MAGNETIC PRINTER USING PERPENDICULAR RECORDING

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ABSTRACT

Within the past years, many attempts have been made to make magnetic printing a viable alternative to the electrophotographic (xerographic) process. Most of them have tried to make use of available magnetic components such as longitudinal recording heads and/or magnetic tapes.

A different approach, developped by the CII-Honeywell Bull Non Impact Printer Engineering at Belfort, France, has resulted in a magnetic parallel printer which eliminates most of the disadvantages suffered by both the Xerographic process and the magnetic tape approach, i.e. the need to continuously change or regenerate the printing medium when it is a photoconductive material or a magnetic material.

The key point here is the use of a solid mechanical magnetic drum. This has been made possible by the development of a new type of magnetic recording head. The main heads features are (a) Perpendicular Recording, (b) Closed loop flux path, (c) Multi-turn Capability, (d) Multiplexed controls, (e) Ability to be packed at high density.

Actually, these perpendicular heads can be seen as the printing field counterpart of the growing interest for high density perpendicular recording that presently takes place in the Data Recording field.

INTRODUCTION

The idea of magnetic printing is not new : as a matter of fact it had already been mentioned in 1839(1). However, one had to wait until the 1950's to see real active work on this technique (2)(3). In the 60's and 70's several companies were reported to have put more or less research effort on it (4)(5). Some real scale models were even built(6).From an industrial point of view little if any has come from these earliest experiences. If most of them already tried to make use of a solid mechanical magnetic drum, it seems that the major technical problem they had to cope with was the implementation of a large number of recording heads along the drum.

In effect, magnetic dots capable of attracting magnetic toner particles require much more energy than just retaining bits of information on a memory medium ; in turn, using a high level of magnetization implies effective recording fields. Conventional gap heads, that work with fringes rather than with their main flux, require very tight position tolerances with respect to the medium. Different types of heads were also used, for instance perpendicular pole heads ; however, being basically open-ended, those last heads exhibited low efficiency and consequently required too large drive currents to work with (7). A different trend consisted of rejecting the solid drum and, instead, elected to use a soft magnetic medium such as a magnetic continuous tape. Actually the first -- and to date the only -- commercial printer that was ever announced and installed in the field, made use of a conventional narrow type, computer-like, magnetic tape : It was a rather low speed device (180 lines per minute), put on the market place initially by Data Interface and later on by Inforex, approximatly from 1974 to 1976. Also a wide-type approach permitting much higher speeds has recently been presented by A.E. Berkowitz and al. at last year Intermag Conference (8).

The main limitation of the approach probably lies in the fragility and very short life of this medium : the conventional narrow-type tape was specified by the printer vendor as being good for one single 1000-page stack of paper, while the wide tape approach probably does not allow the printing of more than 50 000 pages. In a high duty computer output environment this means replacing the magnetic medium every other day. For the user this means higher cost and lower availability.

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THE CII-HONEYWELL BULL APPROACH

Extensive research and development has been performed at the Belfort plant, France, to design some new solutions to the problem of recording a latent magnetic image on a solid metallic drum. This has led to the development of a complete printer which main characteristics are : (a) high speed, (b) compactness (c) ruggedness, (d) reliability, (e) economy of use. For instance the drum life extends over 10 millions of pages.

Before going through some details about the basic printing process, we will start with a general presentation of the complete printer.

PRINTER DESCRIPTION

The product that has been developed is basically a 6000 lines per minute printer which general aspect and overall dimensions are indicated on fig. 1. It is to be noticed that the real printing mechanism is confined to a 25" x 10" x 10" which makes it one of the most compact device in that speed range.

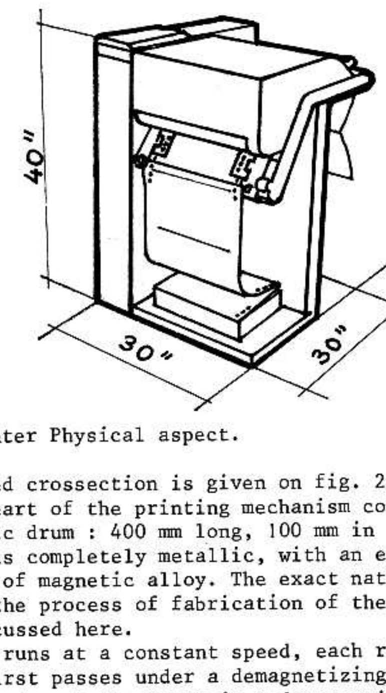

Fig. 1 Printer Physical aspect.

A simplified crossection is given on fig. 2.

The heart of the printing mechanism consists of the magnetic drum : 400 mm long, 100 mm in diameter. This drum is completely metallic, with an external layer made of magnetic alloy. The exact nature of the layer and the process of fabrication of the drum will not be discussed here.

As it runs at a constant speed, each region of the drum first passes under a demagnetizing head whose function is to put the layer in a demagnetized state. The printing station, consisting of 1728 individual recording heads can then record on it partial or complete rows of tiny magnetic dots. The dot configu-

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ration in the rows combined with the vertical scanning due to the drum rotation produces, in matrix form, a latent magnetic image of the page to be printed. Of course the page can be composed of alphanumerics or any graphic information.

Next step consists of passing through the toning or inking station where dry magnetic ink particles are put into contact with the recorded drum, thus resulting in image development. The ink or toner used here is single component, i.e. the development process makes use of only one type of particles, by opposition to the well known cascade development or magnetic brush development techniques, where a mixture of toner and carrier is used, with the associated problems of continuously mixing the two components and of controlling their respective concentration, despite the unpredictable consumption that results from random image density. The single component toner particles are handled by a permanent magnet roller, as in most single component toning systems ; however, unlike most of these systems, the developing effect is obtained by a wedge which creates a pressurized accumulation of toner against the drum instead of simply brushing the surface.

The developed image is then transfered onto plain paper by means of a pressure roller. This roller, in addition to its basic function, permits also the paper to be friction driven in perfect synchronism with the magnetic drum. Use of mechanical transfer, as opposed to the classical electrostatic transfer used in Xerography or other fragile medium printing technique, yields good efficiency and reliability, insensitivity to humidity and, last but not least, avoids the use of high voltage corona wires. It is worthy of note that such a simple rugged approach to the problem of transfering the image is made possible by the mechanical hardness of the magnetic medium.

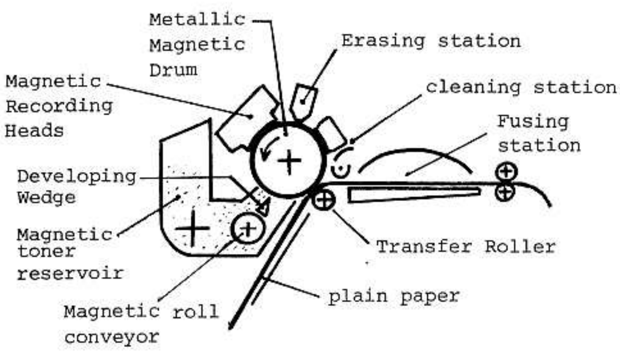


Fig. 2 Printer Cross-Section

After transfer, the excess of toner that remains on the drum has to be cleaned before a new print cycle can be initiated by passing again under the demagnetizing head. Again, the mechanical hardness of the magnetic drum permits the use of a simple rugged approach: the classical rotating brush can be replaced by a static scrapper blade. The scraped toner is removed mechanically by an helicoïdal screw.

The last operation consists of fixing the transferred image on the paper. Although the relatively high pressure created at the transfer level already caused the toner particles to be strongly pressed inside the paper fibers, the use of a fixing station is still necessary. In this station, the conjunction of radiant and conductive heat causes the toner resin to melt and adhere permanently to the paper support.

PERPENDICULAR RECORDING HEADS

The above description was intended to provide a broad brush picture of the complete printer mechanism as well as to recall the main principles of the transfer printing technique. Let us concentrate now on the recording heads.

As explained in the introduction, positioning a large number of heads along a solid drum implies many constraints in the design, construction and manufacturing of the heads. Actually, coming up with a print station of 1000 to 3000 individual heads requires special emphasis on the following factors : ability for the heads to be packed at high density, possibility to control each individual head with relatively low drive current, sufficiently short response time to permit unexpensive multiplexed control, and last but not least capability to be produced by means of highly automated processes.

The new type of head, that has been developed to satisfy the above requirements, is schematically represented on fig. 3.

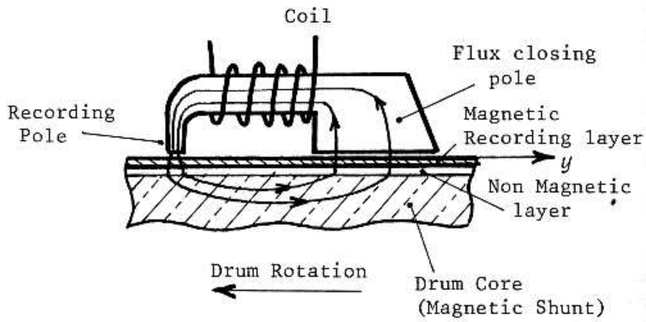
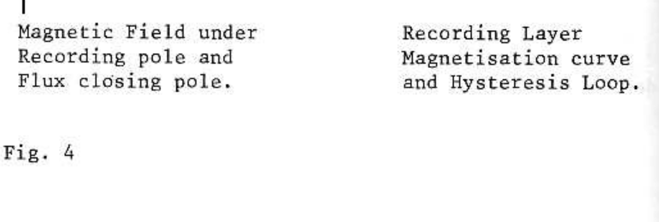


Fig. 3 Perpendicular Recording Head.

The head consists of a thin metallic core of high permeability bearing a wound coil. This core has a recording pole and a flux-closing pole. Both poles are facing the drum surface. When the head coil is energized, a magnetic flux is created in the closed magnetic circuit composed of the head core and the drum ferromagnetic core which acts as a magnetic shunt. Two gaps exist in this closed magnetic circuit, one at the level of the recording pole, the other at the level of the flux-closing pole. In both gaps the magnetic field is substantially perpendicular to the drum external magnetic layer that passes through these two gaps. The key point here is the fact that the flux-closing pole is much longer than the recording pole. Thus, the field intensity H1 under the recording pole is much higher than the field intensity H2 under the flux-closing pole. By positio-



Magnetic Field under Recording pole and Flux closing pole.

Recording Layer Magnetisation curve and Hysteresis Loop.

Fig. 4

ning the recording threshold of the drum magnetic layer between H1 and H2, one can see that the recording pole will really record a magnetic dot on the layer, while the flux-closing pole will not.

The basic advantage of the closed loop magnetic circuit lays in its higher efficiency compared to open ended poles. This, combined to the fact that the head lay-out permits to use a coil with as many turns as desired (by simply elongating the head core), allows to control the head with drive currents in the range of 100 mA.

The perpendicular recording of the layer yields a very sharp dot definition. Actually the remanent magnetic dots are substantially square in shape as shown on the photograph of fig. 5.

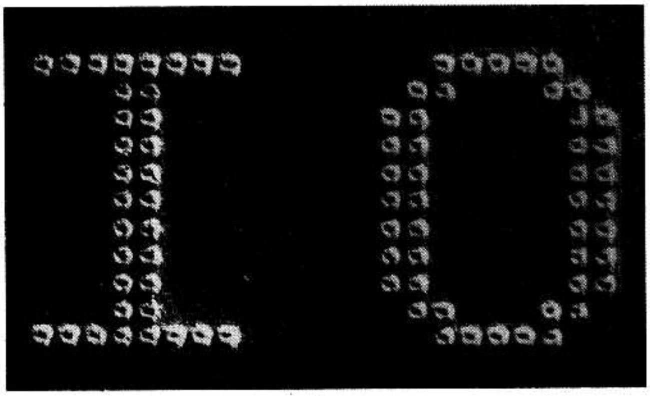


Fig. 5 Latent magnetic image.

Also, as the dot size is directly correlated to the recording pole size, each individual dot can be recorded with only one pulse of current.

This permits multiplexed controls. For instance, for 6000 lines per minute magnetic printer, printing at 8 lines per inch with a resolution of 120 dots per inch, the time allowed to record one complete row of dots is roughly 600 microseconds. The response time of the magnetic circuits being less than 10 microseconds, 48 drivers are sufficient to control the 1728 recording heads using a time shared multiplexing scheme structured in 36 groups of 48 heads (fig. 6).

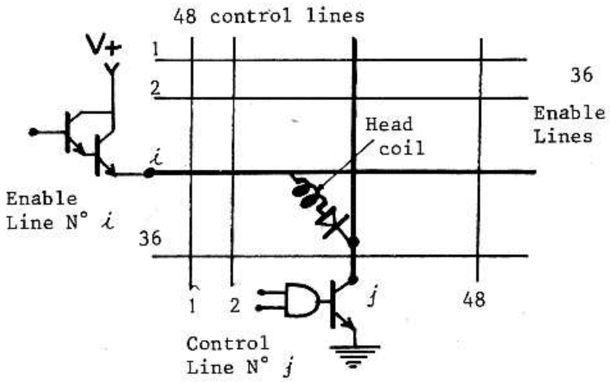


Fig. 6

Finally, it is to be noticed that the overall shape and lay-out of the head core is well suited to high density packing : the longest dimension of the core expands in the longitudinal direction, i.e. the direction of drum motion or vertically with respect to the paper, while in the transverse direction, i.e. parallel to the drum axis or horizontally with respect to the paper, the head core is very flat (typically 100 micrometers for a resolution of 120 dots per inch). This enables to pack the wound head cores at the required pitch to constitute a complete encapsulated module.

The module size has been chosen to hold 192 heads. Figure 7 shows how the heads are arranged in two rows inside the module : one row for even heads, one row for odd heads. However, all the recording poles are perfectly in line.

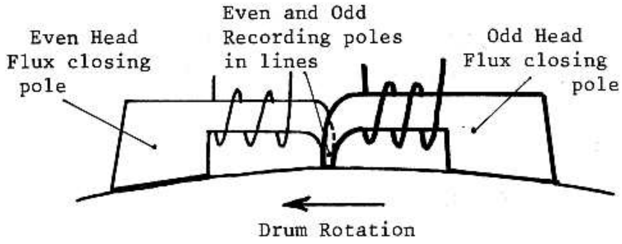


Fig. 7 Heads Lay-out.

9 modules, placed side by side, constitute a complete print station of 1728 heads.

Although the electronic aspect is out of the scope of this paper, let us mention that the electronic components used to time-multiplex the heads are also encapsulated inside each module. This permits control of any configuration of dots, out of the 1728 heads, with only 48 control lines bussed from one module to the other, while the module selection is achieved with a total of 36 enable lines (4 lines by module).

The numerical data indicated in the above presentation are pertinent to 120 dots per inch prototypes that have been built and fully tested.

Higher resolution heads of 180 and 240 dots per inch have already been designed and built using the same principles but of course with thinner head cores and higher packing densities. The following table summarizes the main technical data for the different heads.

Table 1 Print station Architecture for a 14-inch wide printer.

Resolution (dots per inch)	120	180	240
Module size (# of heads)	192	288	336
Control lines (bussed)	48	48	48
Enable lines (per module)	4	6	7
Number of modules	9	9	10
Print station (# of heads)	1728	2592	3360
Control current (mA)	150	100	70
Control time allowed (μs)	18	8	4

MAGNETIC DEVELOPMENT OF PERPENDICULARLY MAGNETIZED DOTS

The last section has presented the recording heads, their main principles as well as the way they are implemented in the printer. We will concentrate now on the development of the latent magnetic image that has been created by the heads on the drum magnetic layer. A mathematical 3-dimensional Model has been developed to study the image development of an arrangement of perpendicularly magnetized dots. Complete description of the Model is out of the scope of this paper. Rather, we will try to give some simplified indications as to the type of results that have been obtained.

Let us consider a magnetic dot of idealized square shape as represented on fig. 8. The dot dimensions are $2a \times 2a$ in the $x\ y$ plane (drum surface) and e in the z direction (e being the thickness of the drum external magnetic layer). The magnetized dot is separated from the drum core by a non magnetic underlayer of thickness c.

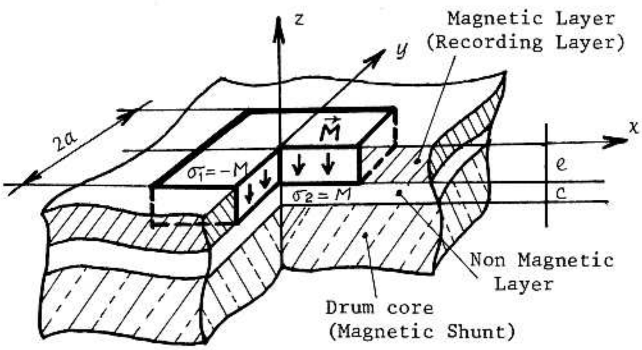


Fig. 8 Idealized Square dot.

As a first approximation, we will assume here that the magnetization $\vec{M}$ inside the dot is substantially uniform. That means that one can analyse the external magnetic field of the dot as resulting from two surface distributions of respective densities $\sigma_1 = -M$ and $\sigma_2 = +M$, while the volume distribution inside the layer is considered as negligible : $\rho = \text{div.}\ \vec{M} \simeq 0$. We have also to take into account the effect of the drum core which acts as a high permeability magnetic shunt (or keeper). Due to the high permeability, the magnetic field is practically perpendicular to the drum core surface.

Thus, we can represent the effect of the drum core by introducing a symmetrical dot (image theory). Finally, the complete system consisting of the dot plus the drum core can be analysed as the superposition of four surface distributions as indicated in fig. 9.

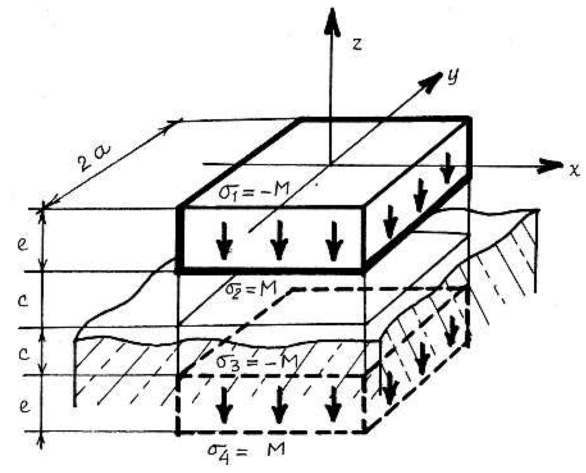


Fig. 9 Symmetrical dot simulates the effect of the drum core.

A single surface distribution of uniform density σ, with a square boundary of side length $2a$, develops at the point (x, y, z) the potential :

$$V_i(x,y,z) = \frac{\sigma i}{4\pi} \int_{-a}^{+a} \int_{-a}^{+a} \frac{d\xi\, d\eta}{\sqrt{(x-\xi)^2 + (y-\eta)^2 + z^2}} \qquad (1)$$

Classical calculations leads to the analytical expression :

$$V_i(x,y,z) = \frac{\sigma i}{4\pi} \Big[F(x+a, y+a, z) - F(x-a, y+a, z) + F(x-a, y-a, z) - F(x+a, y-a, z) \Big] \qquad (2)$$

Where f (X, Y, Z) is the harmonic function :

$$F(X,Y,Z) = X\ \text{Arg Sh} \frac{Y}{\sqrt{X^2+Z^2}} + Y\ \text{Arg Sh} \frac{X}{\sqrt{Y^2+Z^2}} - Z\ \text{Arc tg} \frac{XY}{Z\sqrt{X^2+Y^2+Z^2}} \qquad (3)$$

The potential developed by the dot can be obtained by adding the individual potential of the 4 surface distributions of respective densities : $\sigma_1 = -M$, $\sigma_2 = +M$, $\sigma_3 = -M$, $\sigma_4 = +M$:

$$\begin{aligned} V(x,y,z) = \frac{-M}{4\pi} \Big[& +F(x+a,y+a,z) - F(x-a,y+a,z) \\ & +F(x-a,y-a,z) - F(x+a,y-a,z) \\ & -F(x+a,y+a,z+e) + F(x-a,y+a,z+e) \\ & -F(x-a,y-a,z+e) + F(x+a,y-a,z+e) \\ & +F(x+a,y+a,z+e+2c) - F(x-a,y+a,z+e+2c) \\ & +F(x-a,y-a,z+e+2c) - F(x+a,y-a,z+e+2c) \\ & -F(x+a,y+a,z+2e+2c) + F(x-a,y+a,z+2e+2c) \\ & -F(x-a,y-a,z+2e+2c) + F(x+a,y-a,z+2e+2c) \Big] \end{aligned} \qquad (4)$$

The magnetic field $\vec{H}$ at the point (x, y, z) is easily derived by $\vec{H} = -\overrightarrow{\text{grad}}.\ V$.

The components Hx, Hy and Hz can thus be analytically expressed as a function of the system parameters. Although the above expressions permit the representation of the potential and the field at any point of the 3-dimension space, the curves of fig. 10 only give the horizontal and vertical components of the magnetic field $\vec{H}$ in the symmetry median plane of the dot ($y = 0$).

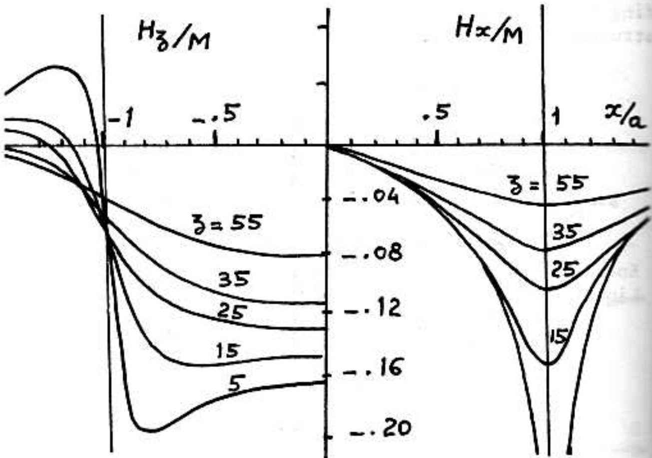


Fig. 10 Magnetic Field Components for a square dot (Constant Altitudes z in micrometers).

For magnetization in the range of 1000 Gauss and dot size of 150 micrometers, the external field at distances of 10 to 40 micrometers from the layer is found to be only a few hundred Oersteds. However, from the standpoint of image development, the important thing is not the field intensity but the magnetic force applied to the toner particles. This force is related to the field gradient rather than to the field itself. The simple component toner used basically consists of thermoplastic resin particles (particle size ranging from 10 to 50 micrometers) enclosing a large number of tiny submicron magnetic fillers. Image development results from the magnetic force applied by the magnetized dot to these magnetic fillers.

Let $\vec{m}$ be the resulting magnetic momentum of a toner particle located at the point (x, y, z) where the magnetic fields is $\vec{H}\ (x, y, z)$. Accounting for the particle orientation in the field, the magnetic force on the toner particle can be written as :

$$\vec{F} = \mu_0\ m\ \overrightarrow{grad}\ H \qquad H = \sqrt{Hx^2+Hy^2+Hz^2} \qquad m = |\vec{m}| \tag{5}$$

Figure 11 gives the horizontal and vertical components of the magnetic force, in the dot symmetry median plane, as a function of the standardized coordonate x/a and for various altitudes z with respect to the drum magnetic layer.

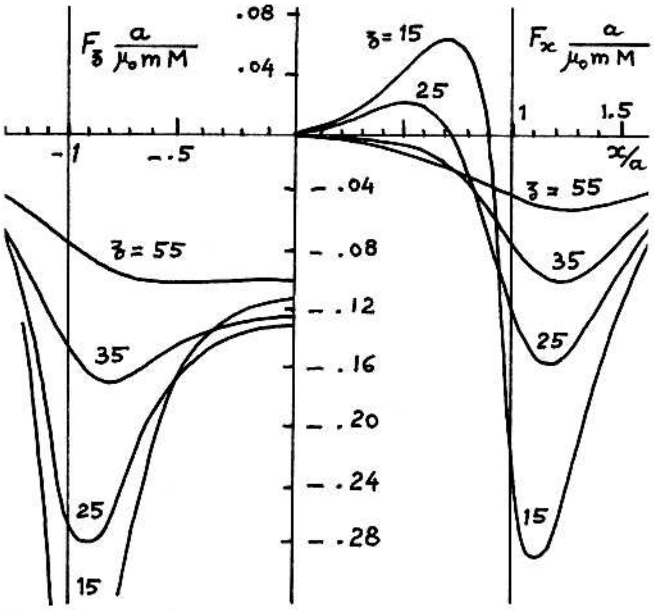


Fig. 11 Magnetic Force Components for a square dot.

Analysis of the curves shows that, at very low altitudes with respect to the drum magnetic layer, the toner particles tend to accumulate along the edges of the square dot, producing the so-called "donnut effect". This will appear for very small particles. However, as the altitude z is increased, this edge effect progressively disappears and is finally inverted for altitudes of 30 to 50 micrometers from the drum surface, that is to say that toner attraction is then maximum on the middle of the dot ; this is achieved by using rather big particles or by accumulating a sufficient quantity of small or medium particles. Experimental work has confirmed the validity of the above model and analysis.

Though they are easy to program on a computer, the above analytical expressions -- even if completely explicated -- are not simple enough to provide a clear insight into the parameters trends and influences. It is thus interesting to derived simplified expressions that, if less accurate, have the advantage of better exhibiting these trends and influences. Such simplified expressions can be obtained by just retaining the first order term in series expansions of the complete analytical expressions.

Assuming the magnetic layer thickness e and the non magnetic underlayer thickness c much smaller than the dot size a leads to the first order approximations of table 2.

Table 2	Vicinity of the dot center	Vicinity of the dot edges	Large distance from the dot
Magnetic attraction varies as	$\frac{mMe}{a^3}$	mMe	$mMe\ a^2$

M = dot magnetization $\quad 2a$ = dot size
m = magnetic momentum of the toner particle $\quad e$ = magnetic layer thickness

One important finding of the above analysis lies in the fact that development quality at the center of the dot rapidly increases with the print resolution $(1/a^3)$. This has been experimentally verified by the test results of 180 and 240 dots per inch heads compared to the 120 dots per inch initial heads.

Just to give an example of the additional possibilities of the Model that has been developed, a 3-dimensional plot of the iso-force surface : Fz = constant is indicated in fig. 12 for a typical "corner" configuration of 3 dots.

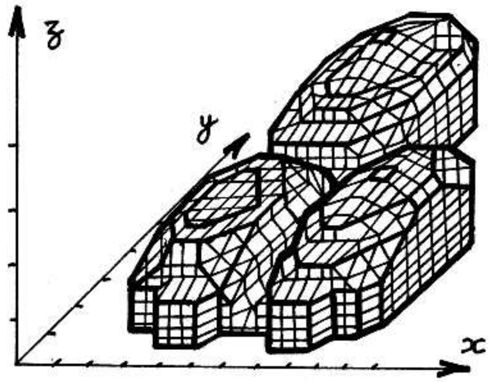
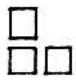


Fig. 12 Development of a "corner" configuration of 3 dots.



CONCLUSION

The use of perpendicular magnetized dots to compose the latent image on the print medium has proved to yield many advantages at the level of image recording as well as at that of image development : perfectly square dots of constant size whatever their position within the print pattern are obtained ; the toning process is controlable and produces even and uniform image development.

The work on perpendicular recording heads, metallic drum, magnetic development, as well as on associated functions not covered in details in this paper (such as toner transfer onto plain paper, image fixing, drum cleaning and toner recycling), has permitted the design of a 6000 lines per minute Magnetic Non Impact Printer.

Several prototypes printing at a resolution of 120 dots per inch have been constructed and fully tested. A product aimed at Computer Output Printing applications is ready for production.

Higher density heads printing at 180 and 240 dots per inch have also been developed. The 240 dots per inch resolution produces a print quality that is perfectly compatible with Word Processing applications. A further product aimed at these last applications will soon be available.

REFERENCES

(1) Jones, "Printing by magnetism", Mechanics Magazine, Vol. 31, N° 385, P 385 - 1839.
(2) R.B. Atkinson, S.G. Ellis, "Ferrography", Journal of the Franklin Institute, Nov. 1951.
(3) T.M. Berry, J.P. Hanna, "Ferromagnetography", High Speed Printing with shapped Magnetic Fields - G.E. Review, July 1952.
(4) S.J. Begun, "Theory of Magnetography", IRE National Convention, March 1958.
(5) Datamation, July 1972.
(6) A.E. Brewster, "A High Speed Magnetic Printout System", Electronics & Power, Feb. 1968.
(7) N.A. Allen, C.A. Watson, "Perpendicular Recording and its application in magnetographic Printing", Intermag Conference, April 1969.
(8) A.E. Berkowitz, J.A. Lahut, W.H. Meiklejohn, R.E. Skoda, J.M. Wang, "A High Speed Magnetic Printer", Intermag Conference, 1979.