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Magnetic-Field Design Considerations for a Plated-Wire Memory

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Abstract—Permeable keepers are used in a plated-wire memory to reduce the adjacent bit interference and the current requirement. Computations of a magnetic field have been performed to determine the quantitative effect of the keeper size on the field enhancement in the region where the information is to be stored and on the field reduction outside this region. The field enhancement can be interpreted as the reduction in current for a given magnetic field, and the reduction of the fringing field as the reduction in adjacent bit interference. The numerical results which represent valuable design considerations for a plated-wire memory are presented in graphical form.

Index Terms—Effect of keepers, magnetic-field computations, plated-wire memory, reduction of fringing field, reduction of interference.

INTRODUCTION

THE PLATED-WIRE memory has recently shown great potential as a nondestructive, high-storage-density, random-access, high-speed, low-power-consumption, low-weight memory. Its state of the art was reviewed by Fedde and Chong at the 1968 INTERMAG Conference [1]. The basic principle of a memory element is schematically illustrated in Fig. 1(a). A fine copper-beryllium wire, which is electroplated with a thin permalloy film [2], is perpendicularly placed between two straps carrying word current of opposite direction. An anisotropy is established during the plating so that the magnetization vector curls around the supporting wire in the easy direction of magnetization without an axial component. The element is bistable in that the sense of rotation of the magnetization may be either clockwise or counterclockwise. An interaction of the magnetic fields due to simultaneously flowing bit and word currents is utilized to restore or to change the sense of rotation of the magnetization. In this way, one can either write information into or read stored information out of the plated wire. Additional background materials may be found in [3], or the interested reader can trace his search to the original literature through Chang's bibliography [4].

A storage element is determined by the crossing of current straps and a plated wire in the memory matrix. The density of such elements is limited by the fact that the pulsing of the word current to read or to write one bit of information may influence bits stored in adjacent memory elements. Magnetic keepers backing up the current straps are used to reduce the adjacent bit interference. In addition, these keepers provide an enhancement of the magnetic field between the current straps, thus permitting reduction of the word current for a given magnetic field. The conflicting needs of shorter bit length and reduced adjacent bit interference demand an examination of the quantitative effect of limited keepers on the magnetic field, assuming a realistic configuration. Magnetic field calculations have been carried out on the basis of idealized models. Ravi and Koerber [5] and Feltl and Harloff [6] ignored the presence of the thin information-storing film and calculated the magnetic field between two current straps backed up by semi-infinite keepers. This kind of in-
vestigation was recently extended to the case of keepers with limited size [7]. Dove and Long [8] considered the demagnetizing field in the plated wire due to spatially periodic applied fields. A first attempt to account for the presence of both the plated wire and keepers (but of semi-infinite extent) was recently reported by Dove [8b] and, in particular, by Mo and Rabinovici [9].

For a high-density, low-power consumption, and light-weight memory, there is an important tradeoff between the width and the thickness of the keepers and the bit spacing on the plated wire. A study of this tradeoff is possible only by calculating the magnetic fields when keepers of varying width and thickness consisting of different permeable materials are present. An integral/matrix equation technique was developed for the calculation of a magnetic field produced by stationary current in the presence of permeable material [10]. This technique is applied to a model for the plated-wire memory element, consisting of two plane and parallel current straps which are backed up by permeable keepers of limited cross section. The plated wire is simulated by an infinite slab of permeable material in order to make the problem two-dimensional. The relative permeability of the slab is determined by the condition that the reluctance of the model is equal to that of the actual device.

The magnetic field inside the simulated wire has been computed numerically for different configurations of the plated wire. The graphical results exhibit the influence of the keeper thickness and width on the magnetic field inside the simulated wire, assuming two different widths of the current straps. The field enhancements due to the presence of the keepers are indicated in each graph. An enhancement can be interpreted as the reduction of current for a given magnetic field.

**Definition of the Problem and Its Solution**

The problem under investigation is illustrated in Fig. 1(b), showing the view upon the cross section of a memory element. Two "infinitely" thin straps of 2a-unit width are located at ±b units from the x axis where unit is a short hand for any unit of length. These straps which carry current of opposite direction are backed up by permeable keepers with the relative permeability \( \mu_b \). Each keeper is 2w units wide and placed c units away from the x axis, assuming a keeper thickness of either 1 or 3 units. The plated wire is simulated by a 4-unit thick slab in order to obtain a two-dimensional problem. This slab is assumed to be 100 units wide for computational reasons. Assuming that unit stands for \( 10^{-3} \) inch, our model represents a realistic configuration for a plated-wire memory element.

In the actual memory element, the plated wire consists of a copper–beryllium core with about 125-\( \mu \) diameter, electroplated with a 1-\( \mu \) thick permalloy film. The hysteresis loop of this uniaxial anisotropic film is customarily described by the Stoner and Wohlfarth model [11]. Accordingly, if the applied magnetic induction remains below the saturation level \( B_s \), the relative permeability of the anisotropic film (in the hard direction) is given by the slope of the linearized hysteresis loop, i.e.,

\[
\mu_{film} = \frac{B_s}{H_K}
\]  

(1a)

where \( H_K \) denotes the anisotropy field. In the problem defined above, the plated wire is simulated by a 4-unit thick slab of permeable material. In order to obtain a physically realistic model, the condition is adopted that the magnetic flux through the slab should be approximately equal to that through the wire plating at the \( x=0 \) plane. Unfolding the wire plating makes a continuous sheet 125\( \pi \) \( \mu \) in length. This length corresponds roughly to the distance between the axes of adjacent plated wires. Accordingly, we have for the equivalent relative permeability \( \mu_w \) of the slab simulating the plated wire

\[ 1 \text{ This model was suggested by Professor A. V. Pohm of Iowa State University, Ames, Iowa.} \]
\[ \mu_w = \frac{\delta_{\text{plating}}}{\delta_{\text{slab}}} \mu_{\text{ilm}} \approx 10^{-2} \frac{B_S}{H_K} \]  

where \( \delta_{\text{plating}} \approx 1 \mu \) is the thickness of the wire plating and \( \delta_{\text{slab}} \approx 100 \mu \) is the thickness of the slab.

The two-dimensional magnetic field which is produced by a steady wire current can be described by an inhomogeneous Fredholm vector integral/matrix equation \([10]\). This equation has been solved by iteration using an IBM system 360. The numerical results are presented and discussed in the following section.

To simplify computation, we took advantage of the symmetries of the configuration with respect to the \( x \) and \( y \) axes (see Fig. 1(b)). Thus, the calculation was restricted to the first quadrant, as indicated by the greater detail in Fig. 1(b). For ease of reference, we shall henceforth talk of one keeper and one strap. Their half-dimensions are given by the respective quantities \( a, b, c, \) and \( w \), which specify the coordinates in the first quadrant. The cross sections of the permeable media were approximated by square meshes for computational reasons, and the magnetic field was determined at the center of each square \([12]\).

**Magnetic Field Inside Simulated Plated Wire**

The magnetic-field distributions are given by the solution of the aforementioned integral/matrix equation. Only the distribution inside the slab simulating the plated wire is explicitly shown and discussed in detail; distributions of magnetic field inside a keeper were presented in \([7b]\). The slab extends into the first quadrant by 2 units (see Fig. 1(b)) and is, therefore, approximated by two strings of squares with \( \Delta x = \Delta y = 1 \) unit. The field was always computed at the center of each square, i.e., for \( y = 0.5 \) and 1.5, but numerical results are presented only for \( y = 0.5 \). This plane is indicated by the dash–dot line in Fig. 1(b). The particular configurations for which the results are presented are determined by \( a = 10 \) or 16 units both with \( b = 5 \) units, and \( c = w \) were chosen as stated. The keeper is assumed to be either 1 or 3 units thick.

The effective permeability of the keeper material usually encountered in practice is in the order of magnitude of 10. Therefore, the computations to be presented were performed with \( \mu_k = 10 \) as a typical value for the relative permeability. The saturation induction \( B_S \) of the permalloy wire-plating is usually 8 to 12000 G and the anisotropy field \( H_K \) is, say, about 5 to 10 Oe.\(^2\) Using (1b), we calculate the typical values of 10 and 25 for the effective permeability of the simulated wire. Hence, in order to study the effect of the relative permeabilities on the magnetic field, we present the numerical results for both \( \mu_c = 10 \) and 25, assuming \( \mu_k = 10 \).

The dependence of the magnetic field on the choice of both \( \mu_c \) and \( \mu_w \) has been investigated in \([10]\).

The \( x \)-component of the magnetic \( B \) or \( H \) field is the quantity of prime interest. The \( B_x \)-component is plotted versus \( x \) for \( x \) up to 45 units in Figs. 2 through 6. The heavy solid curve is the reference curve exhibiting the magnetic field in the absence of the keeper. When the keeper is introduced, the magnetic field between the current strap increases. The relative field enhancement is always indicated in the lower left corner of those figures. This field enhancement can be interpreted as the reduction in current for a given field at the center due to the use of keepers. The main portion of each figure is devoted to show the effect of the keeper on the fringing field beyond the current straps for a given magnetic field at the center.

Fig. 2 illustrates the effect on the magnetic field of the keeper thickness and width, assuming \( a = 10 \) units, \( b = c = 5 \) units, and \( \mu_k = \mu_w = 10 \). When a 1-unit thick keeper which precisely backs up the current strap is introduced, the field at the center increases by about 24 percent and the fringing field reduces, as shown by the broken curves. An increase of the keeper thickness to 3 units leads to a 39 percent field enhancement at the center and a somewhat larger reduction of the fringing field (dash–dot curves). The numerical results for a 3-unit thick keeper exceeding the current strap by 10 units on each side (\( a = 10 \) units and \( w = 20 \) units) are displayed by the thin solid curves. The magnetic field under the current strap spreads out, yielding a field enhancement at the center of about 45 percent. This overhanging keeper has a noticeable effect on the fringing field beyond its extent, i.e., for \( x > 20 \). Right under it, the field is somewhat enhanced and more uniform.

Fig. 3 illustrates the same cases as Fig. 2 except that \( \mu_w \) is increased from 10 to 25. The field enhancements at the center are now approximately 27, 46, and 55 percent, respectively.

Fig. 4 exhibits the effect on the magnetic field of an air gap between the current strap and keeper, assuming a 3-unit thick keeper with \( \mu_k = \mu_w = 10 \), which precisely backs up the current strap (\( a = w = 10 \) units, \( b = 5 \) units). The curves illustrating the case of no gap, i.e., \( c = 5 \) units, are repeated from Fig. 2 for ease of reference (thin solid curves). When current strap and keeper are separated by one unit (\( c = 6 \) units), the field enhancement at the center is substantially reduced to about 31 percent, and the fringing field increases noticeably (dash–dot curves). A further increase of the separation to 4 units leads to a field enhancement at the center of only 14 percent and a substantial increase of the fringing field. This result is not unexpected since the shielding effect of the limited keeper reduces rapidly as the keeper is removed more and more from the current strap. Fig. 5 exhibits the same cases as Fig. 4, except that \( u_k \) is in-

\(^2\) The ranges for these values have been chosen somewhat larger than customarily specified in practice.

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**Fig. 2.** $B_x$-component of magnetic induction is plotted versus $x$ at $y=0.5$ for different thicknesses and widths of the keeper with $\mu_k = 10$, assuming $a = 10$ units and $\mu_m = 10$. The curves in the lower left corner exhibit the relative field enhancement due to the use of keepers.

**Fig. 3.** Same results as shown in Fig. 2 except that $\mu_m$ is increased from 10 to 25.

**Fig. 4.** $B_y$-component of magnetic induction is plotted versus $x$ at $y=0.5$ for different separations between current strap and keeper with $\mu_k = 10$, assuming $a = 10$ units and $\mu_m = 10$. The 3-unit thick keeper just backs up the current strap. The curves in the lower left corner exhibit the relative field enhancement due to the use of keepers.

**Fig. 5.** Same results as shown in Fig. 4 except that $\mu_m$ is increased from 10 to 25.
increased from 10 to 25. The corresponding field enhancements at the center are now approximately 37 and 17 percent, respectively.

Fig. 6 illustrates the effect on the magnetic field of the keeper thickness and width for a different width of the current strip, namely \(a = 16\) units, assuming \(b = c = 5\) units and \(\mu_k = \mu_w = 10\). When a 1-unit thick keeper which precisely backs up the current strip \((a = w = 16\) units\) is introduced, the field at the center increases by about 18 percent, and the fringing field reduces, as shown by the broken curves. An increase of the keeper thickness to 3 units leads to a 34-percent field enhancement at the center and a somewhat larger reduction of the fringing field (dash-dot curves). The numerical results for a 3-unit thick keeper exceeding the current strip by 14 units on each side \((a = 16\) units and \(w = 30\) units\) are displayed by the thin solid curves. The field enhancement at the center is about 37 percent. Comparing these results with those illustrated in Fig. 2 reveals the effect that the width of the current strip has upon the magnetic field.

The numerical results presented in the lower left corners of Figs. 2 through 6 may be interpreted as relative values of the magnetic field due to the choice of the current \(I\). To obtain absolute values, we multiply the numerical results \((1 + \text{field enhancement})\) by \(B_n\) where for \(a = 10\) units, \(B_n/I\) is either 2.3 if \(\mu_w = 10\) or 4.1 if \(\mu_w = 25\), and for \(a = 16\) units, \(B_n/I\) is 1.9. Then, if the current \(I\) is measured in amperes, the absolute value of the magnetic induction is obtained in gauss \(\times\) (meter/unit). The dimensionless ratio (meter/unit) takes care of the particular unit (of length) which, as stated above, can be chosen at convenience.

**Conclusion**

Permeable keepers are used in a plated-wire memory to reduce the adjacent bit interference and the current requirement, but they add somewhat to the weight. A tradeoff to optimize the design necessitates the knowledge of the magnetic field produced by the keepered current strips inside the plated wire as a function of the design parameters. The numerical results presented above are rather valuable in this respect since they show quantitatively the effect on the magnetic field of the keeper thickness, width, and location for two permeabilities of the wire plating, assuming two different widths of the current strips. They exhibit the enhancement of the magnetic field in the region where the information is to be stored and the reduction of the fringing field outside this region. The field enhancement can be interpreted as the reduction in current, and the reduction of the fringing field can be interpreted as the reduction in adjacent bit interference, both due to the use of permeable keepers.
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Unified Interval Classification and Unified 3-Classification for Associative Memories

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Abstract—Algorithms for a unified interval classification and a unified 3-classification for use in associative memories are presented. The former, which is more generally known as between-limits classification, achieves the classification of the words of an associative memory into those within and those without an interval marked by two given limits; the latter achieves the classification of the words into the three classes, between the given limits, above the upper limit, and below the lower limit. The term "unified," used for both, denotes the contraction of the two limit classifications which are required in the straightforward approach to either classification into one carried out simultaneously with respect to both given limits. Due to this unification, the presented algorithms are capable of achieving considerable time savings in associative memories of a frequent type. The designs of cryogenic associative memories of this type, containing certain circuit requirements for the performance of the algorithms, are also presented.

Index Terms—Algorithm, associative memory, between-limits classification, classification into three classes, cryogenics, interval classification, microprogram, one-pass classification, parallel search and processing memory, 3-classification, unified classification.

I. INTRODUCTION

The conventional methods of determining all words of a given set of words of an associative memory which lie in the interval specified by two limits require the consecutive performance of two limit classifications; the words found to lie both above the lower limit and below the upper limit are the words lying in the interval [1], [2]. Each of these classifications requires one pass through the digits of the words; therefore, two passes are required for the complete interval classification.

This paper describes a unified interval classification which determines all words lying in the given interval in a single pass through the digits of the words. For associative memories with bit-serial operation of their data sections and bit-parallel operation of their tag sections, this method is faster than the conventional methods. The paper then shows how a minor modification of the unified interval classification yields a unified 3-classification. This method, too, is faster than the corresponding conventional methods for associative memories of the type mentioned. In the subsequent discussion, the term "bit" is used to denote the storage facility, and the term "digit" to denote the stored value.

A. Memory Requirements

The performance of the algorithms of this paper places the following requirements on the associative memory.

1) The memory must possess tagging capability of its individual words; that is, each word register must contain, besides the data bits, a number of tag bits in

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1 For unified interval classifications using a different principle, see [3], [4]. For interval classifications whose efficiencies lie between those of the conventional and the unified methods, see [5], [6].