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THE TRANSIENT MAGNETIZATION PROCESS AND OPERATIONS IN THE PLUNGER TYPE ELECTROMAGNET

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ABSTRACT

D.C. electromagnets are generally used in electric devices such as an electromagnetic switch, an electromagnetic relay, an electromagnetic value, etc.. The transient magnetization affects the determination of the electromagnetic force and the performance characteristic. However, there are few reports on the details of the transient phenomena in an electromagnet.

The purpose of this paper is to describe two phenomena which are obtained from the numerical analyses and some experiments. One is the time lag of magnetic flux due to the skin effect. The other is the transient magnetization process near the gap in the plunger type electromagnet made of solid core.

INTRODUCTION

The performance characteristic of an electromagnet is affected by the establishment of magnetic flux. The skin effect is important for the establishment of magnetic flux in a solid core, and it is very important in high speed operation.
In addition, the flux distribution is complicated in the large electromagnet which is used in the control system. Therefore, we must take into account that the permeability is not always constant in the core. The analysis of the finite length electromagnet as shown in Fig. 1 is very difficult, if there is leakage flux and the magnetization curve is nonlinear. Although it is said that the leakage flux is low in the plunger type electromagnet, the leakage near the gap cannot be neglected.

We analyzed the magnetization in the electromagnet by using the finite element method. It is very effective for processing complicated structure and boundary conditions.

PLUNGER TYPE D.C. ELECTROMAGNET

Figure 1 shows the cylindrical plunger type D.C. electromagnet used in this investigation. The yoke, the stopper and the plunger are made of solid iron, and there is a gap at the center. The exciting coil is 3300 turns of copper wire, and the exciting current 1A corresponds to the current density $3.9 \times 10^5 A/m^2$.

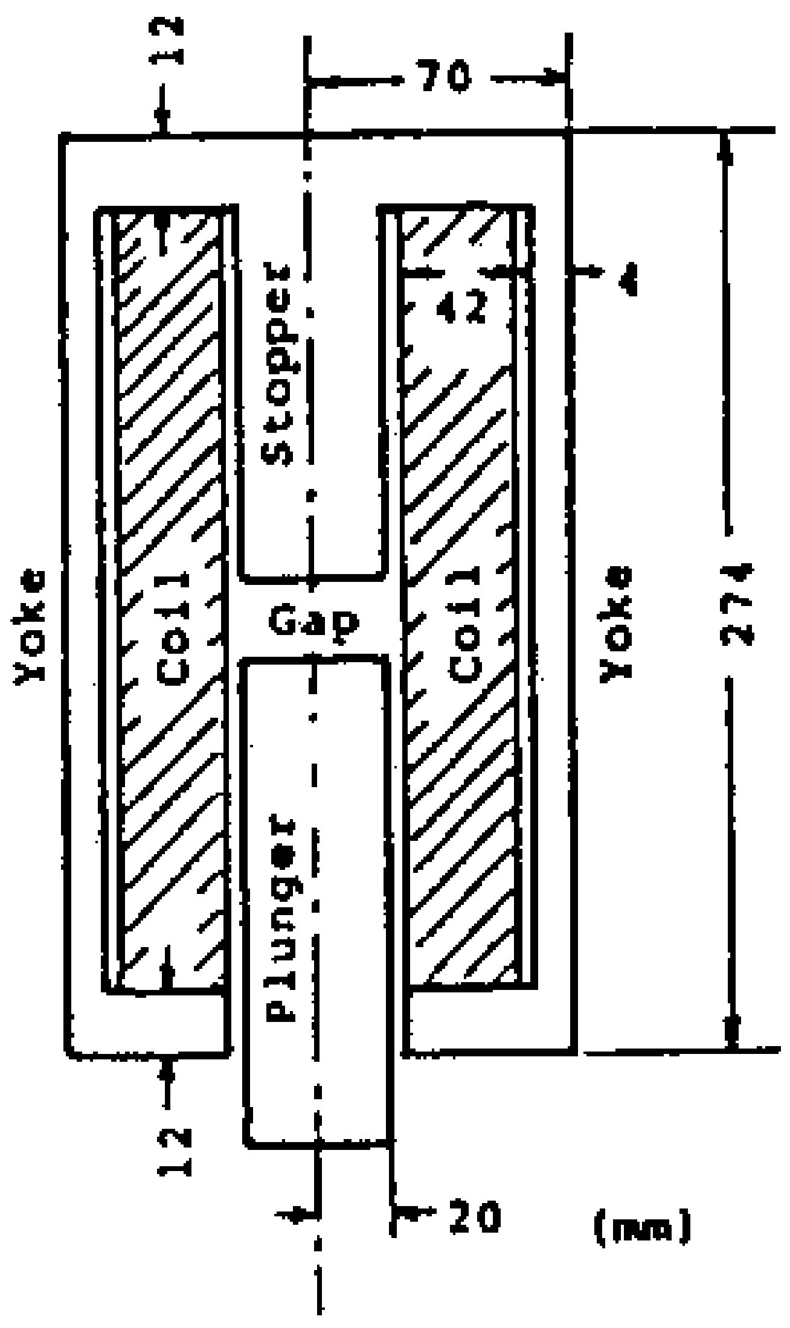

Fig. 1
Plunger type D.C. electromagnet

ANALYSIS OF STEADY STATE

The magnetic vector potential in the circular cylindrical coordinates satisfies the nonlinear partial differential equation;

$$\frac{\partial}{\partial r}\left\{\frac{1}{\mu r}\frac{\partial}{\partial r}(rA_\phi)\right\}+\frac{\partial}{\partial z}\left\{\frac{1}{\mu r}\frac{\partial}{\partial z}(rA_\phi)\right\}=-J_\phi+\sigma\frac{\partial A_\phi}{\partial t} \qquad (1)$$

where $A\phi$, $J\phi$, μ and σ are the vector potential, the current density, the permeability and the conductivity respectively. The above equation can be expressed by the nonlinear energy equation;

$$F=\iint_R\left(\int_0^B\frac{1}{\mu}b\,db\right)r\,dr\,dz-\iint_R\left(J_\phi-\sigma\frac{dA_\phi}{dt}\right)A_\phi\,r\,dr\,dz \qquad (2)$$

Therefore, the solutions which minimize the equation (2) correspond to the solutions of the differential equation (1).

The term $\sigma\frac{\partial A\phi}{\partial t}$ in equation (1) is the eddy current. However, it is omitted for the analysis of the steady state, and the same term is omitted similarly in equation (2).

The solutions are obtained by the finite element method[1-3] but the calculation region is efficiently determined in order to save the memory capacity and operation time of computer. In this case, the leakage flux is very low outside of the yoke, the calculation is performed inside of the yoke of the electromagnet. The region is subdivided into 546 triangular elements.

Figure 2 shows the steady flux distribution when the exciting current is 1A and the gap length is fixed to 10mm. The leakage flux near the gap is higher than that near the stopper and the plunger.

Figure 3 shows the calculated results and the experimental results for the flux density. The latter is measured by the search coils around the stopper, the gap and the plunger. The agreement is excellent in both results. The flux in the gap is about a half of that in the cores with the ratio of 10mm gap to 40mm core diameter.

The flux saturates partly at the combined part of the yoke and the stopper when the exciting current increases. Therefore, the permeability is different in each part and the whole flux distribution is not proportional to the current. It affects the electromagnetic force.

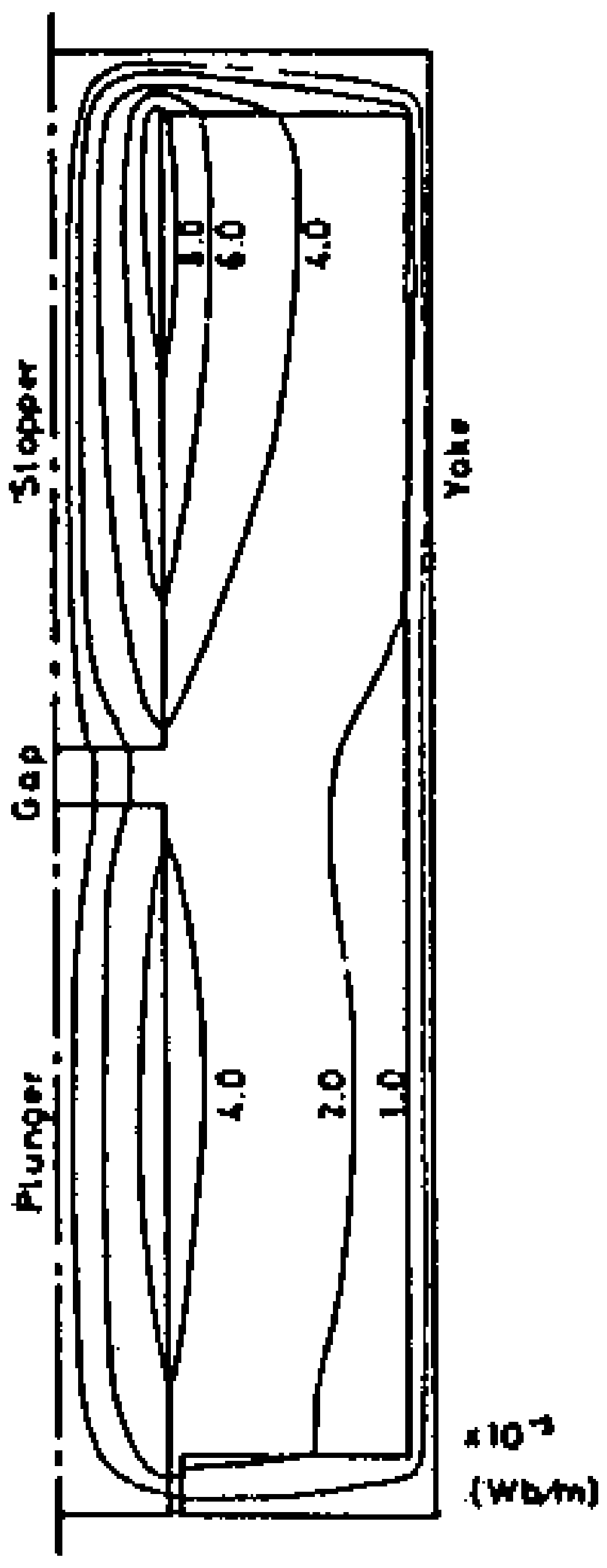

Fig. 2
Steady flux distribution

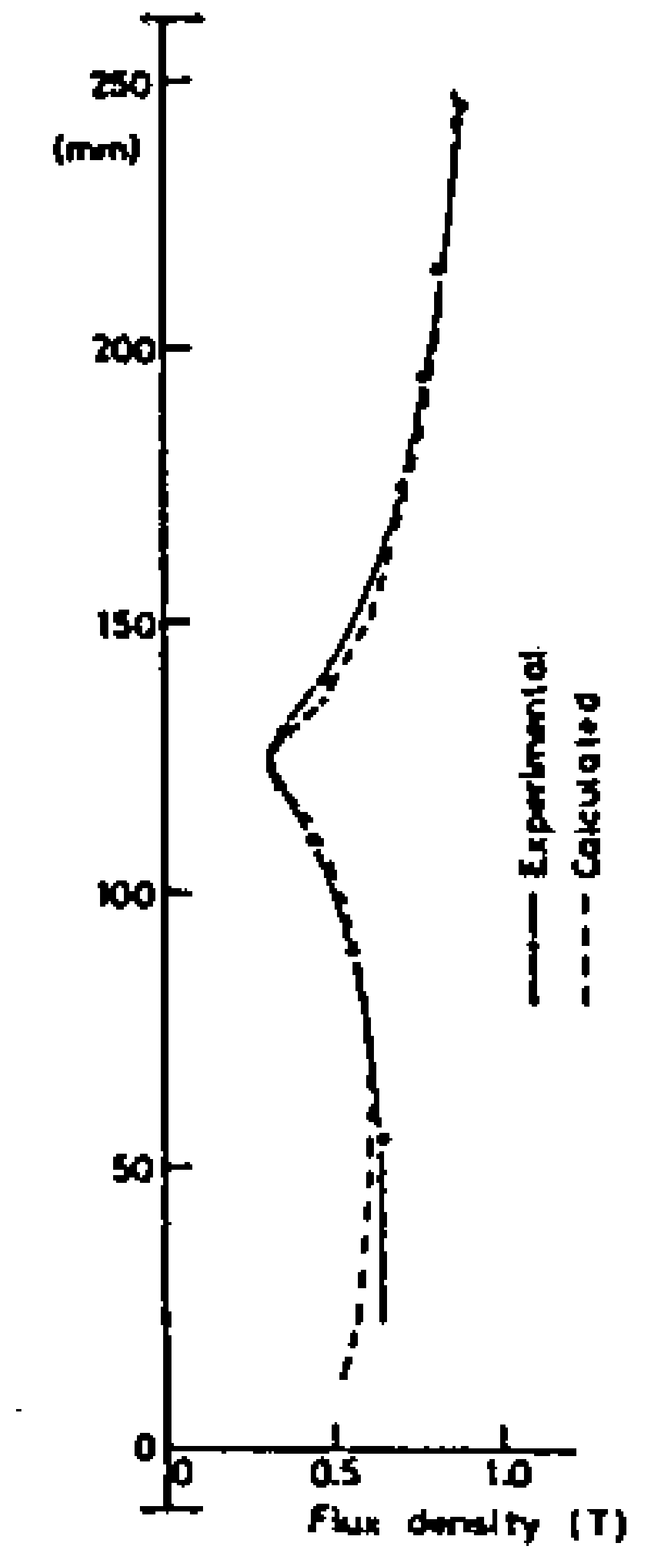

Fig. 3
Flux density at the stopper the gap and the plunger

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ANALYSIS OF TRANSIENT PHENOMENA

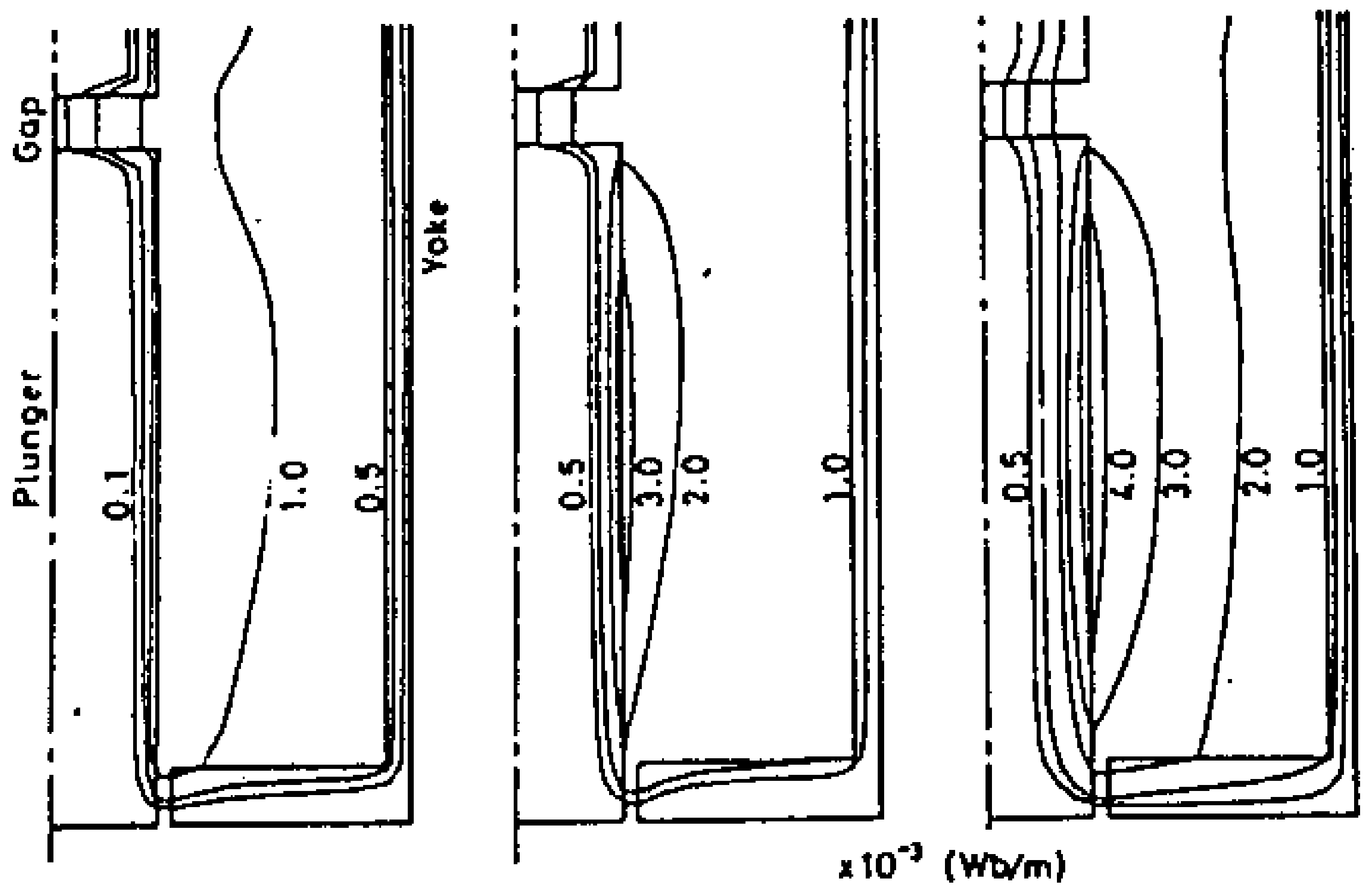
The term of time dependence is included in equations (1) and (2), and the eddy current must be added in the exciting current. The calculation is by the finite element method.

Figure 4 shows the calculated results for the flux distribution after the application of exciting current. However, the gap length is fixed to 10mm.

The results are calculated based on the current is expressed as;

$$I = I_0(1-e^{-\frac{t}{\tau}}) \qquad \tau \text{ : Time constant} \qquad (3)$$

Just after the current is applied, the flux concentrates at hte surface of the plunger as shown in Fig. 4(a). As the time elapses, it permeates to the inner part as shown in Fig. 4(b) and (c). When we observe the flux near the gap, the initial magnetic path expands as shown in Fig. 4(a). We interpret this to mean that the flux in the gap is always uniform because there is no skin effect, and the flux density of the pole face is also uniform. This phenomenon is very remarkable and we term it "pole face effect".[4,5]



(a) t=10 ms (b) t=20 ms (c) t=50 ms

Fig. 4 Time dependence of flux distribution I_0= 1A τ=20ms

Figure 5 shows the time behavior of the flux density distributions at cross section L which is 23mm apart from the gap. The curves correspond to the calculated region numbers 1 to 5. The increase of the flux at the inner region increase slowly due to the skin effect. However, at the outer region it increases more quickly than the exciting current does and the overshoot phenomenon occurs. These results show that the flux at the initial condition concentrates in the outer region as mentioned above, and as the time elapses the flux tends to the steady state in all regions. This corresponds to the results shown in Fig. 4.

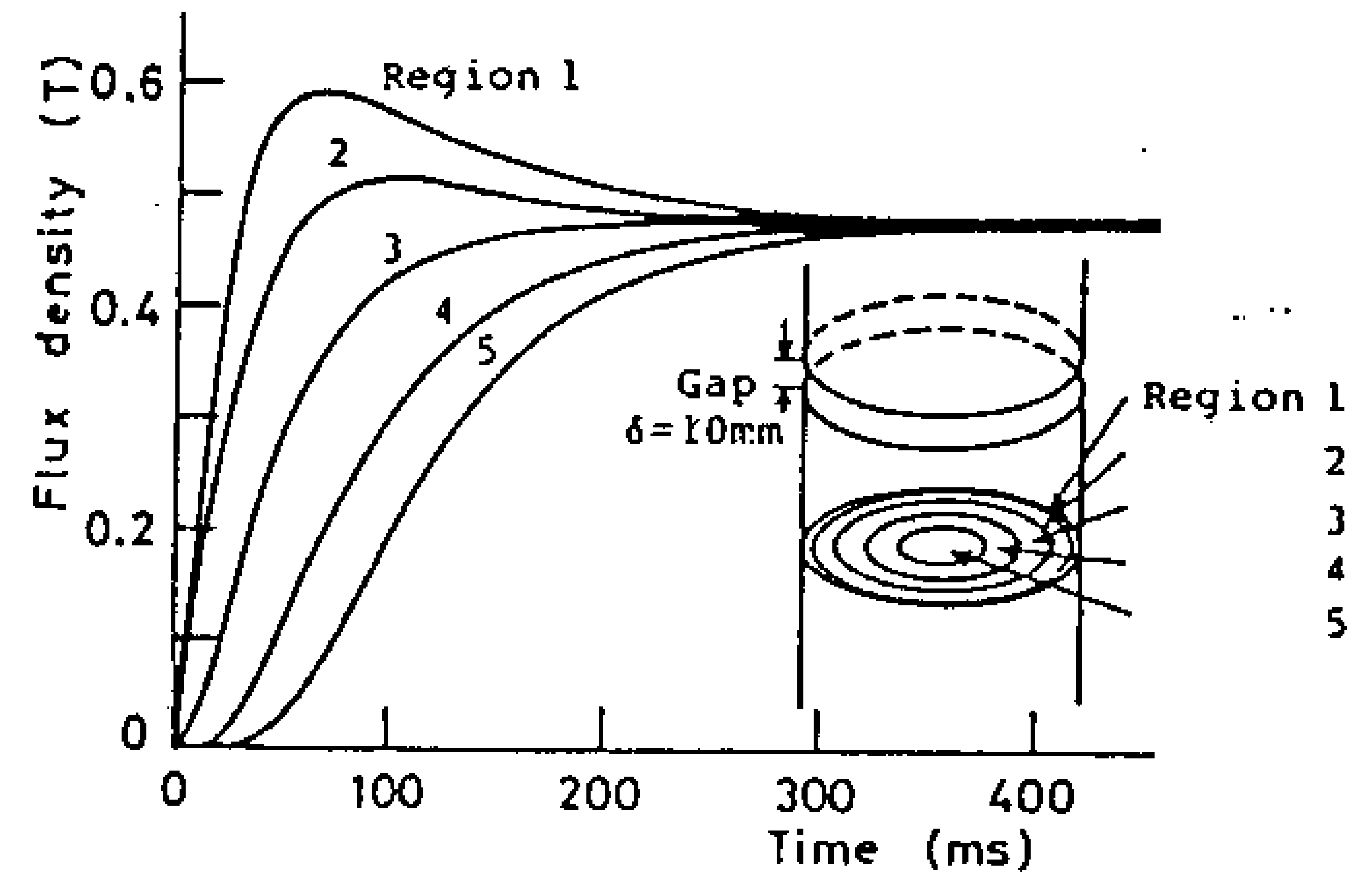


Fig. 5 Time behavior of flux density in the plunger

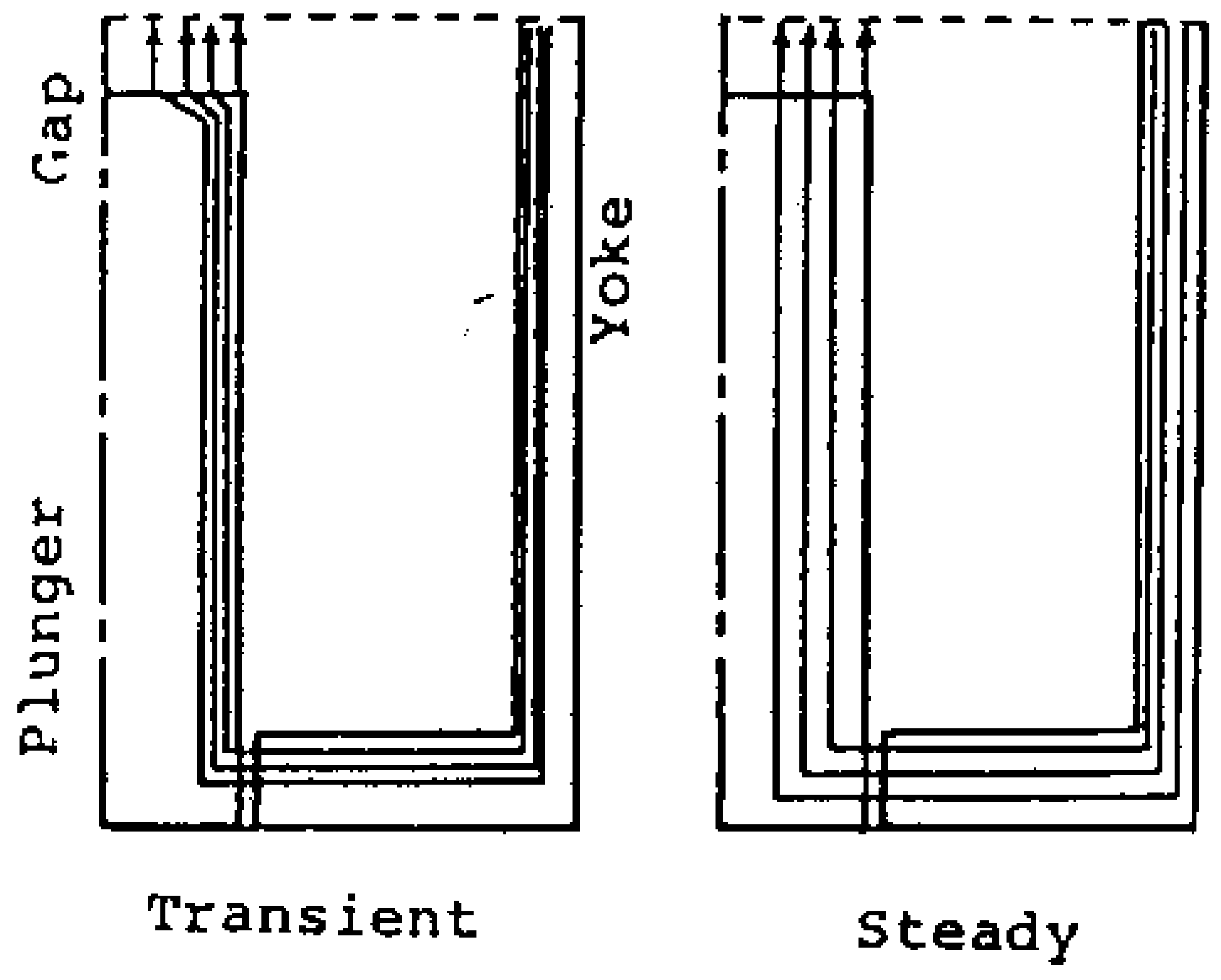


Fig. 6 Magnetic paths

It is thought that the transient and steady magnetic paths are as shown in Fig. 6. Therefore, the permeability or magnetization characteristic of cores is an important factor in plunger operation.

EXPERIMENTAL RESULTS

A. FIXED PLUNGER

Figure 7 shows the structure of search coils for the measurement of the flux in the plunger. Cutting the plunger into some cross sections, there are five search coils in the very narrow slots of concentric circles at each cross section. Therefore, the measurement of the flux distribution is possible by using two adjacent coils.

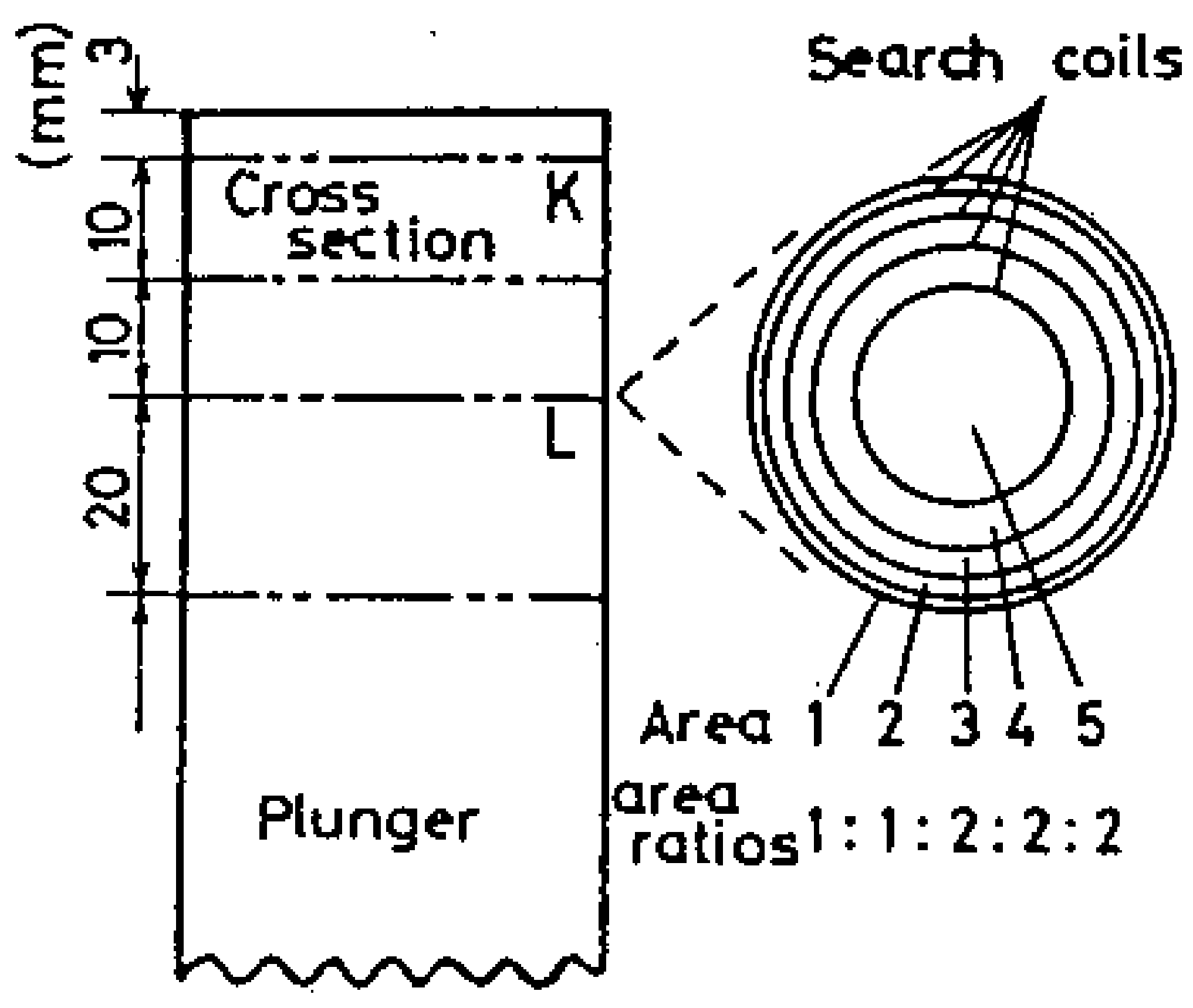


Fig. 7 Location of search coils in the plunger

Figure 8 shows the time behavior of the flux density distribution at cross section L, when the gap length is fixed to 10mm. The skin effect and the overshoot phenomenon are shown in the figure. They agree with the calculated results. As the time constant of the exciting current is smaller, the overshoot is more remarkable. However, when the time constant is larger than 100ms, the phenomenon be hardly observed. These results show that the flux distribution leans to the outer part as the time constant is small.

The steady state values are not always equal due to the effects of residual magnetism.

However the overshoot can hardly be observed at cross section K which is only 3 mm apart from the gap. It is evident that the flux does not concentrate in the outer part of core because of the pole face effect.

Figure 9 shows the time behavior of total flux at cross section L. The response of the total flux when the

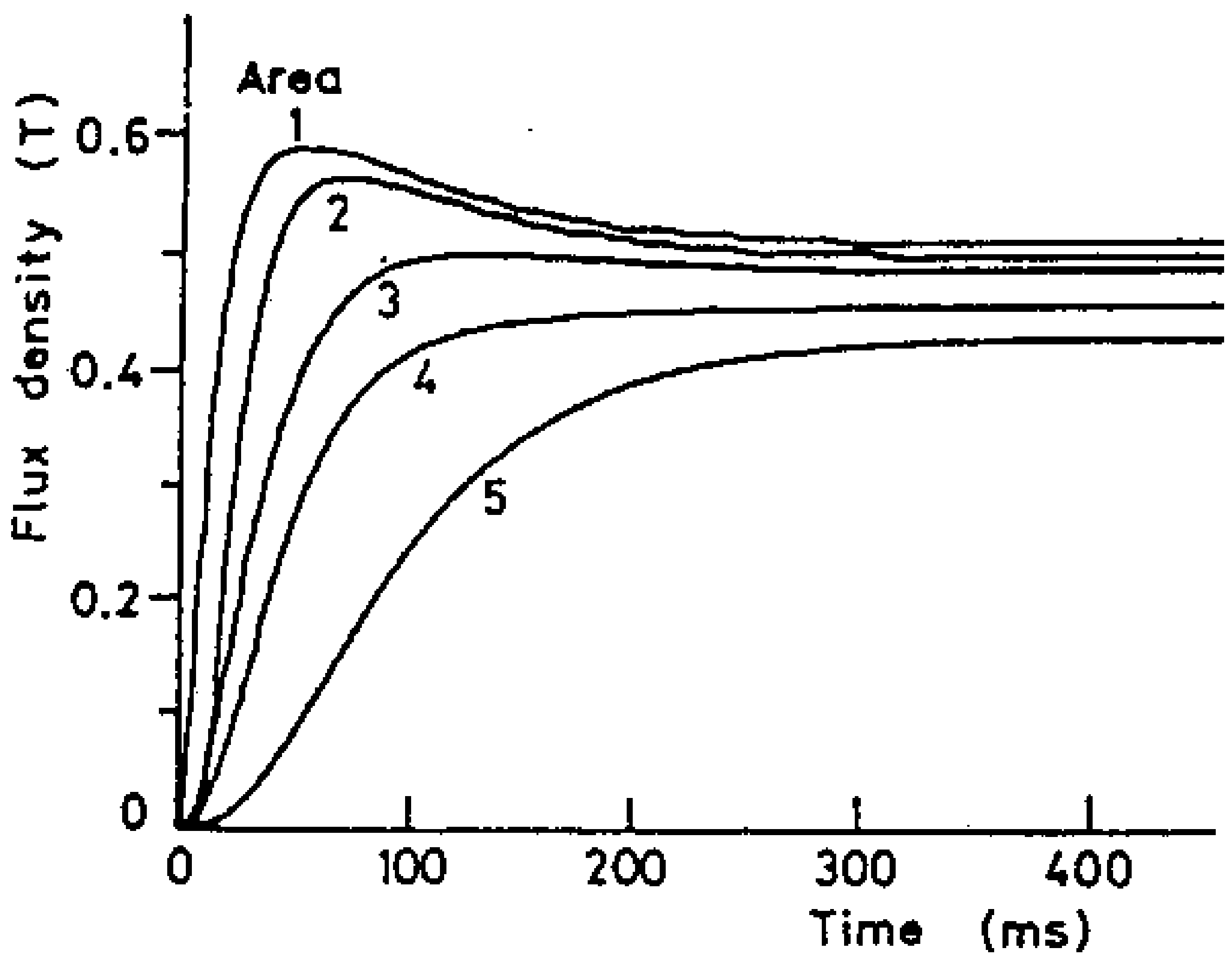


Fig. 8 Time dependence of flux density at cross section L

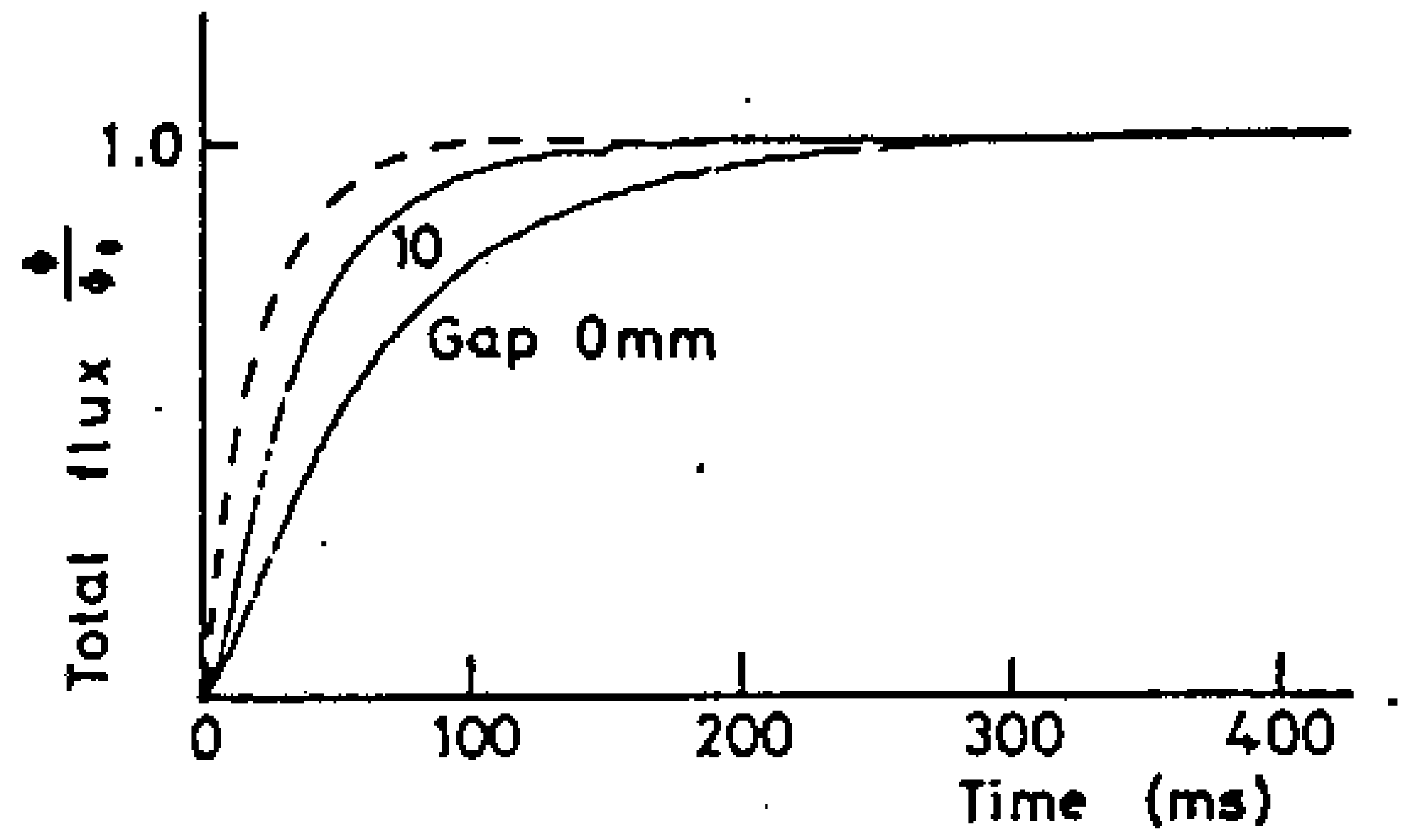


Fig. 9 Time behavior of total flux at cross section L

gap length is 10mm is quicker than that when the gap length is zero because the particular magnetization occurs near the gap. Consequently it is known that the magnetization of the iron core which includes a gap is different from that of the infinite iron core.

B. PLUNGER OPERATION

Figure 10 shows the performance characteristics of the plunger for different gap lengths with the same exciting current. Although the pattern of each curve is different, the operating time is proportional to the gap length. It is a remarkable result. The magnetic force with large gap is weak due to the small absolute value of flux and leakage. However it is strong with small gap. Moreover, when the plunger operates, the eddy current and the induced current due to velocity occur in the iron core. Therefore the analysis of the magnetization is very complicated.

When the gap is sustained at 10mm, and the plunger begins to move toward the stopper, the flux increases with the gap length. Figure 11 shows the time behavior of the total magnetic flux at cross section L under these conditions. The total flux increases rather rapidly on the initial step, then slows down in the middle stage and finally increases very rapidly.

The weight of the plunger is 2.6 Kg, and it is balanced by using a lever and a weight in these experiments. The mass affects the operation characteristic of the plunger.

The quantitative analysis of the experiments is now performing.

CONCLUSION

The analysis of the steady and transient state are described in this paper. Consequently, the skin effect in the iron core and the particular magnetization near the gap are shown. The transient magnetic path and the magnetic force depend on the exciting current and the materials.

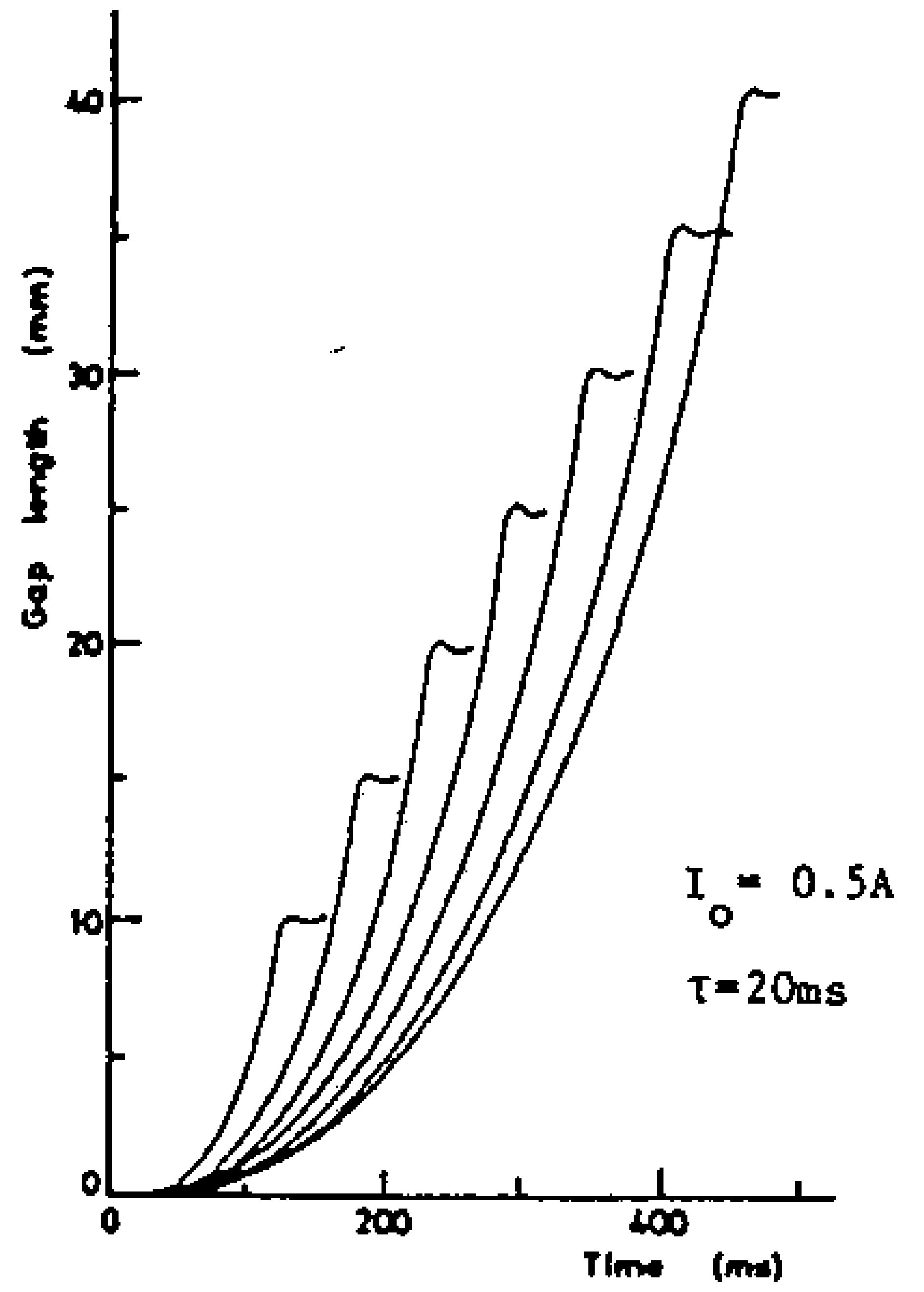


Fig. 10 Performance characteristics of the plunger with different gap lenghs

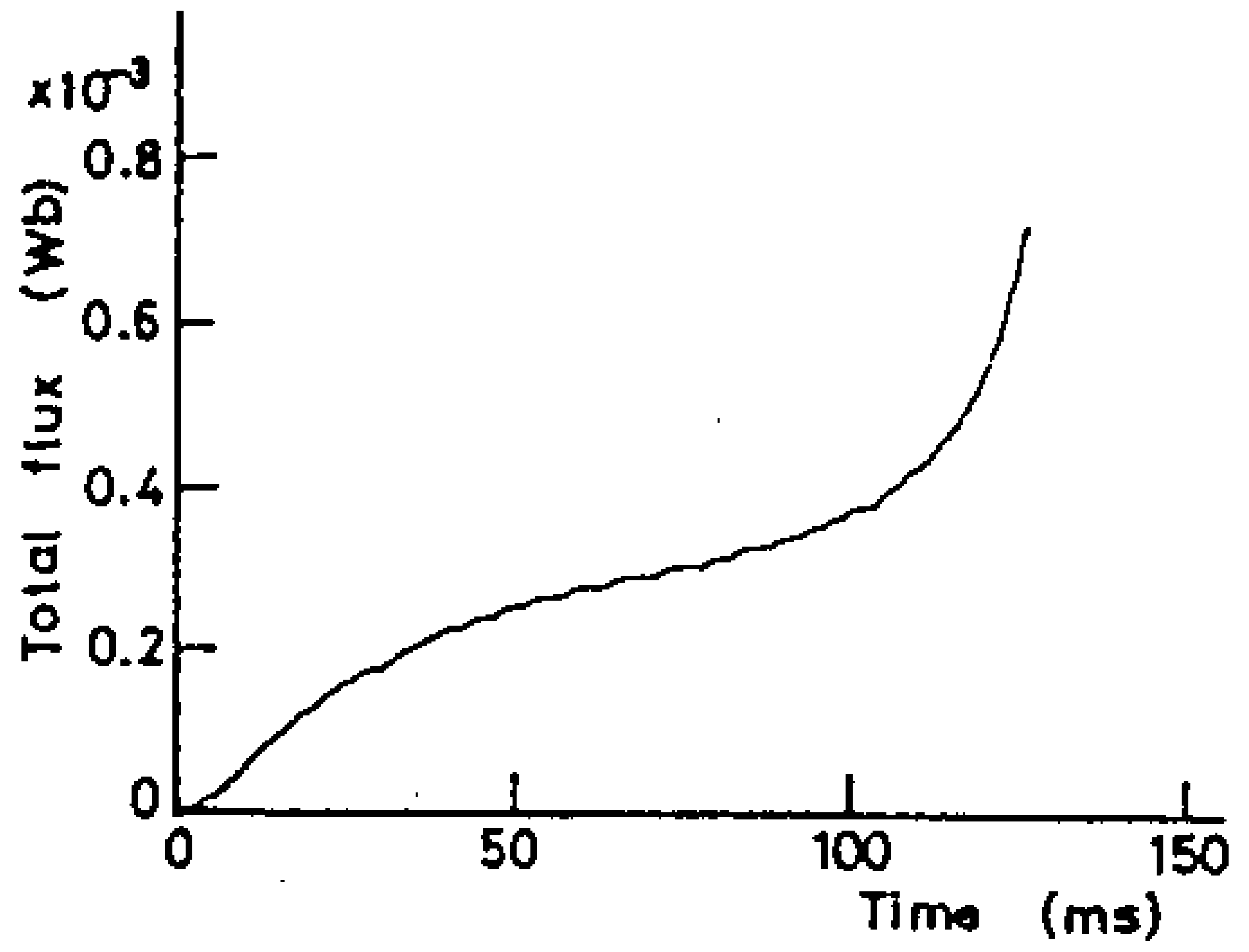


Fig. 11 Time dependence of total flux at cross section L

These results are very effective for the determinations of the optimum structure and the optimum exciting current, when the electromagnets are used in large scale or high speed operation.

We are studying the effect of induced current due to velocity and other problems in detail.

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