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Frequency Dependence of the Complex Initial Permeability of MnZn Ferrite

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The body can be viewed from the next page.

Frequency Dependence of the Complex Initial Permeability of MnZn Ferrite*



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1 Introduction

With the trend toward digital high-speed signal processing of office automation equipment, communications equipment, etc., growing stronger equipment and systems must function in a stable manner under a complex electromagnetic environment (EMC: electromagnetic compatibility). Noise filters using cores of soft magnetic material are manufactured as one measure to cope with this EMI (electromagnetic interference). Soft ferrites used as core materials are broadly divided into NiZn(Cu) ferrites used in the high-frequency range up to about 300 MHz, and MnZn ferrites used in a relatively low-frequency range up to about 1 MHz. With MnZn ferrites it is possible to obtain the highest initial permeability among the soft ferrites, and materials with a relative initial permeability of about 18 000 are manufactured as commercial products. Kawatetsu Ferrite Corp. has commercialized MA040 to MA100 (relative initial permeability: 4 000–10 000) as high-permeability MnZn ferrites used in such noise filters for EMC, and other high-tech products[1)].

It is desirable that ferrite cores used in noise filters and other equipment maintain high initial permeability to a higher-frequency range because a large impedance is required in the frequency range where noises are to be removed. In MnZn ferrites, however, magnetic relaxation and resonance occur in a low-frequency range with an increase in permeability, and the limit of usable frequencies becomes about 1 MHz although the initial permeability can be high compared with NiZn ferrites. This phenomenon is the same behavior as that of Snoek's limit[2)] displayed by NiZn ferrites, and natural resonance[2)] and domain-wall resonance[3)] have been considered the causes. On the basis of an analysis of the electromagnetic behavior within the core that is derived from the sample dimensions and macroscopic electromagnetic properties, this paper reports that the frequency dependence of the initial permeability of MnZn ferrites can be explained as a dimensional resonance[4)] of the electromagnetic waves within the core, and not as a natural resonance or domain-wall resonance.

2 Calculation of Frequency Characteristic of Complex Initial Permeability

2.1 Derivation of Precise Solution of Complex Initial Permeability Based on the Maxwell Equations

On the assumption that an MnZn ferrite core is an

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electromagnetically homogeneous medium (the permittivity ε, permeability μ, and resistivity ρ are constant in a DC or a low-frequency range), the spatial distribution of AC electromagnetic fields that propagate at a frequency f (angular frequency $\omega = 2\pi f$) while changing like a sine wave is derived from the Maxwell equations. The apparent permeability to the applied magnetic field is found by averaging the magnetic flux density that varies within the core. The permeability that can usually be measured by an impedance analyzer, etc., is this apparent value.

Presuming a homogeneous toroidal medium with a radius a of a circular cross sectional area, the distribution of electromagnetic fields within the core can be analytically found from the Maxwell equations. If each of ε, μ and ρ of the medium does not depend on the electric field E, magnetic field H or current I and is constant (μ is within the range of initial permeability,) then the magnetic field within the core is given by the following equation using cylindrical coordinates[5]:

$$H(r) = H_a \frac{J_0(kr)}{J_0(ka)} \cdots\cdots (1)$$

Here H_a is the magnetic field on the core surface ($r = a$) and J_0 is the zeroth order Bessel function. k is expressed as the following equation:

$$k = \sqrt{\omega\mu\,(\omega\varepsilon - j/\rho)} \cdots\cdots (2)$$

Here j is the imaginary unit. Next, the total magnetic flux Φ within the cross section of the magnetic path of the core is found as follows:

$$\Phi = 2\pi \int_0^a \mu H(r) r \,\mathrm{d}r \cdots\cdots (3)$$

When the relationship $\int r J_0(kr)\mathrm{d}r = J_1(kr)r/k$ is used, Φ is calculated as follows:

$$\Phi = \frac{2\pi a\mu}{k} \cdot \frac{J_1(ka)}{J_0(ka)} \cdot H_a \cdots\cdots (4)$$

J_1 is the first order Bessel function. Therefore, the magnetic flux density B averaged by the cross sectional area of core is calculated as follows:

$$B = \frac{\Phi}{\pi a^2} = \frac{2\pi}{ka} \cdot \frac{J_1(ka)}{J_0(ka)} \cdot \mu H_a \cdots\cdots (5)$$

Therefore, the apparent permeability μ_a is expressed by complex numbers as follows:

$$\mu_a = \mu_a' - j\mu_a'' = \frac{2\pi}{ka} \cdot \frac{J_1(ka)}{J_0(ka)} \cdot \mu \cdots\cdots (6)$$

If μ is the initial permeability μ_i, then μ_a, i.e., the apparent initial permeability μ_i, changes as the functions of ρ, ε, a and f.

It becomes evident that when the cross section of a core is constant, resistivity and permittivity exist as the factors governing the frequency characteristic of μ_i of a core which has a constant initial permeability at a low frequency and direct current. For metallic magnetic materials, resistivity is low and permittivity can be almost completely disregarded. In the case of polycrystalline MnZn ferrites that are ordinarily used, however, resistivity is relatively low (0.1 to 10 $\Omega \cdot$ m) and relative permittivity is high (up to 10^5). In consideration of the foregoing, Brockman et al.[6] demonstrated by an approximate solution of Eq. (6) that the electromagnetic waves within the core become standing waves and cause resonance, resulting in the occurrence of dimensional resonance in which μ_i' increaes a little at a certain frequency and then decreases abruptly. Because the calculations were in good agreement with the measurements, it has been understood from the conditions under which the standing waves of electromagnetic waves are generated that dimensional resonance occurs in large cores with a crosssectional radius of more than about 10 mm[7]. However, because this calculation was made using an approximate solution, the accurate behavior of the initial permeability for changes in the resistivity, permittivity and dimensions is calculated again using a precise solution of Eq. (6).

2.2 Effect of Resistivity

According to the classical concept of eddy current, eddy current losses can be reduced in inverse proportion to the resistivity ρ of a core if ρ rises, in which case it can be expected that permeability does not attenuate even at high frequencies. **Figure 1** (a) shows the calculation results of the frequency dependence of complex initial permeability μ_i'/μ_0 when the direct current measurement gave an initial permeability μ_i'/μ_0 of 10 000 and resitivities of 0.06, 0.3 and 1.2 $\Omega \cdot$ m (μ_0 denotes the permeability in a vacuum). To make the analysis by avoiding the effect of permittivity, the radius a of the effective circular cross sectional area was determined to be 3.45 mm by taking the permittivity in a vacuum ε_0 to be ε in Eq. (6) and assuming a standard ring shape of 31 mm in outside diameter, 19 mm in inside diameter and 6–7 mm in height. When the resistivity is 0.06 $\Omega \cdot$ m, μ_i' starts to attenuate at a frequency of 100 kHz. However, a constant value is kept to about 1 MHz when the resistivity is raised to 1.2 $\Omega \cdot$ m. If the initial permeability can be kept at a constant value, the frequency characteristic can be improved by simply raising resistivity. In cores that are actually manufactured, however, high-resistivity phases are formed at the grain boundaries by adding additives such as SiO_2 and CaO. For this reason, resistivity is high in these cores; however, the initial permeability decreases due to the effect of these impurities. Because the cores with various resistivities shown in Fig. 1 (a) show initial permeabilities μ_i'/μ_0 of approximately 10 000, 7 500 and 5 500, the calculation results of the frequency characteristic of initial permeability of each core are shown in Fig. 1 (b).

In each of the calculation results, the frequency dependence of μ_i' shows only the relaxation phenome-

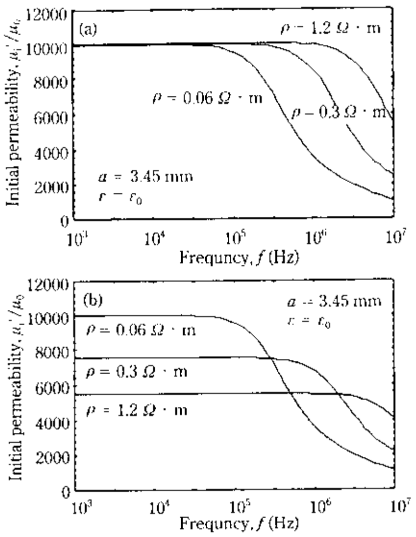

Fig. 1 Calculated frequency dependence of the complex initial permeability, μ_i'/μ_0, for MnZn ferrite cores having various resistivities, ρ, under the conditions in which the redius, a, of the circular cross section of the cores is 3.45 mm and the permittivity, ε, is ε_0 which is the permittivity of free space

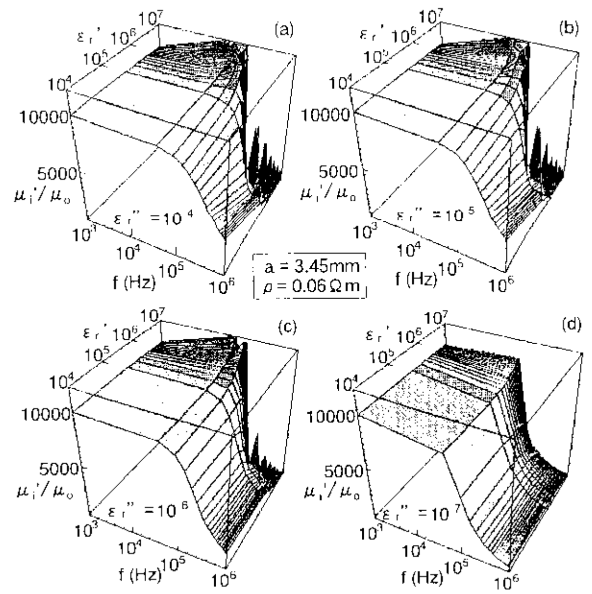

Fig. 2 Changes of the frequency dependence of the complex initial permeability, μ_i'/μ_0, for various complex permittivities, ε_r' and ε_r'', under the conditions in which the radius, a, of the circular cross section of the cores is 3.45 mm and the resistivity, ρ, is 0.06 $\Omega \cdot$ m

non and a phenomenon in which μ_i' increases once and then decreases abruptly does not occur. Furthermore, the frequency characteristic increases to a few MHz in the core with μ_i'/μ_0 of 5 500 and a decrease from hundreds of kHz in actual cores cannot be reproduced. This is a likely explanation because only the relaxation phenomenon due to eddy current losses were calculated and the effect of permittivity was disregarded.

2.3 Effect of Permittivity

In MnZn ferrites, the value of complex relative permittivity ε_r is very high in both the real part and the imaginary part, as described in Chapter 3, and is approximately 10^5 to 10^6 even at high frequencies. Compared with usual ferroelectric substances, the dielectric losses given by the imaginary part are great although those of the real part are also great; this is a characteristic of polycrystalline MnZn ferrites. This means that the grain boundaries having much higher resistivity work as condensers, with the result that the losses of displacement currents that flow through the grain boundaries become so large that they cannot be neglected.

Figure 2 shows how the frequency characteristic of μ_i'/μ_0 varies depending on the complex relative permittivities ε_r' and ε_r'' at an initial permeability μ_i/μ_0 of 10 000 and a resistivity of 0.06 $\Omega \cdot$ m in direct current measurement. The same core shape as in the previous section was adopted and the radius a of the effective circular cross sectional area was determined to be 3.45 mm. As shown in Fig. 2 (a), the frequency characteristic of μ_i' decreases in the manner of relaxation type when ε_r' of the real part of complex relative permittivity is up to approximately 10^5, whereas when ε_r' increases to much over 10^5, μ_i' increases once at about 100 kHz and then decreases abruptly and the value fluctuates greatly after that. The lower the value of the imaginary part ε_r'', the more remarkable this tendency will be. As shown in Fig. 2 (a) to (d), the fluctuation behavior of μ_i' no longer occurs with increasing ε_r'' and begins to show the frequency characteristic of the relaxation type even when ε_r' is high.

2.4 Effect of Core Dimensions

When the dimensions of a core are large, the frequency characteristic of initial permeability behaves in such a manner that the relaxation phenomenon due to an increase in eddy current losses or dielectric losses overlaps with the resonance phenomenon. **Figure 3** shows how the frequency characteristic of μ_i'/μ_0 varies depending on the cross-sectional radius r of a core at an initial permeability μ_i/μ_0 of 10 000 and a resistivity of 0.06 $\Omega \cdot$ m in direct current measurement. The same core shape as in the previous section was adopted and the complex relative permittivity ε_r was set at $10^6 - j10^6$.

When resistivity is 0.06 $\Omega \cdot$ m, the decrease in μ_i'/μ_0 is remarkable at a radius r exceeding about 10 mm; in an extreme case where $r = 100$ mm, μ_i'/μ_0 decreases to approximately 2 000 even at a low frequency of 1 kHz. When resistivity increases to 0.3 $\Omega \cdot$ m, the radius at which μ_i' does not decrease becomes large and the frequency characteristic is improved. When the radius is

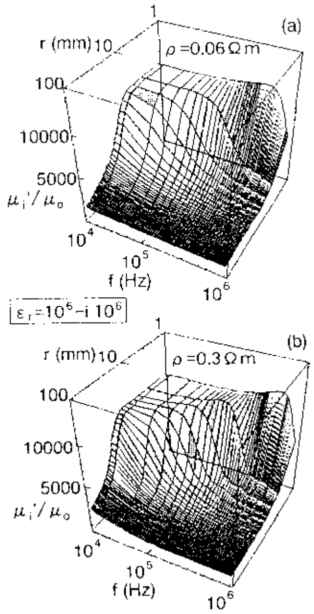

Fig. 3 Changes of the frequency dependence of the complex initial permeability, μ_i'/μ_0, for various radii of the cross section of the core in two cases for resistivity ($\rho = 0.06$ and $0.3\ \Omega \cdot$m) under the condition in which the complex relative permittivity, ε_r, is $10^6 - j10^6$

relatively small, an increase in μ_i' from about 100 kHz followed by a decrease is observed and the behavior of dimensional resonance is reproduced.

3 Comparison with Measured Values of Complex Initial Permeability

3.1 Method of Experiment

Permeability and permittivity were measured by means of an impedance analyzer (HP 4194A) using toroidal cores with an initial permeability μ_i/μ_0 of approximately 7 000 to 15 000 fabricated by the usual manufacturing method of MnZn ferrites. A coil of 10 turns was applied to each toroidal core and the frequency characteristic of complex initial permeability ($\mu_i = \mu_i' - j\mu_i''$) was measured. Using cylindrical samples cut from the core, the frequency characteristic of the complex impedance ($Z = R + jX$) was measured. Electrodes were attached to the cylindrical sample with a conductive binder and the real and imaginary parts of the complex impedance were measured by the four probes method at frequencies in the range of 1 kHz to 13 MHz. An equivalent circuit that reproduces this was assumed as shown in **Fig. 4** and the complex relative permittivity ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$) was found. It is the permittivity when the core provided with electrodes is regarded as a condenser and can be found by making calculation

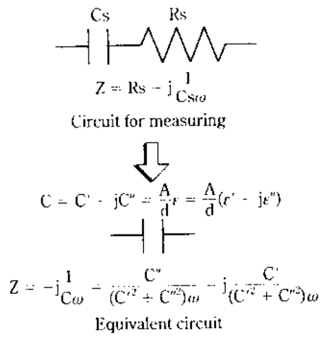

Fig. 4 Equivalent circuit of MnZn ferrite for determining the complex permittivity. The impedance, Z, is presented by the serial resistance, R_s, and the serial capacitance, C_s (Z is also represented by an equivalent complex capacitance, $C = C' - jC'$, and then the complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, is calculated using C, the cross sectional area, A, and the length, d, separating contacts)

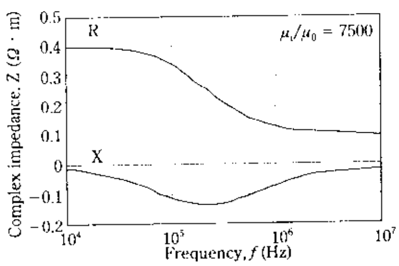

Fig. 5 Frequency dependence of the complex impedance, Z ($= R + jX$), of a MnZn ferrite cylindrical sample with the μ_i/μ_0 of 7 500

using the capacitance C, area of electrode A, and plate spacing d.

3.2 Results of Experiment

3.2.1 Frequency characteristic of complex permittivity

Figure 5 shows the frequency characteristic of the complex impedance Z ($= R + jX$) of a core with an initial permeability μ_i/μ_0 of 7 500. The resistance (R) that indicates a value of $0.4\ \Omega \cdot$m under a direct current begins to decrease at about 10 kHz and reactance ($-X$) begins to increase at the same time. The behavior shown in Fig. 5 holds well for the grain structure in which grains with low resistivity and permittivity are divided by the grain boundaries having high resistivity and permittivity. The displacement currents that flow through these grain boundaries flow into the grains as the frequency increase, thereby generating Joule losses; these currents increase abruptly at frequencies of more than

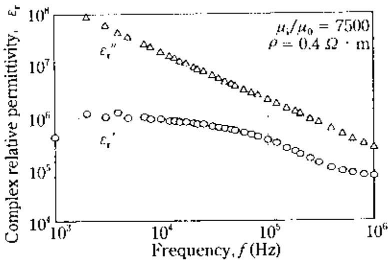

Fig. 6 Frequency dependence of the complex permittivity derived from the data of Fig. 5 using the equivalent circuit as shown in Fig. 4

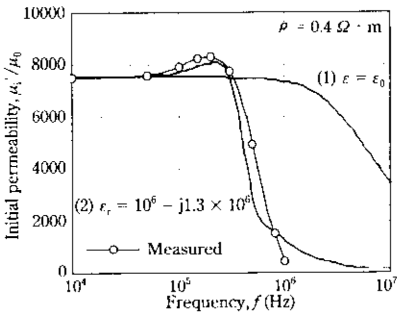

Fig. 7 Frequency dependence of the complex initial permeability, μ_i'/μ_0, measured on a MnZn ferrite core with $\mu_i/\mu_0 = 7\,500$ and $\rho = 0.4$ $\Omega \cdot$m in comparison with the calculated curves under two conditions of permittivity, (1) $\varepsilon = \varepsilon_0$ and (2) $\varepsilon_r = 10^6 - j1.3 \times 10^6$

about 1 MHz. Next, **Fig. 6** shows the frequency dependence of the complex relative permittivity ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$) found from the complex impedance shown in Fig. 5. At 1 kHz, $\varepsilon_r' = 10^6$ and $\varepsilon_r'' = 10^8$; both are very high. ε_r' is constant up to about 100 kHz and decreases exponentially after that. ε_r'' decreases exponentially from low frequencies. These high complex relative permittivities are not observed either in single-crystal samples or in samples not containing trace additives that precipitate at the grain boundaries; they reflect the property of grain boundaries.

3.2.2 Frequency characteristic of complex initial permeability

The frequency dependence of μ_i'/μ_0 of a core with an initial permeability μ_i/μ_0 of 7 500 at 1 kHz is shown in **Fig. 7**. This core is a ring sample 20 mm in outside diameter, 10 mm in inside diameter and 4 mm in height and has a radius r of effective circular cross sectional area of 2.5 mm. The measured value of μ_i' begins to increase at about 50 kHz, shows a peak at about 200 kHz and decreases abruptly after that. The calculation of μ_i' by Eq. (6) was made in the following cases of two permittivity conditions; the results are also shown in Fig. 7.

(1) Case where the effect of permittivity is ignored and the radius of effective circular cross sectional area of the core and the values of initial permeability and direct-current resistivity at 1 kHz are used as parameters.

(2) Case where the radius of effective circular cross sectional area of the core, the values of initial permeability and direct-current resistivity at 1 kHz, and a complex relative permittivity $\varepsilon_r' = 10^6 - j1.3 \times 10^6$ are used as parameters.

In (1), μ_i' does not decrease at frequencies up to about 1 MHz and decreases beyond that due to the relaxation arising from eddy current losses. A peak near 200 kHz does not appear in this case. In Case (2), where the effect of permittivity is taken into consideration, a peak near 200 kHz followed by a decrease is reproduced.

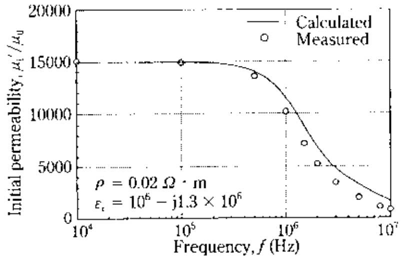

Fig. 8 Frequency dependence of the complex initial permeability, μ_i'/μ_0, measured on a MnZn ferrite core with $\mu_i/\mu_0 = 15\,000$ and $\rho = 0.02$ $\Omega \cdot$m in comparison with the calculated curve under the condition of permittivity, $\varepsilon_r = 10^6 - j1.3 \times 10^6$

The frequency dependence of μ_i'/μ_0 of a core with an initial permeability μ_i/μ_0 of 15 000 at 1 kHz is shown in **Fig. 8**. As with the core in Fig. 7, this core is a ring sample of 20 mm in outside diameter, 10 mm in inside diameter and 4 mm in height. The amounts of additives are reduced to raise the permeability at low frequencies and the resistivity of the core is reduced to 0.02 $\Omega \cdot$m. The measured values show a relaxation curve in which the value of μ_r' begins to decrease at frequencies exceeding 30 kHz and does not show a peak of resonance. The frequency characteristic of initial permeability μ_i'/μ_0 was calculated by Eq. (6) using a radius of effective circular cross sectional area $a = 2.5$ mm, the values of initial permeability $\mu_i/\mu_0 = 15\,000$ and direct-current resistivity $\rho = 0.02$ $\Omega \cdot$m at 1 kHz, and a complex relative permittivity $\varepsilon_r' = 10^6 - j1.3 \times 10^6$ as parametrs. The result of this calculation conditions is also shown in Fig. 8. Although there is a small difference in the high frequency range, the relaxation at frequencies of about 30 kHz and higher is well reproduced and the same behavior as with the measured values is shown.

4 Discussion

Various mechanisms have been proposed to explain that the initial permeability of soft ferrites has a frequency dependence that decreases at high frequencies. In addition to relaxation due to eddy current losses, these mechanisms are broadly divided into the concept of natural resonance due to the rotation of magnetic domains, and the concept of domain-wall resonance that occurs due to the movement of domain walls. For MnZn ferrites, therefore, the resonance frequency f_r at which permeability begins to decrease is calculated based on these two kinds of mechanism and calculated values are compared with measured values.

4.1. Natural Resonance

When an external magnetic field is applied to a ferromagnetic substance, the magnetic moment begins the precession of the equinoxes around the axis of easy magnetization and resonates at a natural frequency, causing an abrupt change in permeability. The minimum value of this natural resonance frequency f_r is expressed by J. L. Snoek et al. as follows:

$$f_r = \nu M_s/(3\pi\mu_0\mu_r) \cdots\cdots (7)$$

Here μ_r is relative permeability. Technically, this term refers to the relative magnetic susceptibility χ_r $(=\mu_r - 1)$. However, because it is sufficiently higher than 1, μ_r is used. ν is the gyromagnetic constant. For ferrites, ν is 0.221 MHz $\cdot$ A^{-1} $\cdot$ m. M_s is saturation magnetization and μ_0 is the permeability in a vacuum and $4\pi \times 10^{-7}$. If the general value for high-permeability MnZn ferrites M_s = 0.42 T is used, Eq. (7) becomes as follows:

$$f_r = 7.84 \times 10^3/\mu_r \text{(MHz)} \cdots\cdots (8)$$

As is apparent from Eq. (8), the natural resonance frequency is determined by permeability only when M_s is constant; the higher the value of permeability, the more easily resonance will occur at low frequencies. f_r is 1.05 MHz at μ_r of 7 500 kHz and 523 kHz at μ_r of 15 000. From the measured values shown in Figs. 7 and 8, f_r is estimated at about 200 and 30 kHz, respectively, and is lower than 1/5 the calculated values of Eq. (8). As far as MnZn ferrites are concerned, permeability begins to decrease with relaxation or resonance at frequencies much lower than the resonance frequency expected in natural resonance. Therefore, it is difficult to adopt the concept of natural resonance.

4.2 Domain Wall Resonance

The frequency of domain-wall resonance is given by the following equation[8] using the total area of domain walls S and the domain-wall thickness δ in the unit volume:

$$f_r = 10^4 M_s \sqrt{(S\delta/\mu_r)} \quad \text{(MHz)} \cdots\cdots (9)$$

Technically, the term of μ_r is the relative magnetic susceptibility χ_r $(=\mu_r - 1)$. However, because it is sufficiently higher than 1, μ_r is used. Because the accurate magnetic domain structure of MnZn ferrites has not been clarified, the calculation is made by assuming the magnetic domain width to be 4 μm[9] and the domain-wall thickness to be 0.1 μm and 1 μm. In a case where μ_r = 7 500 and M_s = 0.42 T, f_r is 7.7 MHz and 24.2 MHz respectively, for the above domain-wall thicknesses. Furthermore, when μ_r = 15 000, f_r is 5.4 MHz and 17.1 MHz similarly. These values are much higher than the measured values compared with the calculations of natural resonance frequency and the domain-wall resonance appears unlikely to be the cause of the decrease in μ_i at frequencies below about 500 kHz shown in Figs. 7 and 8, even given that the magnetic domain width and domain-wall thickness are presumed values.

4.3 Summary

As is apparent from the foregoing discussion, the frequency characteristic of initial permeability for MnZn ferrites cannot be explained by natural resonance or domain-wall resonance, and the calculation of the electromagnetic waves within the core made by considering the resistivity, permittivity and dimensions of a core in the preceding sections can best reproduce measured values. It can be considered that this is a kind of dimensional resonance that is caused by a relatively low resistivity peculiar to MnZn ferrite cores, a high permeability and a very high permittivity that does not occur in metallic magnetic materials even if the radius of a cross sectional area is 2.5 mm or less. Contrary to conventional belief, only large cores cause dimensional resonance, in cores of any dimensions that can be actually manufactured, the frequency dependence of μ_i' is either the relaxation type or the resonance type depending on the balance among the three parameters of resistivity, permittivity and permeability.

Among the three parameters, the effect of permittivity on the frequency characteristic has not been given much importance. It is expected that in materials of relatively high initial permeability, very little effect will be obtained if resistivity only is raised while keeping the level of μ_i' at low frequencies. For example, if the complex relative permittivity is taken as 10^6-$j10^6$ for a core with μ_i/μ_0 = 10 000 at 1 kHz, f_r cannot be raised beyond about 200 kHz even by raising resistivity from 0.05 $\Omega \cdot$ m to 0.3 $\Omega \cdot$ m; in this case, the frequency characteristic only changes from the relaxation type to the resonance type as shown in **Fig. 9**. Even if resistivity is raised further, the resonance phenomenon occurs and μ_i' will decrease abruptly without fail. Therefore, in order to improve the frequency characteristic of high-permeability materials, it is probably necessary to conduct development in such a manner that the permittivity of cores is reduced.

5 Conclusions

The frequency dependence of complex initial permeability of MnZn ferrites was analyzed from the electro-

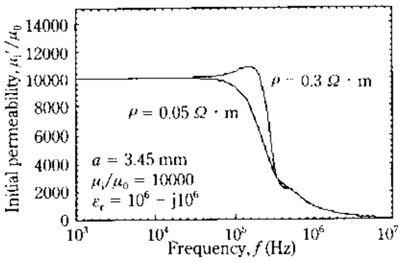

Fig. 9 Calculated frequency dependence of the complex initial permeability, μ_i'/μ_0, for two samples with the resistivities of 0.05 $\Omega \cdot$ m and 0.3 $\Omega \cdot$ m under three constant conditions in which the radius, a, of the cross sectional area is 3.45 mm, the initial permeability, μ_i/μ_0, is 10 000 and the relative complex permittivity, ε_r, is $10^6 - j10^6$

magnetic behavior within a core that is calculated from the dimensions, resistivity and permittivity of the core. It was possible to reproduce a decrease in the complex initial permeability due to relaxation or resonance at relatively low frequencies that is observed in experiments and cannot be explained by natural resonance or domain-wall resonance. The following results were obtained.

(1) The frequency dependence of complex initial permeability of MnZn ferrites that have a constant initial permeability at low frequencies is found from a precise solution of the Maxwell equations and is determined by the dimensions, resistivity and permittivity of cores.

(2) In usual polycrystalline MnZn ferrites, the very high permittivity caused by grain structure is a great factor that determines the frequency dependence of complex initial permeability.

(3) The relaxation-type or resonance-type frequency dependence of complex initial permeability of MnZn ferrites can be derived from the electromagnetic behavior within a core if the dimensions, resistivity and permittivity of the core are taken into consideration; measured values can be reproduced well.

(4) In the case of MnZn ferrites, a decrease in the initial permebility accompanied by resonance that occurs in the range below 1 MHz cannot be explained by the conventional concept of natural resonance or domain-wall resonance. Instead, this phenomenon can be interpreted as a kind of dimensional resonance corresponding to the dimensions of each core, which are determined by the macroscopic electromagnetic properties of cores.

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