the espression

$$f_u \approx CI_s/(\mu_a - 1), \tag{10}$$

where C is a certain constant of the material of the ferrite (see table), which is approximately equal to the gyromagnetic ratio of the electron spin, $C \approx ge/2mc \approx e/mc = 17.6$ mc/oersted.

The theoretical basis for Eq. (10) may be found:

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[25] S.V.Vonsovskii, *Modern theory of magnetism* GITTL,Moscow-Leningrad, 1952.

a) in the case of the predominance of the process of rotation in the theory of Landau and Lifshitz[16] and of Snoek[18] with Eq. (11) arising from it;
b) in the case of the predominance of displacement processes in the theory of Landau and Lifshitz[16] and of Döring [17] with Eq. (12) arising from it for 90° boundaries; c) in the case of the approximate equality of the weighting factors for the processes of displacement and of rotation, in the approximate equality of the resonance frequencies of the material of the ferrite due to both types of processes of magnetization

$$f_{0\,\mathrm{rot}}=\frac{ge}{4\pi mc}H_i\approx\frac{1}{\pi}\frac{ge}{2mc}\frac{k}{I_s} \tag{11}$$

$$\approx\frac{4}{3}\frac{ge}{2mc}\frac{I_s}{\mu_{a\,\mathrm{rot}}-1};$$

$$f_{0\,\mathrm{dis}}=(ge/2mc)\sqrt{\delta/d}\,[I_s/(\mu_{a\,\mathrm{dis}}-1)]. \tag{12}$$

Here H_i is the internal effective magnetic field due to the anisotropy of the material of the ferrite, $H_i\approx 2k/I_s$; k is the anisotropy constant; μ_{rot} is the initial permeability due to rotation; $\mu_{a\,\mathrm{rot}}\approx 4I^2/k$; δ/d is the ratio of the effective thickness of the boundary layer to the size of the ferromagnetic domain; phenomenologically, based on the experimental data of Ref. 14 one can assume that $\delta/d\sim 1/(\mu_{a\,\mathrm{dis}}-1)$; $\mu_{a\,\mathrm{dis}}$ is the inital permeability due to displacement; g is the Landé spectroscopic splitting factor which, at room temperature and depending on the composition of the NiZn-ferrite, may vary[26-28] within a range not greater than from 1.93 (Zn-ferrite) to 2.36 (Ni-ferrite) and which consequently can be approximated by $g=2$.***

9. Examination of graphs 6 and 7 shows that the nature of the curves of $\mu(f)$ and $\rho'(f)$ is also preserved in the state of residual magnetization.

It is known both from theory[30] and from experiment[21] that in ferrites for which $I_R/I_S\approx 0.5$, if the

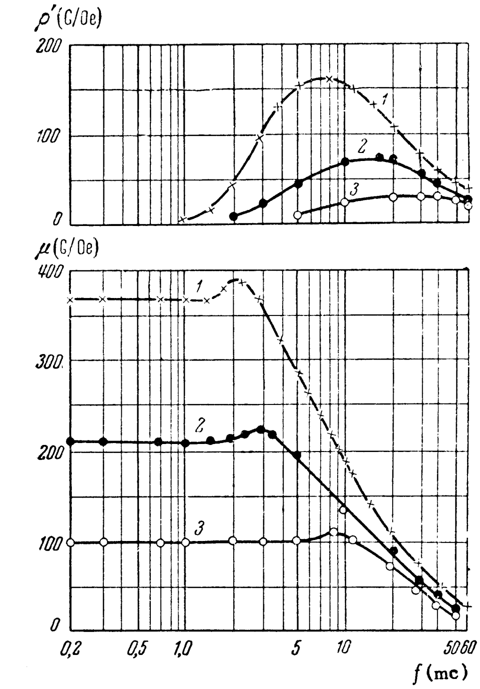

FIG. 9. Magnetic spectra of sample 3 of 0-400 for various values of the constant magnetizing field: *1-H=0; 2-H=*1.8; *3-H=*4.5 oersteds.

complex permeability $\mu'=\mu-j\rho'$ is determined exclusively by processes of rotation of the magnetization vector, then the value $\mu'_R=\mu_R-j\rho'_R$ in a state of residual magnetization must be equal to the value of μ' in the demagnetized state; however, if μ' is determined primarily by the displacement of boundaries, then μ'_R must be considerably lower than μ' in the demagnetized state.

In the case of 0-2000-I the value of the ratio $\mu_{aR}/\mu_a=0.72$, and $(\rho'_R/\rho')_{\mu=\mu_a}=0.5$. As the frequency is increased, the curves of $\mu(f)$ for both states of the substance of the ferromagnetic approach one another rapidly and coalesce at the frequency $f=3$ mc. At frequencies of 10 to 30 mc, a certain increase of μ_R above μ is observed which would not be shown on the scale of our graph. The curves for $\rho'(f)$ coalesce at $f=15$ mc and beyond that are practically identical. In the case of 0-200, $\mu_{aR}/\mu_a=0.96$, $(\rho'_R/\rho')_{\mu=\mu_a}=0.85$ and the spectra of both states of the ferrite substance differ little from one another.

If the coming together of the curves of μ' and μ'_R is taken as evidence of the gradual growth with frequency of the relative importance of rotation

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*** In particular, taking into account the data of Ref. 29 and the fact that in the determination of the g-factor the influence of H_i was not taken into account in Refs. 26-28.

[26] H.G.Beljers and D.Polder, Nature 165, 800 (1950).

[27] T.Okamura and Y.Torizuka, Collection of articles entitled *Problems of Modern Physics* 5, 182 IIL, Moscow (1952).

[28] E.I.Kondorskii and N.A.Smolkov, Doklady Akad. Nauk USSR 93, 237 (1953).

[29] T. Okamura, Y. Torizuka and Y. Kojima, Phys. Rev. 88, 1425 (1952).

[30] S.V.Vonsovskii and Ia. S.Shur, *Ferromagnetism*, State Technical Publishing House, Moscow-Leningrad, 1948.

processes, then one may suppose that in 0-200-I, in very weak fields, magnetization by means of rotation processes takes place only starting at a frequency $f \sim 10$ mc and that consequently the radiofrequency dispersion at lower frequencies must be described, according to Döring, by Eq. (12)

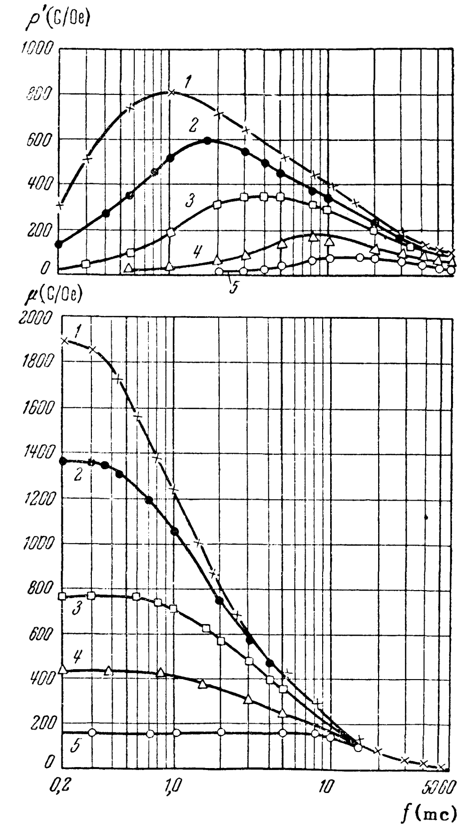

FIG. 10. Magnetic spectra of sample 10 of 0-2000-I for various values of the constant magnetizing field: *1*-H=0; *2*-H=0.1; *3*-H=0.2; *4*-H=0.5:*5*-H=1.5 oersteds.

In 0-200, rotation processes are possibly the dominant factor which determines the character of the whole radiofrequency dispersion, which will be described, according to Snoek, by Eq. 11. Taking into account the fact that samples 0-2000-I and 0-200 have approximately the same composition and differ from each other only in that the sintering temperature t_s is appreciably higher for the sample with the higher permeability, one may suppose++ that the relative importance of the processes of displacement in the ferrite increases with increasing temperature t_s. The theoretical basis for this hypothesis is the decrease in the porosity of the sample and in the values of internal strains which is observed as the sintering temperature is raised.

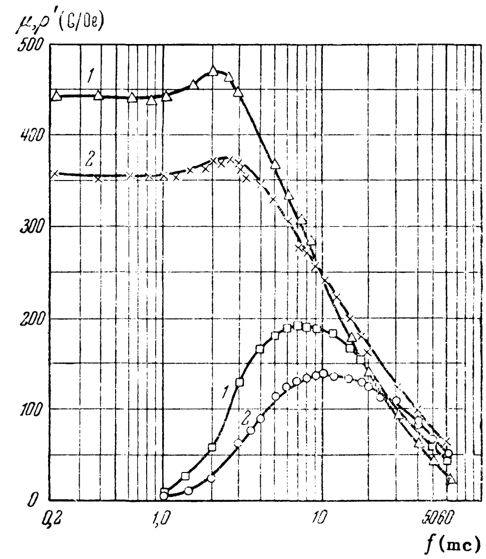

FIG. 11. Magnetic spectra of sample 7 for various axial thicknesses obtained by means of grinding it down; *1*-6.98 mm(weight of sample 21.889 gm); *2*-2.84 mm (weight of sample 9.155 gm).

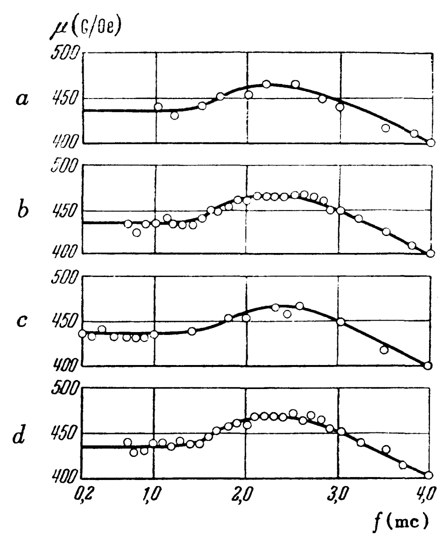

FIG. 12. Dispersion curves of sample 6 of 0-400 in the range 0.2 to 0.4 mc for various windings: *a*-3 turns of ribbon; *b*-7 turns of wire; *c*-14 turns of wire; *d*-7 turns of wire; sides of core metallized.

The values of the tangents of the phase angles due to the losses $\tan \Delta = \rho'/\mu$ for ferrite samples

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++ This assumption needs testing on a large number of samples of ferrite of the same composition sintered at different t_s.

TABLE

Data for toroidal cores which have been studied.

No. of sample	μ_a in gauss/oersted	I_s, gauss	H_c, oersteds	I_R, gauss	ε	f_u, mc	C, mc/oersted	Toroid dimesnsions in mm. external diameter	internal diameter	axial thickness
1	225	145	1,45	80	19	25	39	37,3	23,8	7,08
2	234	140	1,4	80	20	25	41	37,2	23,7	7,05
3	365	220	0,8	96	17	8	13	38,05	24	6,96
4	370	220	—	96	16	7,5	13	67,75	42,3	14,03
5	434	210	—	100	19	8	16	57,15	34	11,34
6	438	220	0,79	97	16	8	16	38,2	24	6,82
7	443	220	0,8	98	18	8	16	38,2	24,2	6,98
8	1680	200	0,1	98	—	1,2	9	37,9	24,15	7,11
9	1750	195	0,1	96	—	1,0	9	37,9	24,05	6,96
10	1880	200	0,1	98	—	1,0	9,3	37,9	24,1	7,05

are shown in Figs. 6 and 7, from which it may be seen that the nature of the dependence of tan $\Delta(f)$ on the frequency apparently varies but little with a variation in the value of the ratio $(\mu_{a\,rot}-1)/(\mu_{a\,dis}-1)$ for the ferrite. For a rough estimate of the value of tan Δ in the frequency range 0.01 $0.01\, f_u \lesssim f \lesssim f_u$ one can use[6] the expression

$$\operatorname{tg}\Delta \sim f/f_u \sim (f/C)(\mu_a - 1)/I_s, \qquad (13)$$

which establishes the practically important connection between tan Δ and the fundamental parameters of the ferrites.

10. Examination of the graphs of Figs. 8,9 and 10 shows that the nature of the spectrum is preserved independent of the influence of the constant magnetizing field. The frequency f_u, according to data[31] on spectra of metallic ferromagnetics, is displaced into the region of higher frequencies as the intensity of this magnetizing field is increased, with the law given by expression (10) being approximately preserved. The preservation of this law has an essential practical significance since this makes it possible to estimate with the aid of formula (13) the order of magnitude of the values of tan Δ for the core in the frequency range $0.01\, f_u \leq f \leq f_u$ for various values of the intensity of the magnetizing field.

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[31] I.M.Kirko, B.O.Grosskaufman and L.D.Daube, Trudy Inst. Phys. Math. Acad. Sci. Latvian SSR 2, 9(1950).

Translated by G. M. Volkoff
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