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ON MAGNETIC DISTORTION IN AUDIO AMPLIFIERS

By
Yoichiro Yamada, Shigeru Okita,
Masanobu Waku, Susumu Matsuoka
Trio-Kenwood Corporation
Zaventum
Belgium

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On Magnetic Distortion in Audio Amplifiers

Yoichiro Yamada

Shigeru Okita

Masanobu Waku

Susumu Matsuoka

Trio-Kenwood Corporation

Meguro, Tokyo, Japan

Abstract

It is usual in audio amplifiers for magnetic materials (used in the transformers, chassis, casing, etc.) to be situated near the signal current circuitry because of circuitry design and mechanism design considerations. This paper is intended to prove that distortion (odd harmonic distortion), due to the effects (L-H curve) of magnetic materials located near the signal current circuit, is generated inside the amplifier and that this distortion, caused by these magnetic materials, depends greatly on the current flowing in the circuitry. We undertook theoretical analysis to find the non-linear impedance curve, which is the cause of the distortion (here, the distortion originating in the B-H curve is treated at the voltage-versus-current ratio), from the harmonic level of the distortion components. Consequently, this report shows that in order to suppress this distortion in the circuit design of an audio amplifier where high current levels are recorded,

it is necessary to consider not only circuit design techniques but also the materials used near the circuitry. It also shows that excellent results were obtained by making this policy applicable to the design of actual amplifiers.

Introduction

Advances in circuit design technology and in circuit parts have made it possible to achieve a value of around -100 dB for the distortion level--a most important yardstick--in the latest audio amplifiers. Yet it is also a fact that engineers are still discussing improvements in performance and seeking ways to transmit the waveforms ideally, which is the objective of an audio amplifier.

In on-going analysis of audio amplifiers, most of the discussion is focused on the distortion which originates in the non-linearity of the active parts which make up the amplification circuits, and there have been a number of suggestions for various circuit systems designed to improve this distortion.

However, an ideal operating state is not necessarily indicated when these circuits are activated inside the actual amplifier structure. This fact is beginning to re-focus attention now that distortion is now being recorded in the order of -100 dB, and so brings the need for technology relating to the structure of the amplifier.

With full consideration given to circuit design technology, we turned our attention to the very faint impedance in the signal current circuit (printed circuit board copper foil and wiring between the circuitry modules) which has hitherto been ignored, and proceeded with our analysis. This very faint impedance in the circuitry was turned into a model by the printed patterns used in actual amplifiers, and by placing this into an aluminum plate (non-magnetic material) box and also into a box made of iron plates (magnetic material) which are used as the materials for actual amplifier casings, we were able to confirm the following phenomenon.

The faint impedance is affected by the B-H curve of the magnetic material and non-linear distortion of an odd number order is generated inside the signal current circuit. The value of this distortion depends greatly on the current flowing through the circuits, the frequency and the distance between the magnetic material and the signal current.

We shall now describe the generation of the distortion by the magnetic material as changes in the impedance which is dependent on the current.

1. Impedance changes in printed patterns due to neighboring materials

Although distortion, which is a specification of considerable importance for audio amplifiers, has undergone remarkable improvement thanks to advances in circuit techniques, there has been very little discussion on the distortion produced by the materials used in the construction of amplifiers. The phenomenon under which the impedance of the signal line undergoes change when metal is placed nearby has been explained by "eddy current." However, research on distortion in the signal current caused by placing specially designated metals nearby has been insufficient.

In order to establish design techniques inclusive of the structural materials in audio amplifiers, we considered the impedance in the wiring materials and printed patterns, and undertook an analysis of the changes in the impedance caused by eddy current and of the generation of distortion caused by special metals.

2. Changes in impedance due to eddy current

In accordance with Maxwell's electromagnetic equation, the current flowing through a signal line generates a magnetic field 'H' (equation: $\mathrm{rot}\,H = \dot{i}$). In accordance with Maxwell's electromagnetic equation ($\frac{1}{\sigma}\mathrm{rot}\,\dot{i} = -\mu \partial H / \partial t$), this magnetic field 'H' generates an "eddy current" which is determined by the permeability and conductivity inherent to the neighboring materials. Eddy current-based impedance changes are changes in the impedance of the actual line when metal is placed near the signal line.

In order to consider the impedance in the wiring materials and printed patterns which has been conventionally neglected, we test-made the printed pattern shown in Fig. 1-a.

Fig. 1-b and Fig. 1-c give the frequency-versus-inductance and frequency-versus-resistance values when the distance between the metal and the printed pattern made into a model is taken as the parameter.

The following observations can be drawn from these measurement data:

(a) The bare copper foil inductance is virtually flat with respect to the frequency.

(b) The inductance of the copper foil housed in a iron case is greater than the bare copper foil in the low frequency range but lower in the high frequency range.

(c) Th bare copper foil resistance is about 50 milliohms, and t tends to increase in the high frequency range. It increases markedly when the foil is housed in the iron case.

(d) The changes in the inductance and resistance when the foil is housed in the steel case depend on the distance between the steel case and the copper foil, and they increase in direct proportion to their proximity.

The above phenomena can be explained by putting the impedance of the copper foil pattern in an equivalent circuit such as the one shown in Fig. 2-a.

In this figure, R_1, L_1, R_3 and C are the resistance, self-inductance, insulation resistance and distributed capacitance, and they indicate the impedance configuration of the copper foil. R2, L2 and M are the resistance, inductance and mutual inductance produced by the eddy current of the neighboring materials.

The impedance, as a result of the eddy current, can be defined by the following equation:

$$Z(S)=\frac{R_3\{(L_1L_2-M^2)S^2+(R_1L_2+R_2L_1)S+R_1R_2}{R_3C(L_1L_2-M^2)S^3+\{L_1L_2-M^2+R_3C(R_1L_2+R_2L_1)\}S^2+\{R_1L_2+R_2L_1+R_1R_2R_3C+R_3L_2\}S+R_2(R_1+R_3)} \quad \cdots\cdots (1)$$

Since with the printed pattern which was made a model, R3 is much greater than 1 and C is much smaller than 1, it is possible to replace it with a simple equivalent circuit with effective inductance Lo and effective resistance Ro as shown in Fig. 2-b.

$$L_0=L_1-M^2L_2/(R_2^2/\omega^2+L_2^2) \quad \cdots\cdots (2)$$

$$R_0=R_1+M^2R_2/(R_2^2/\omega^2+L_2^2) \quad \cdots\cdots (3)$$

Formulae (2) and (3) have the curves shown in Fig. 2-c with respect to the frequency. Since the foil is housed in the steel case, the inductance component is affected by the eddy current in the second section of formula (2) and it shows the tendency to decline. According to formula (3), the resistance component of the copper foil pattern housed in the steel case depends on the frequency, and its tendency to increase tallies with the actual measurement data.

In this way it can be seen that by housing the copper foil in a iron case, the impedance is affected by the inherent R_2 and L_2 due to the relative permeability and conductivity of the steel itself, and that the effects of the eddy current are pronounced across a range (mutual inductance increase region) where the pattern and steel case are located close together.

The changes in the impedance which have been described show a high level of coincidence between the actual measurement data and theoretical expression (equivalent circuit). However, the eddy current itself is not a factor that generates distortion since this is a region of the linear parts that establishes a proportional relationship between the current and voltage of the signal line.

Therefore, it is not possible to use the eddy current as an explanation for the phenomenon whereby specially designated metals near the signal current, on which we have focused our attention, cause distortion in the signal current.

3. Generation of distortion by magnetic materials

In order to confirm that the signal current is distorted by neighboring magnetic materials, we measured the distortion caused by two materials, aluminum (non-magnetic) and iron (magnetic), which were placed near the pattern, using a series circuit with resistance RL and printed pattern impedance Z as the constant-voltage source (see Fig. 3-a). The distortion was measured as the voltage at both ends of resistor R_L.

Fig. 3-b, Fig. 3-c, Fig. 3-d and Fig. 3-e show the output-versus-total harmonic distortion, frequency-versus-total harmonic distortion, output-versus-total harmonic spectrum and the distance-versus-harmonic spectrum, respectively.

The following observations can be made from the measurement data.

(a) The distortion produced by the magnetic material depends on current I and distance (d) between the steel case and the copper foil, and its effects are sufficiently significant until the distance reaches about 50 mm.

(b) The distortion produced by the magnetic material is noticeable in the high frequency range of more than 1 kHz.

(c) The distortion produced by the magnetic material, particularly as far as the actual sound heard is concerned, is predominantly of a stimulative odd number order.

(d) There is hardly any output distortion when the copper foil is brought near a non-magnetic material.

In the past, it has been usual for the distortion, which is one of the most significant specifications for audio amplifiers, to be improved solely by circuit techniques. Now, however, a cause of distortion can be found in the materials used in the actual construction of the amplifiers. We shall now proceed to analyze the mechanisms working to generate distortion by the magnetic material, based on these phenomena.

4. Analysis of magnetic material distortion

4-1. *Equivalent circuit taking magnetic material distortion into account*

A model was made of the circuit configuration of an audio amplifier as in Fig. 4-a.

When this amplifier circuit is housed in a specially designated metal case, the faint impedance of the printed pattern and wiring materials, etc. which generate the distortion is replaced by that of the model circuit in Fig. 4-b.

Z_1, Z_2, Z_3, Z_4 and Z_5 (non-linear impedance which causes distortion) express the impedance changes caused by the circuit parts, printed pattern and wiring materials nearby.

As a recent feature of audio amplifiers, the input impedance and resistors R_1 and R_2 which make up the feedback circuit are in the order of several kiloohms to several tens of kiloohms, and Z_1, Z_2 and Z_3 can be ignored. In the same way, it is acceptable to consider that the contribution of the changing impedance is small with the active elements seeing as the rule of high input impedance and low output impedance is kept for the circuits. Furthermore, as with audio amplifiers, it is not possible to ignore the Z_4 and Z_5 impedances inserted in series to the low impedance of the approximately 100 damping factor and load impedance R_L of 8 ohms, and what is more, this is the line where high current levels flow.

A consideration of these approximations gives the analysis model such as that shown in Fig. 4-c.

The transfer function in the analysis model is as per the following formula.

$$\frac{E_o}{E_i} = \frac{AR_L(R_1+R_2)}{(Z_5+R_L)\{R_1+R_2+R_o+Z_4+AR_1+(R_1+R_2)(R_o+Z_4)/(R_L+Z_5)\}} \quad \ldots.(4)$$

Where A: open loop gain

Z_4 and Z_5 of the model circuit in the above formula are located near magnetic materials and they are dependent on the current. In the same way, the transfer function itself in formula (4) is dependent on the current (this is a cause of the distortion).

Magnetic field 'H', which is produced by the current flowing to the signal line, generates a secondary excitation voltage which is an inherent $-\partial B/\partial t$ in accordance with the B-H characteristics inherent to the neighboring materials.

Fig. 5-a and Fig. 5-b show the B-H curves of iron (magnetic material) and of aluminum (non-magnetic). The $-\mu\delta H/\partial t$ secondary voltage which is determined by the high permeability and hysteresis contained only in magnetic materials is non-linear and it is a cause of distortion.

In the case of the non-magnetic material, the B-H curve is virtually linear and Z_4 and Z_5 in formula (4) become linear elements.

4-2. Analysis of inpedance in magnetic materials (treated as the ratio of voltage to current)

What we did was to calculate the distortion produced by the magnetic materials not as the B-H curve but as changes in the impedance and we obtained significant data which are discussed below.

Fig. 6-a shows a circuit designed to measure the changes in the impedance.

Z expresses the above-mentioned pattern (see Fig. 1-a), and RL the 8-ohm pure resistance. The Z - R_L series circuit is driven by constant-voltage source V_1.

V_2, ΔV_2 and V_Z are the voltage at both ends of RL, the distortion voltage at both ends of RL and the voltage at both ends of Z. The following relationship exists between V_1, V_2, ΔV_2, V_Z and I.

$$V_2 = V_2' + \Delta V_2 \quad \ldots\ldots(5)$$

$$V_Z = V_1 - V_2' - \Delta V_2 \quad \ldots(6)$$

$$I = V_2/R_L \quad \ldots\ldots(7)$$

$$Z = (V_1 - V_2)/I = R_L\ (V_1/V_2 - 1) \quad \ldots(8)$$

The above relationship can be expressed in a vector diagram such as the one shown in Fig. 6-b.

Since ΔV_2 indicates the distortion voltage itself, it serves as a vector with an amplitude and angular velocity which differ at every instant, based on P and Q. Therefore, since the V_2 and V_Z each have ΔV_2 components, this vector is shaken at every instant.

If V1 and V2 are assumed as in the following formulae, then impedance Z can be sought from the formulae:

$$V_1 = V_{11} e^{j\omega t} \quad \ldots\ldots\ (9)$$

$$V_2 = \sum_{i=1}^{\infty} V_{2i} e^{j(i\omega t + \theta i)} \quad \ldots\ldots\ (10)$$

$$Z = R_L \left(V_{11} e^{j\omega t} / \sum_{i=1}^{\infty} V_{2i} e^{j(i\omega t + \theta i)} - 1 \right) \quad \ldots\ldots\ (11)$$

With the actual measurement, the total harmonic distortion was not more than about -80dB and so the distortion component of the magnetic material was detected by a distortion analyzer. Consequently, with the impedance calculation, the V_1 and V_2 (V_2' and ΔV_2) harmonic amplitude and phase were measured and substituted in formula (11) to find the impedance.

Fig. 6-c and Fig. 6-d give the time-versus-impedance and the current-versus-impedance when the pattern is housed in a iron case.

Fig. 6-e and Fig. 6-f give the time-versus-impedance and current-versus-impedance when the pattern is housed in an aluminum case.

From the impedance data it is possible to make the following observations.

(a) When the pattern is placed in a magnetic material case, the impedance is not flat with respect to the time base and it has predominantly second harmonic components.

(b) When the pattern is housed in a non-magnetic material case, the impedance is flat with respect to the time base, and it functions as a real linear element.

The impedance from non-magnetic material is constant with respect to the time base since it depends mainly on the eddy current. Therefore, as long as the current flowing is sinusoidal, it is possible to state that a voltage drop is a region of the linear element where sine waves are always formed.

The impedance from a magnetic material is not constant with respect to the time base.

In this way, even if the current flowing is sinusoidal, the impedance caused by magnetic materials is a non-linear element in which the voltage drop is not a simple sine wave. This makes is possible to explain that the transfer function is distorted since Z_4 and Z_5 in formula (4) are non-linear.

As we have shown above, the mechanism behind the generation of distortion by the neighboring materials has for its origin the non-linear B-H curve which is inherent to magnetic materials such as iron , rather than the effects produced by the eddy current.

4-3. Computation of distortion waveforms by computer

As a way of checking the theory and experiments concerning the generation of distortion by magnetic materials, we employed a large-scale computer to calculate the distortion relating to the distance between the signal line and magnetic material.

For the calculation, we considered a model such as that shown in Fig. 7-a, and adopted the formula below.

$$\frac{L}{L_0} = 2\int_0^{\infty} J_1^2(\zeta a)\left(\frac{1}{\zeta} - \frac{1}{\zeta^2 \ell} + \frac{1}{\zeta^2 \ell} e^{-\zeta \ell}\right) d\zeta$$

$$- \frac{1}{\ell}\int_0^{\infty} \frac{1}{\zeta^2} J_1^2(\zeta a)\left(e^{-\zeta z_2} - e^{-\zeta z_2}\right)^2$$

$$\frac{\left(\frac{h_1}{\zeta} - \frac{\mu_1}{\mu_0}\right)\left(\frac{h_2}{h_1} + \frac{\mu_2}{\mu_1}\right) + \left(\frac{h_1}{\zeta} + \frac{\mu_1}{\mu_0}\right)\left(\frac{h_2}{h_1} - \frac{\mu_2}{\mu_1}\right) e^{2h_1 b_1}}{\left(\frac{h_1}{\zeta} + \frac{\mu_1}{\mu_0}\right)\left(\frac{h_2}{h_1} + \frac{\mu_2}{\mu_1}\right) + \left(\frac{h_1}{\zeta} + \frac{\mu_1}{\mu_0}\right)\left(\frac{h_2}{h_1} - \frac{\mu_2}{\mu_1}\right) e^{2h_1 b_1}} \cdot d\zeta \quad \ldots. \ (12)$$

The Fig. 7-b curve is used for the permeability.

Fig. 7-c, Fig. 7-d and Fig. 7-e show the distortion waveforms when the distance is varied to 10 mm, 30 mm and 50 mm, respectively.

The distortion produced when magnetic material is brought near the model is odd harmonic distortion based on third harmonics, and as long as the distance is not more than 50 mm, the effects of the neighboring metal are unavoidable.

If the above theory relating to the generation of distortion by magnetic materials is put together, it is found to match well the resultsof the above-mentioned experiment.

5. Magnetic distortion countermeasures

In equipment such as audio amplifierswhere mainly steel and other magnetic materials are indispensable for the case, chassis and power transformers, etc., the appointed task is to drive a load of about 8 ohms, the current handled is high and, in wide-band amplifiers ranging from DC to 100 kHz which have appeared in recent years, the effects of electromagnetic induction are also high. All these factors make it difficult to come to grips with magnetic distortion.

In order to keep distortion generated by magnetic materials down to the bare minimum, we have adopted non-magnetic materials for the chassis and case, and housed the power transformer separately. We then compared our prototype with an amplifier in which no steps were taken to suppress the magnetic distortion.

Fig. 8-a and Fig. 8-b show the harmonic spectrum of an amplifier in which no measures have been taken to eliminate distortion caused by magnetic materials and of an amplifier, with exactly the same circuitry, which features a full complement of measures to deal with this distortion.

6. Conclusion

We shall now summarize the main features of the mechanism of distortion caused by magnetic materials which we have been discussing.

(a) The higher the current, the more noticeable the distortion caused by the magnetic materials.

(b) Distortion will be generated by the magnetic materials as long as they are situated less than 50 mm away.

(c) The distortion produced by the magnetic materials is noticeable with a frequency of more than 1 kHz.

(d) As far as the actual sound heard is concerned, odd number order harmonics, which are made stimulative, are predominant in the harmonic distortion.

Because of the above points, the generation of the distortion by the magnetic materials is an electromagnetic combination and so particular attention is required with circuits having a high inductance component.

In the past, the main focus of distortion in audio amplifiers was on crossover and switching distortion, and these were improved by circuit techniques alone.

However, as we have shown in this paper, distortion caused by magnetic materials is of an order which cannot be ignored, and it is necessary to come to grips with it not only with circuit techniques but also with construction materials.

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Fig. 1-a Printed pattern model

Fig. 1-b. Frequency-versus-inductance characteristics

Fig. 1-c Frequency-versus-resistance characteristics

Fig. 2-a Equivalent circuit of printed pattern

Fig. 2-b Simple equivalent circuit of printed pattern

Fig. 2-c L, R frequency response based on eddy current effects

Fig. 3-a Output-versus-total harmonic distortion

Fig. 3-b Total harmonic distortion-versus-frequency

Fig. 3-c Output-versus-harmonic spectrum

Fig. 3-d Distance-versus-harmonic spectrum

Fig. 4-a Equivalent circuit of amplifier

Fig. 4-b Equivalent circuit of amplifier taking case material into account

Fig. 4-c Analysis model

Fig. 5-a B-H curve of iron

Fig. 5-b B-H curve of aluminum

Fig. 6-a Circuit to measure changes in impedance caused by effects of magnetic material

Fig. 6-b Vector diagram of fundamental wave and magnetic material distortion

Fig. 6-c Time-versus-magnetic material impedance

Fig. 6-d Current-versus-magnetic material impedance

Fig. 6-e Time-versus-non-magnetic material impedance

Fig. 6-f Current-versus-non-magnetic material impedance

Fig. 7-a Model to calculate distortion relating to distance between signal line and neighboring metal

Fig. 7-b B-H curve used for calculation

Fig. 7-c Time-versus-impedance of magnetic material at a distance of 10 mm

Fig. 7-d Time-versus-impedance of magnetic material at a distance of 30 mm

Fig. 7-e Time-versus-impedance of magnetic material at a distance of 50 mm

Fig. 8-a Harmonic spectrum of an amplifier using a magnetic material case

Fig. 8-b Harmonic spectrum of an amplifier using a non-magnetic material case

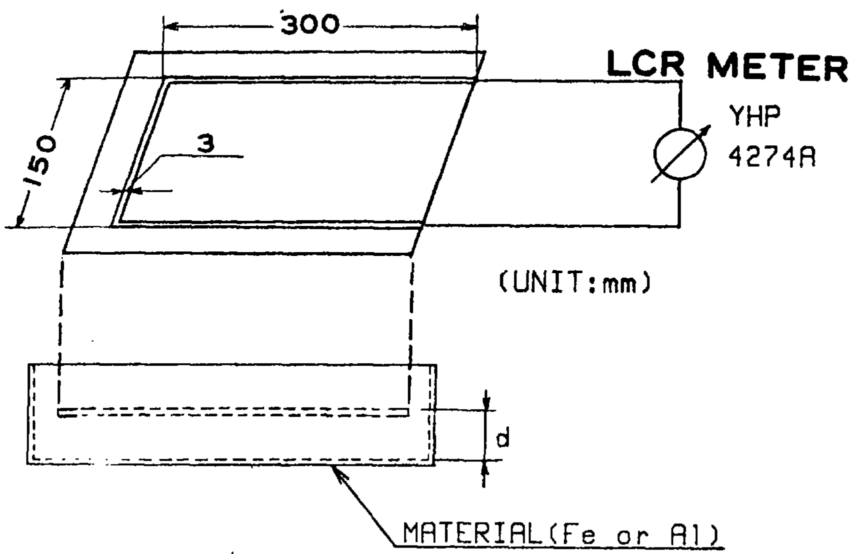


Fig. 1-a Printed pattern model

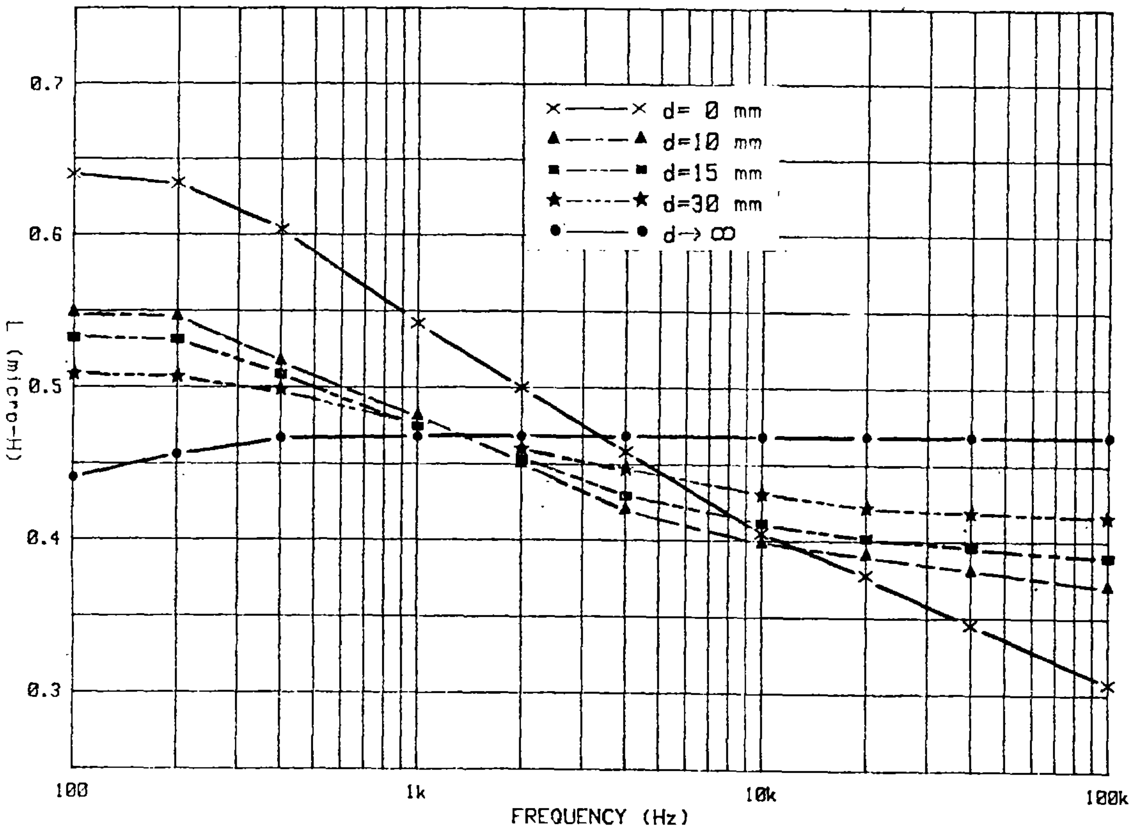


Fig.1-b FREQUENCY vs.INDUCTANCE

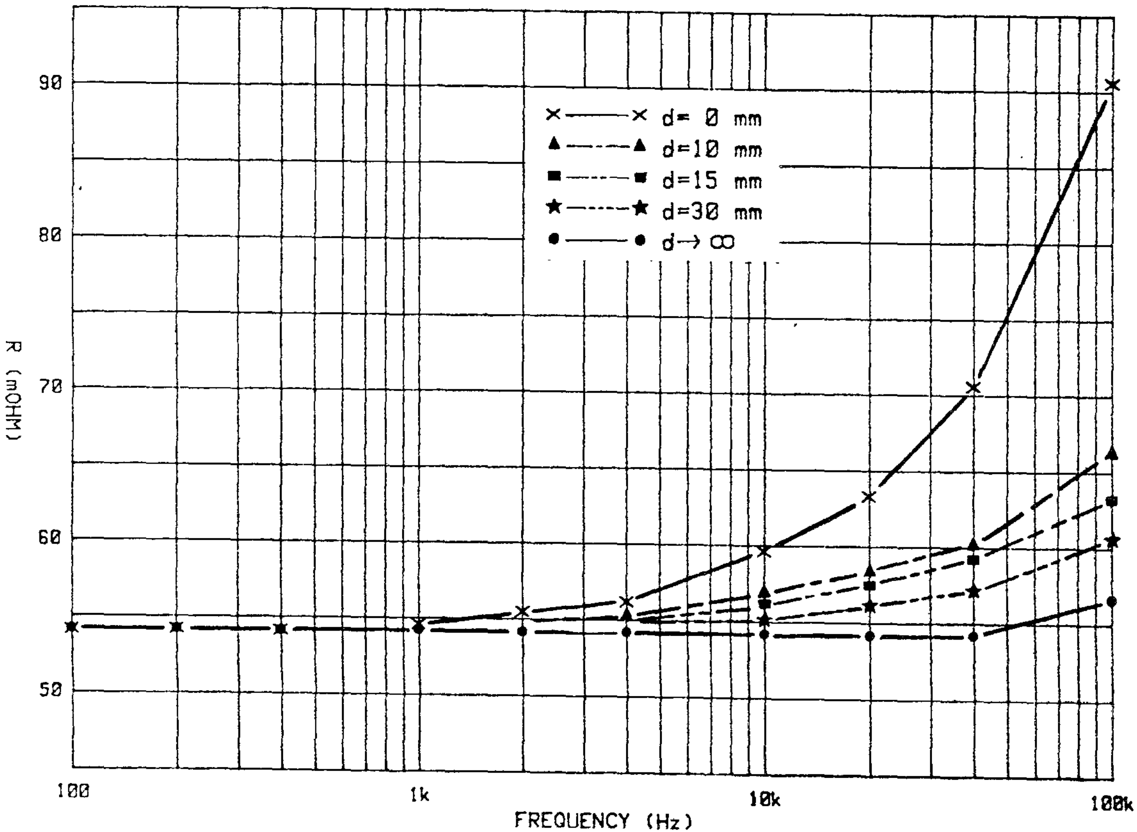


Fig.1-c FREQUENCY vs.RESISTANCE

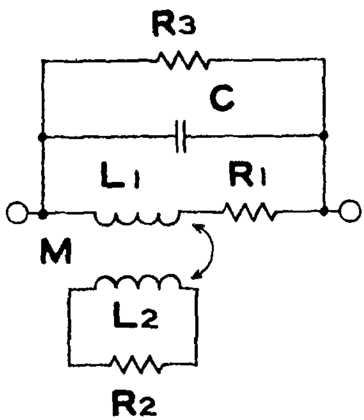


Fig. 2-a Equivalent circuit of printed pattern

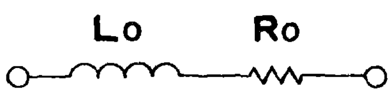


Fig. 2-b Simple equivalent circuit of printed pattern

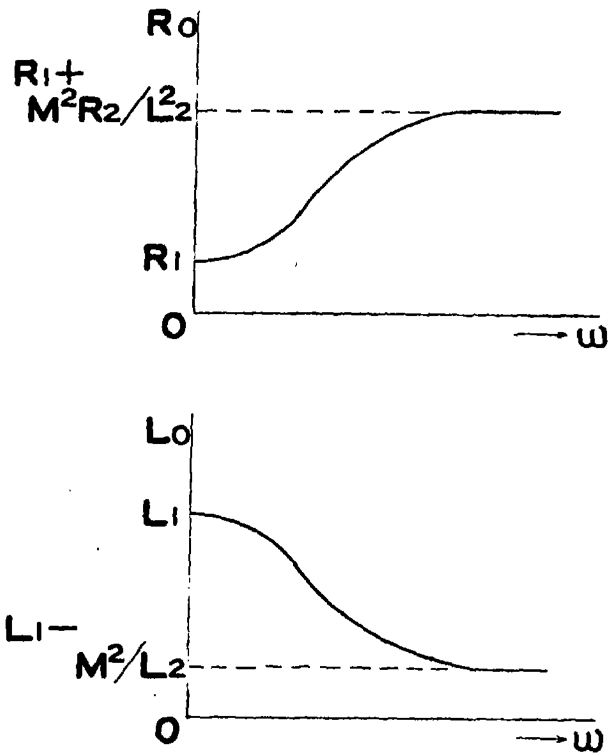


Fig. 2-c L, R frequency response based on eddy current effects

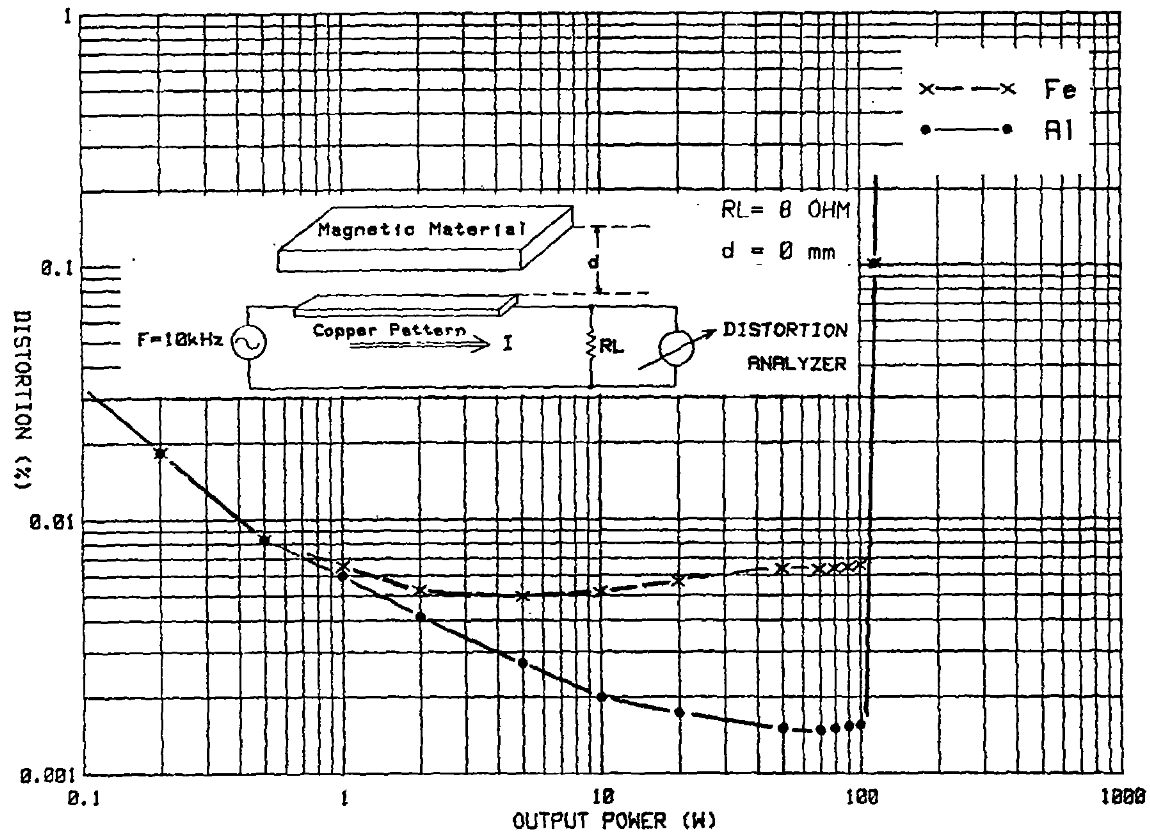


Fig.3-a OUTPUT POWER vs.TOTAL HARMONIC DISTORTION

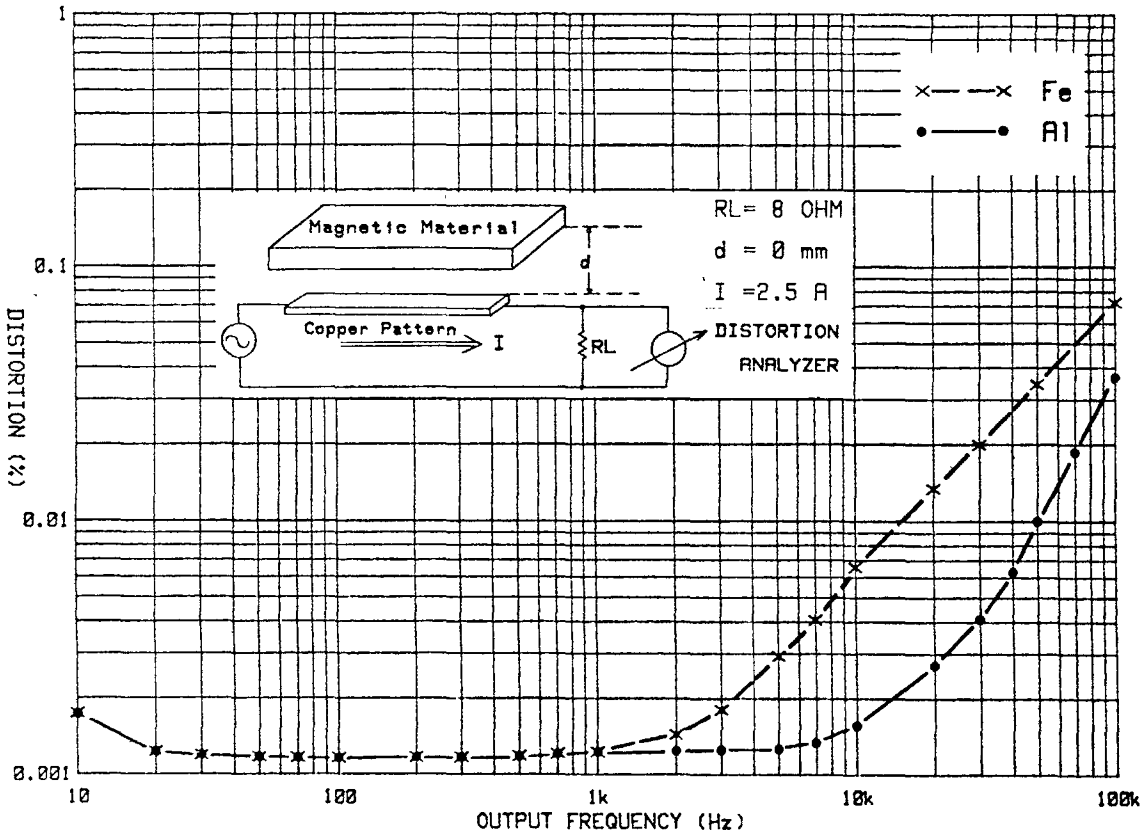


Fig.3-b FREQUENCY vs.TOTAL HARMONIC DISTORTION

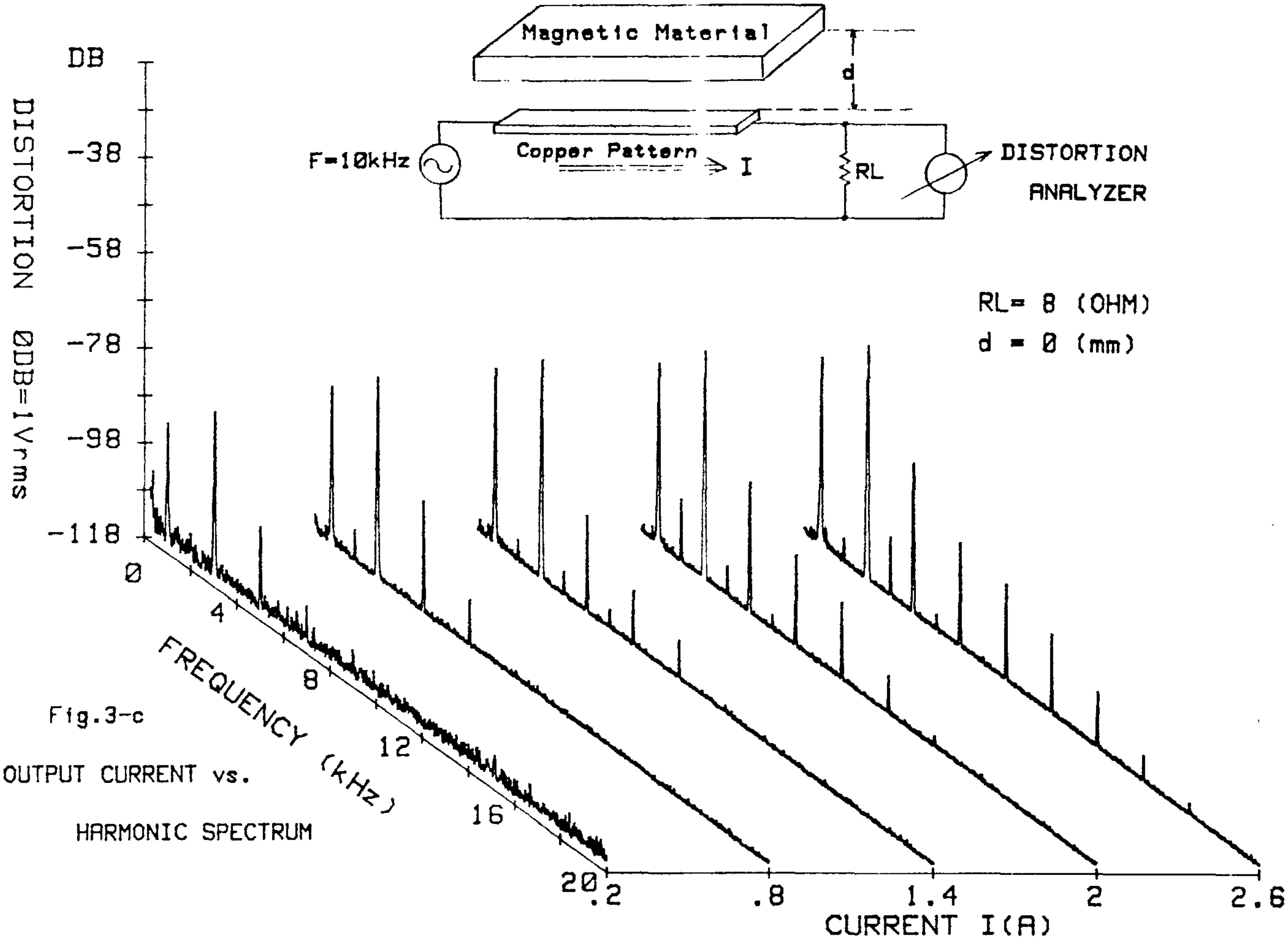


Fig.3-c

OUTPUT CURRENT vs.

HARMONIC SPECTRUM

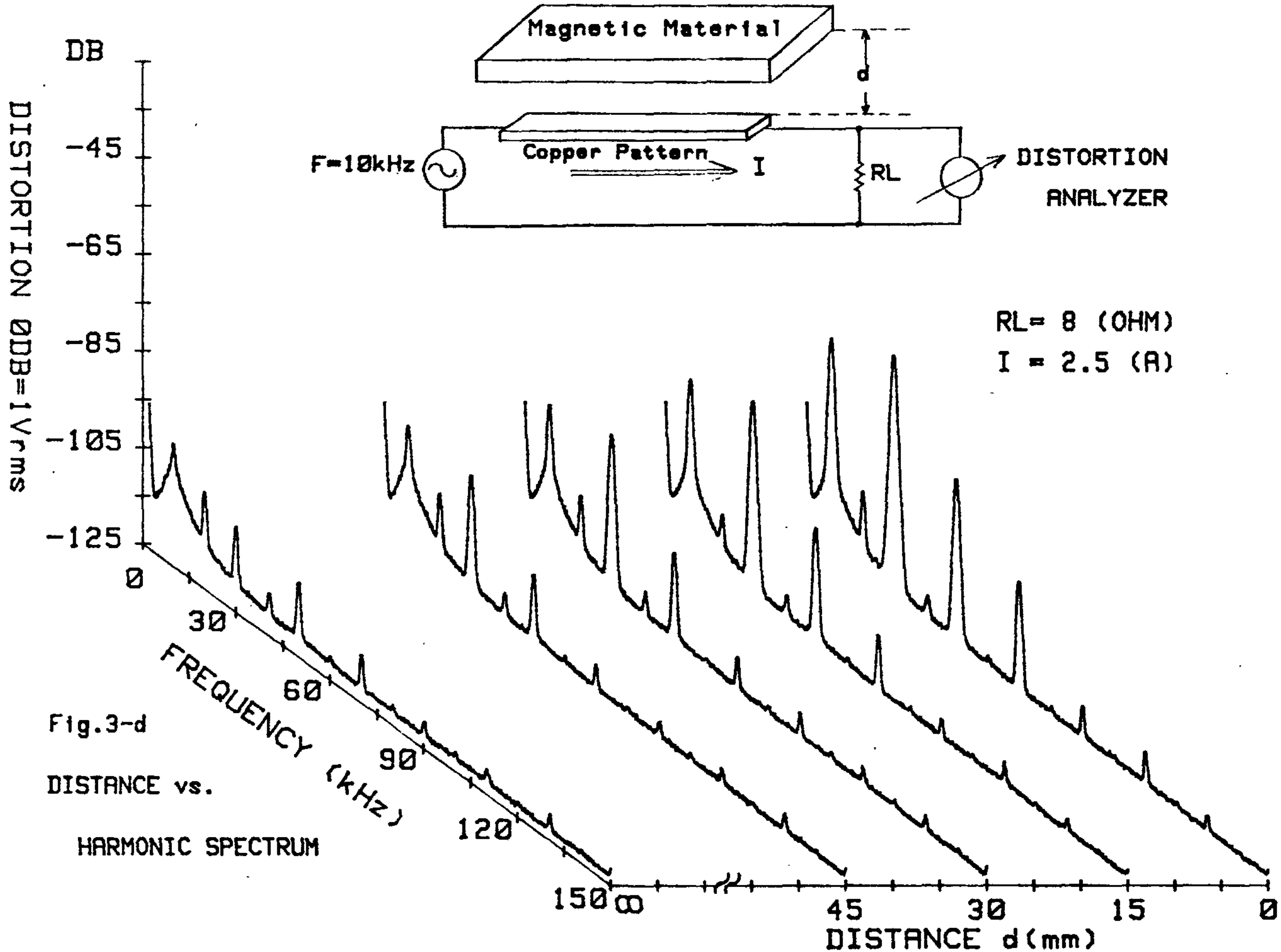


Fig.3-d

DISTANCE vs.

HARMONIC SPECTRUM

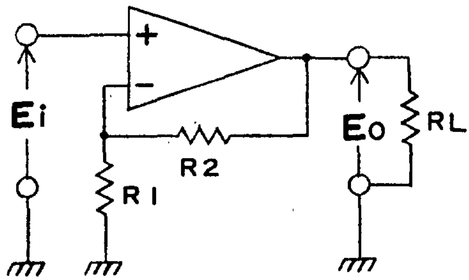


Fig. 4-a Equivalent circuit of amplifier

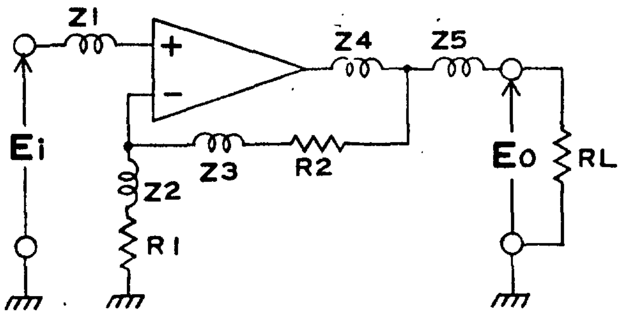


Fig. 4-b Equivalent circuit of amplifier taking case material into account

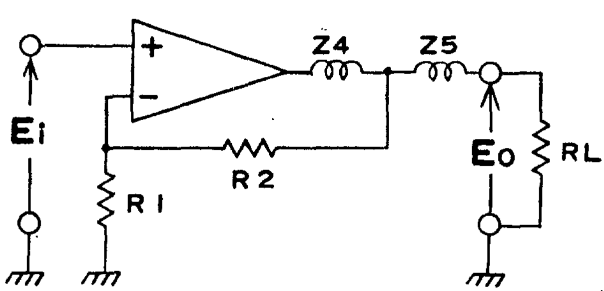


Fig. 4-c Analysis model

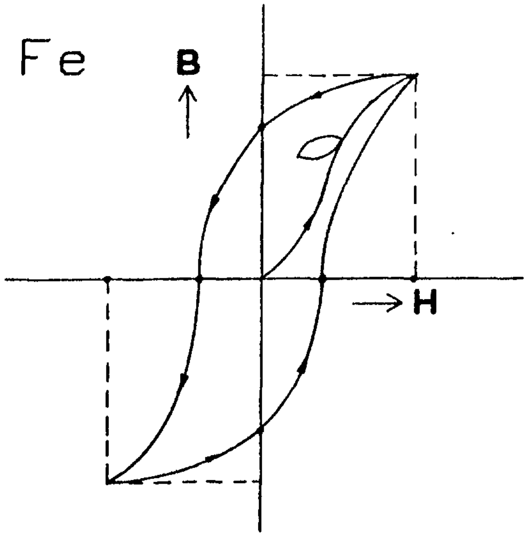


Fig. 5-a B-H curve of iron

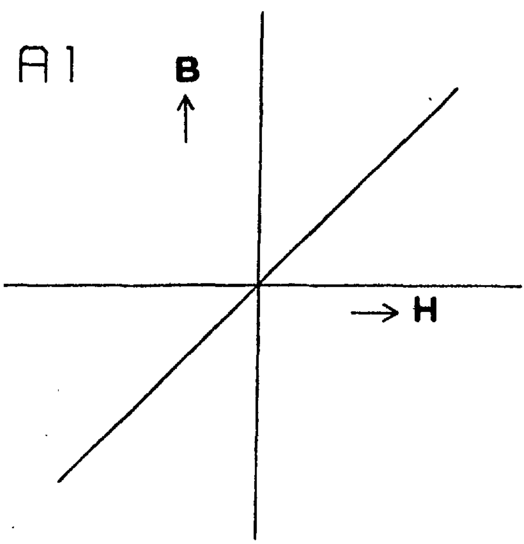


Fig. 5-b B-H curve of aluminum

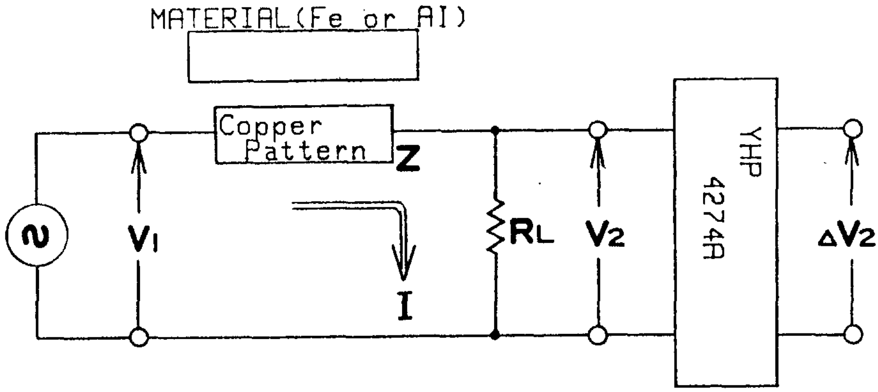


Fig. 6-a Circuit to measure changes in impedance caused by effects of magnetic material

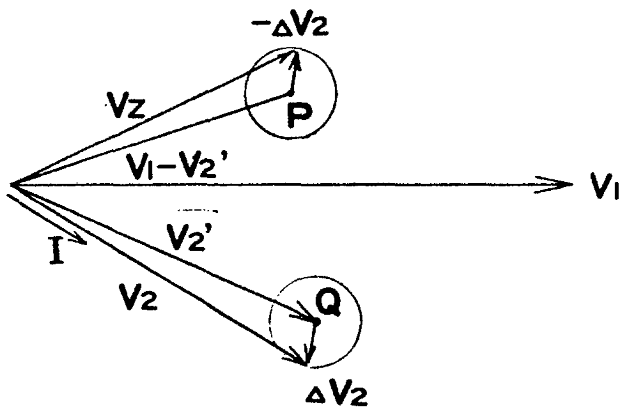


Fig. 6-b Vector diagram of fundamental wave and magnetic material distortion

Fig.6-c TIME vs.MAGNETIC MATERIAL IMPEDANCE

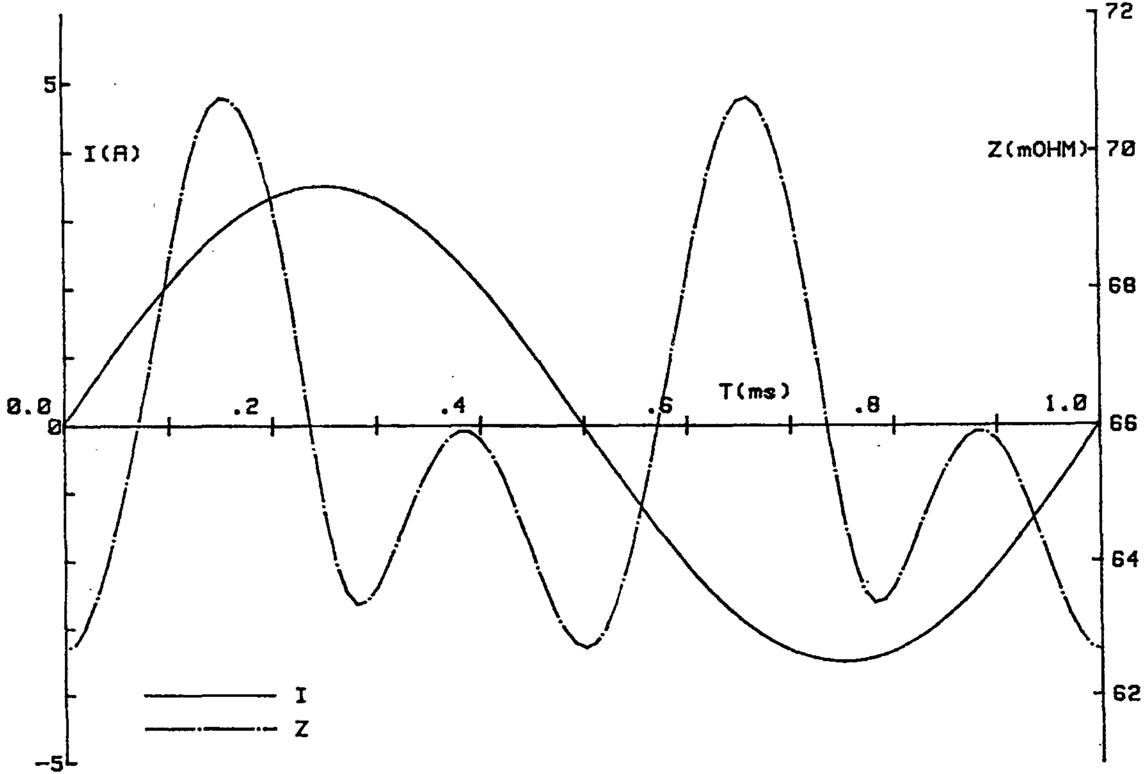


Fig.6-d CURRENT vs.MAGNETIC MATERIAL IMPEDANCE

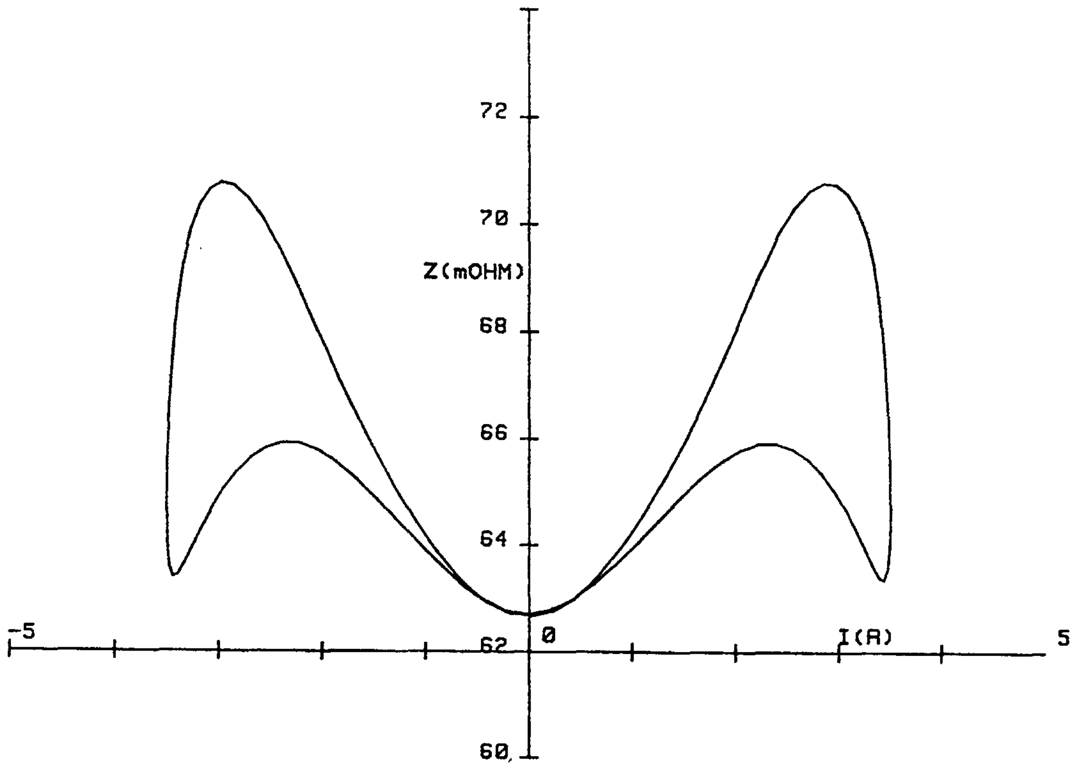


Fig.6-e TIME vs.NON-MAGNETIC MATERIAL IMPEDANCE

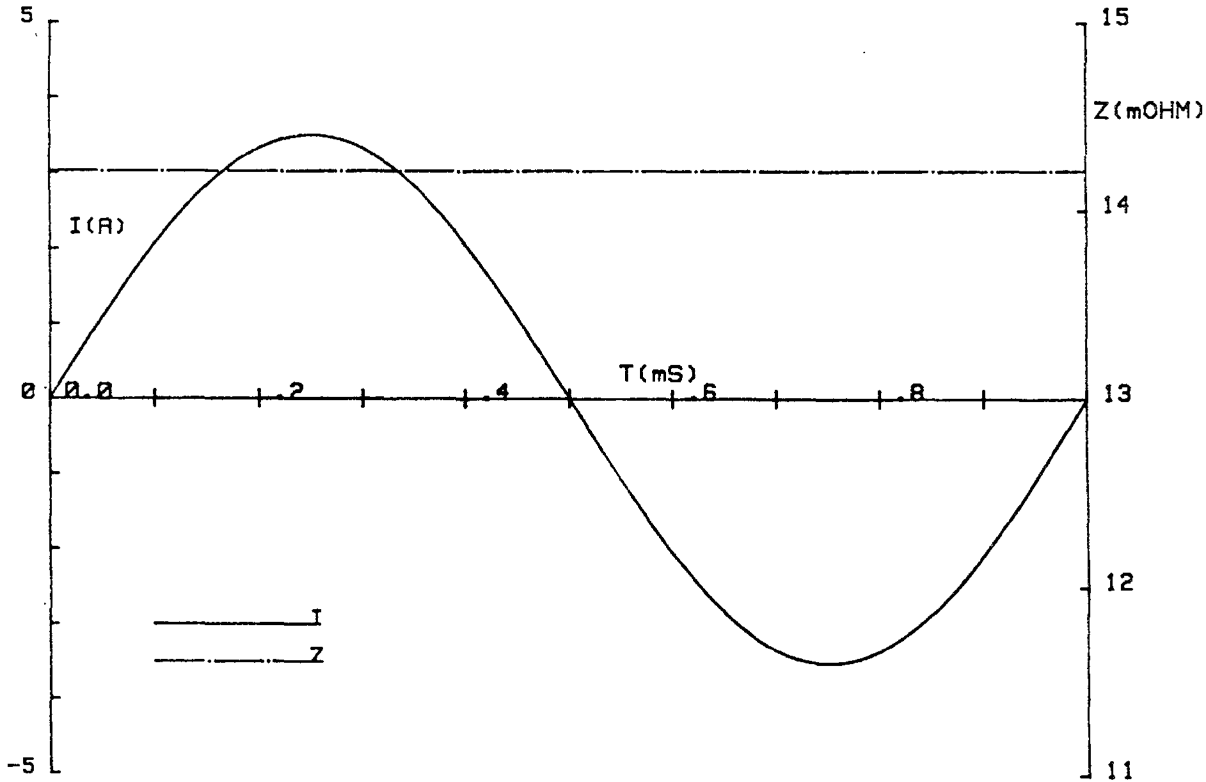
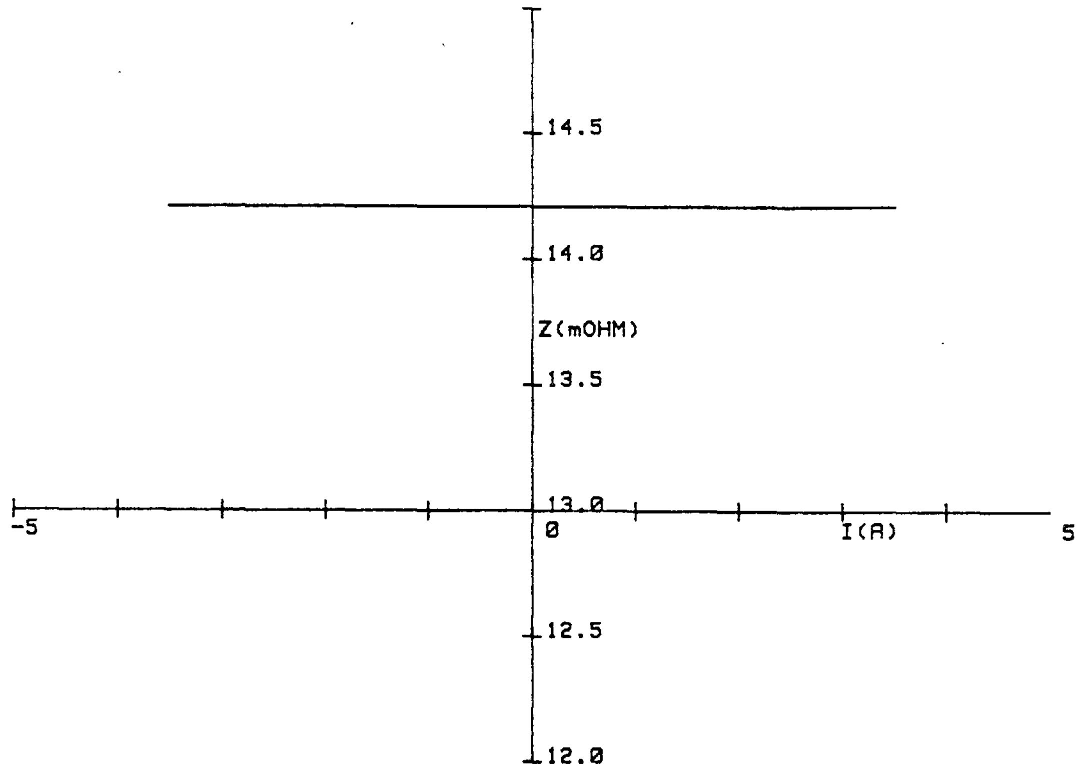


Fig.6-f CURRENT vs.NON-MAGNETIC MATERIAL IMPEDANCE



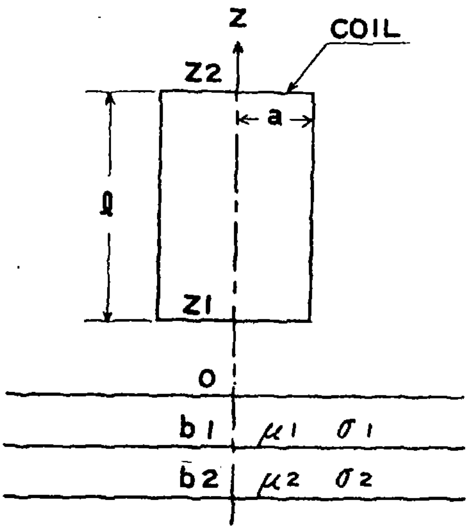


Fig. 7-a Model to calculate distortion relating-to distance between signal line and neighboring metal

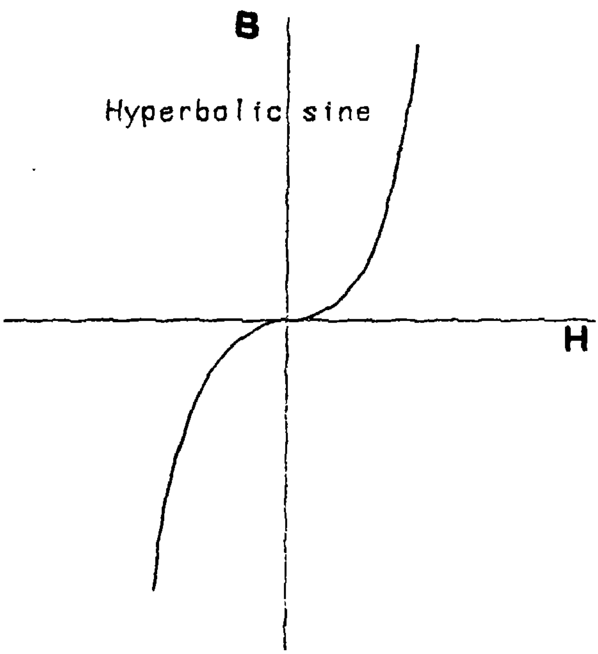


Fig. 7-b B-H curve used for calculation

Fig.7-c TIME vs.IMPEDANCE OF MAGNETIC MATERIAL

AT A DISTANCE OF 10 mm

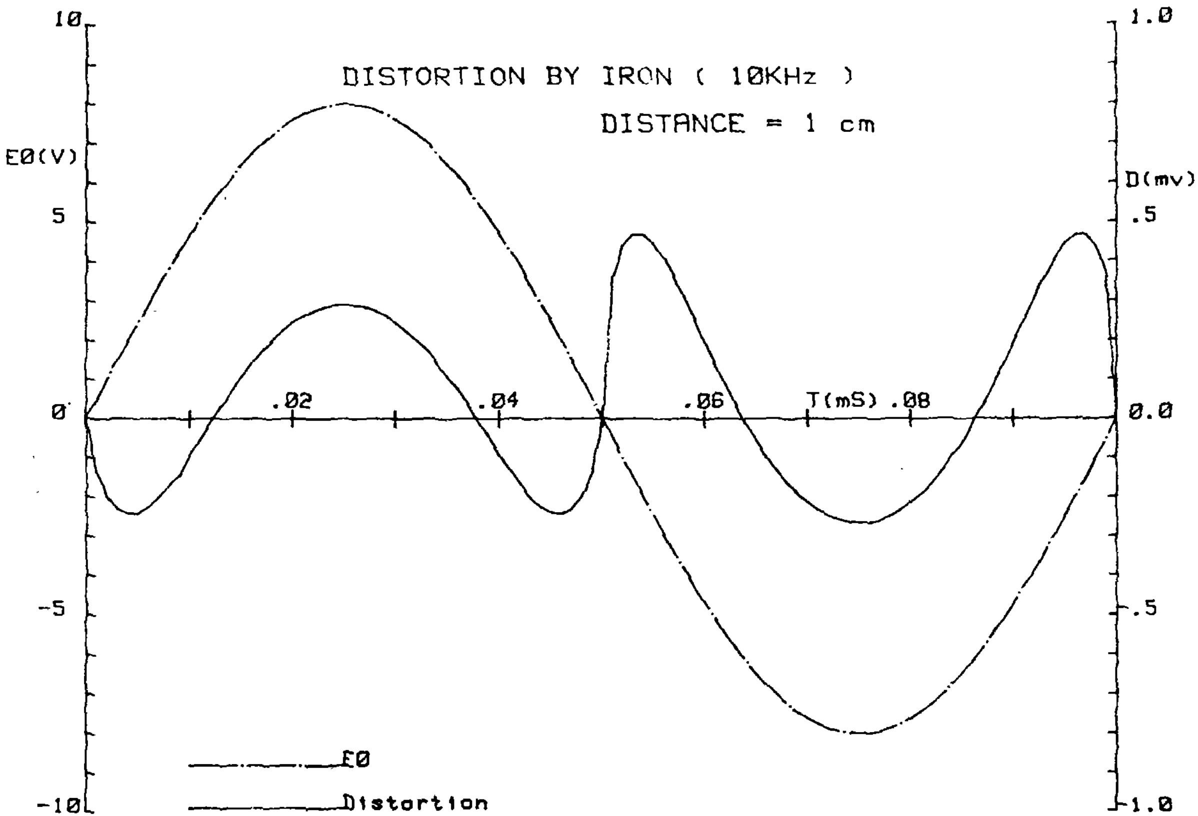


Fig.7-d TIME vs.IMPEDANCE OF MAGNETIC MATERIAL

AT A DISTANCE OF 30 mm

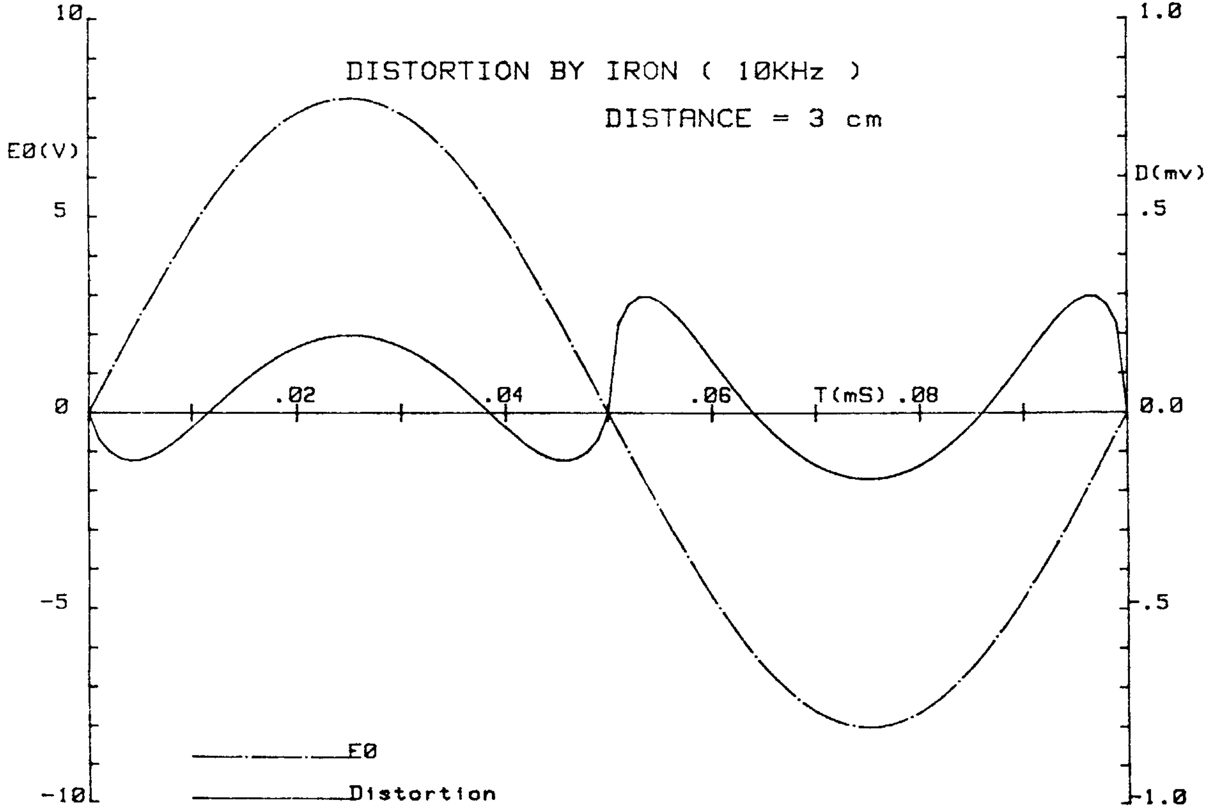
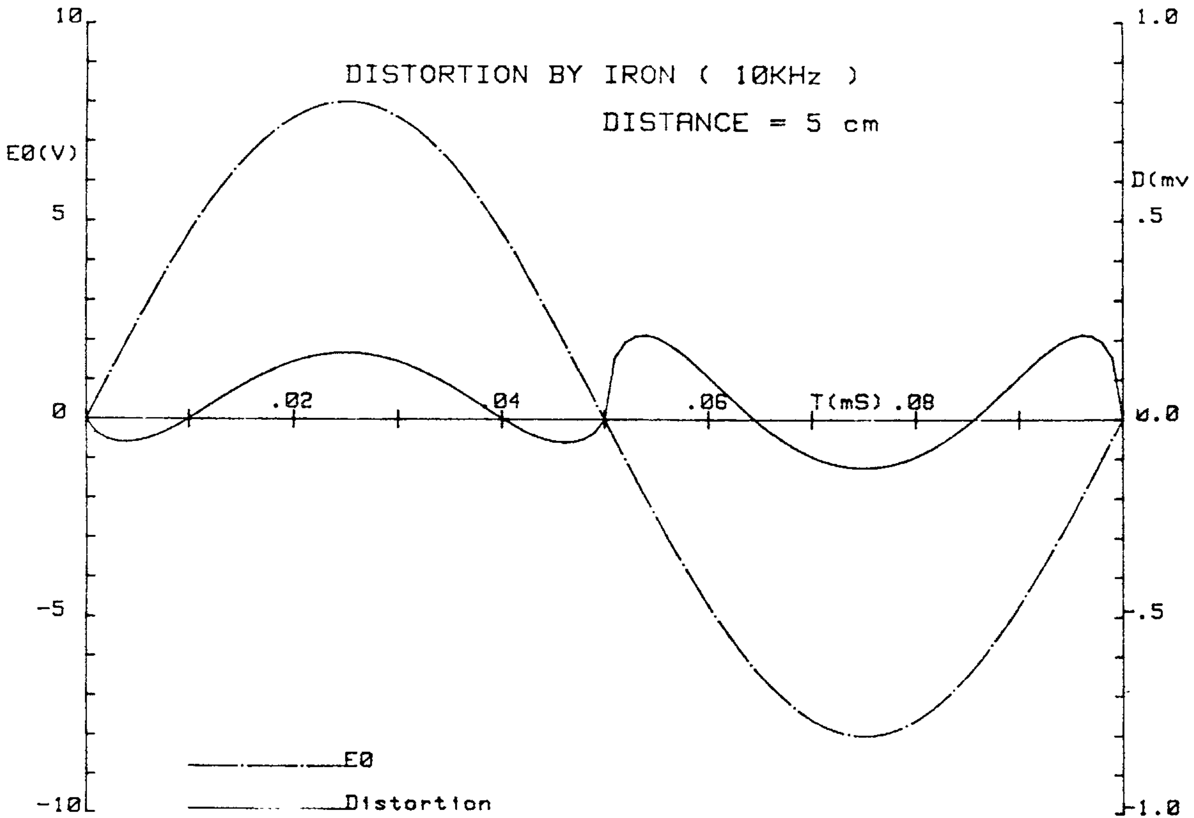


Fig.7-e TIME vs. IMPEDANCE OF MAGNETIC MATERIAL

AT A DISTANCE OF 50 mm



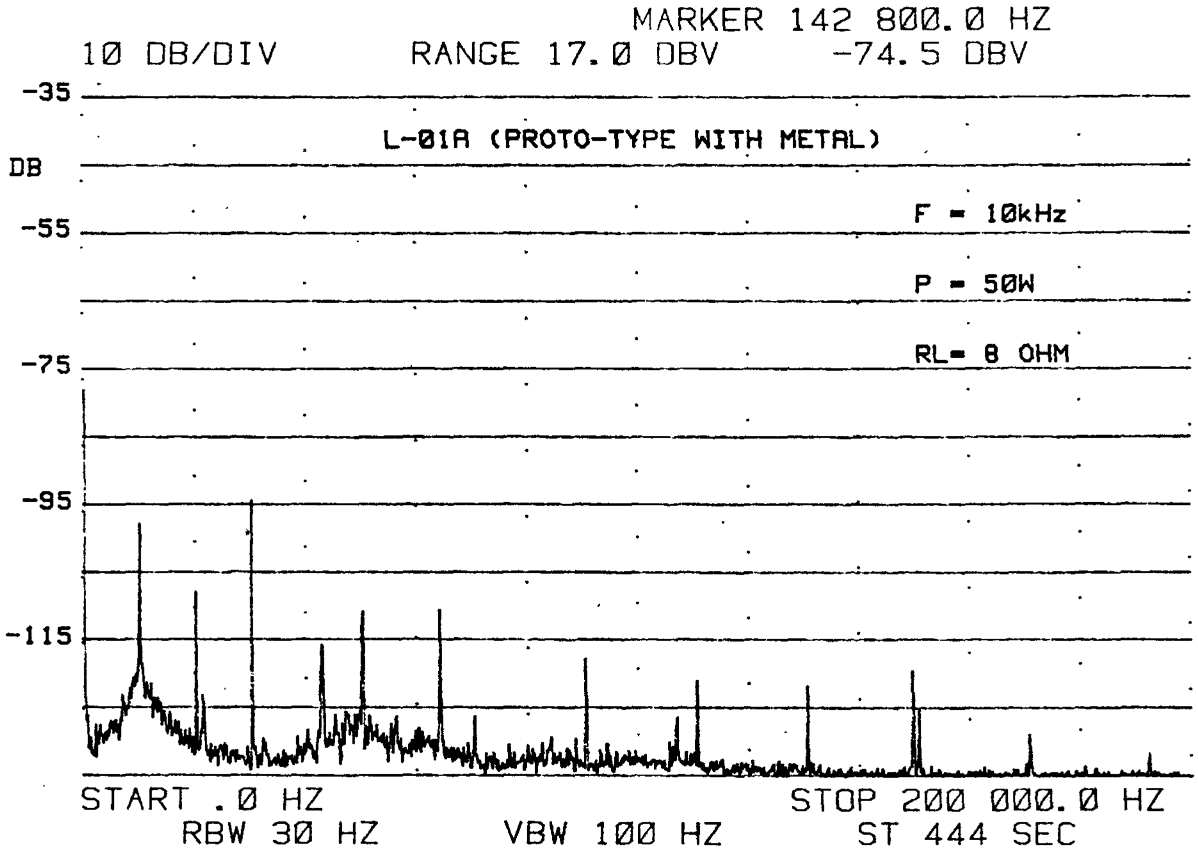


Fig.8-a HARMONIC SPECTRUM OF AMPLIFIER USING A MAGNETIC MATERIAL CASE

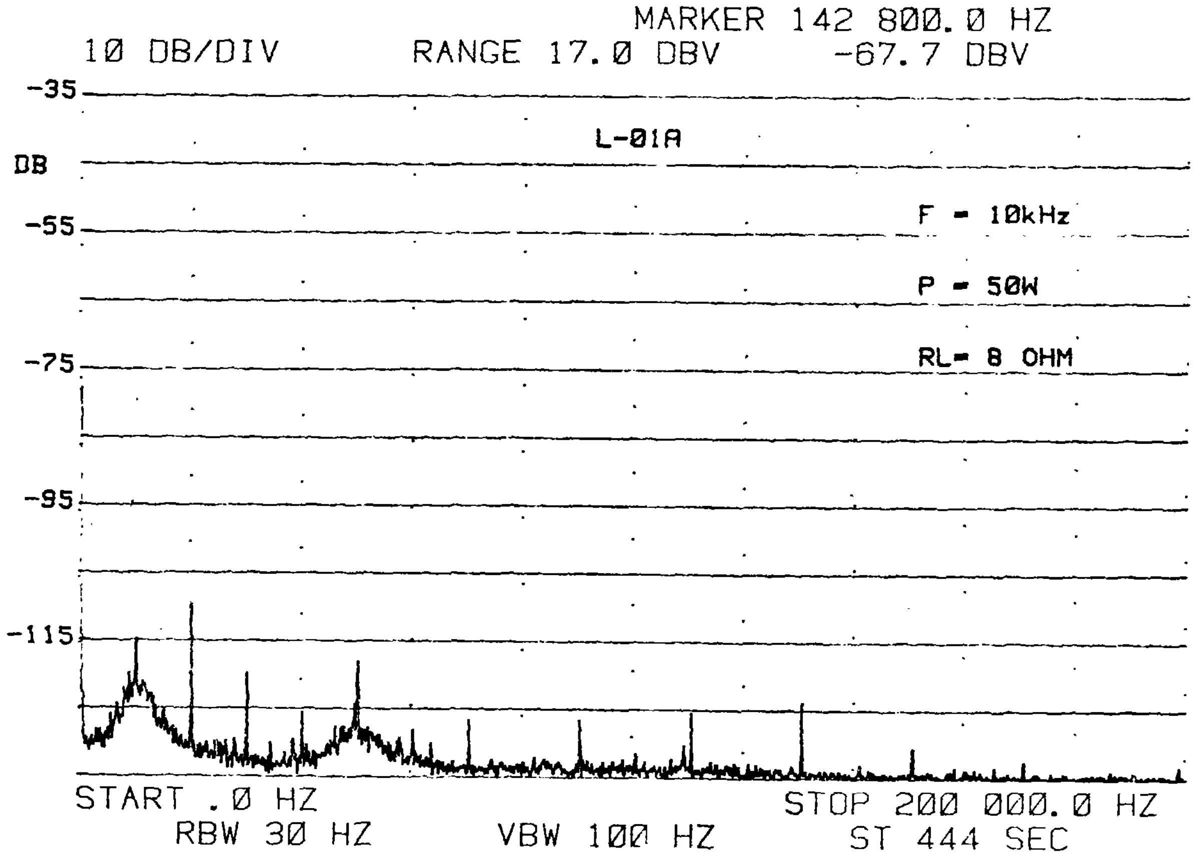


Fig.8-b HARMONIC SPECTRUM OF AMPLIFIER USING A NON-MAGNETIC MATERIAL CASE