An overview of impact printing

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This paper gives an overview of impact printing and reviews some of the more recent advances made in this printing technology. Matrix and fully-formed-character impact-printing technologies are discussed for both serial printers and line printers. The critical electromechanical subassemblies that are described are the hammer unit, the paper-handling system, the inking system, and the type-element system. The mathematics describing printer performance and the operation of some of the subassemblies are presented. The relative simplicity of the impact printer still allows it to be the most economical form of text printing. Its other advantages are reliability, general insensitivity to environment, and the ability to print on the greatest variety of print media.

Introduction

Impact printing, which had been the predominant printing technology for large systems as recently as eight years ago, still plays an important role in satisfying the printing needs of many users. Typically, impact printers are more reliable, lower in cost, more tolerant to a variety of print media (paper types), and less sensitive to environmental conditions than their non-impact counterparts. Additionally, there are unique applications that can be satisfied only by impact printers, such as printing on multipart forms, printing in hostile environments, and higher efficiency for sparse printing. The disadvantages of impact printers are related to their poorer print quality and their lack of flexibility and performance with respect to complex fonts, images, and color. In addition, the acoustic levels for the very low-speed impact printers can be relatively high.

Impact printers can be divided into two different technologies and two different configurations. The two configurations are line printing and serial printing [1]. In the line-printing configuration, all of the characters that comprise a line are printed more or less at the same time; i.e., printing takes place one line at a time. In the serial configuration, printing is performed one character at a time, the characters being printed sequentially. The two impact technologies are fully-formed-character printing and matrix printing. In the former, the entire character is produced by means of a single impact creating a fully formed character. In matrix printing, characters are created as a result of numerous impacts producing dots that form the desired character. Thus, impact printers come in four varieties: fully-formed-character line and serial printers as well as matrix line and serial printers. Some examples are engraved-band printers (fully-formed line), shown in **Figure 1**, wire-matrix (matrix serial) in **Figure 2**, and dot-band (matrix line) in **Figure 3** [1–5].

General printer descriptions

- *Matrix serial*

In a matrix serial printer, the printhead traverses the paper from one side to the other. A character is formed by a sequence of print-wire impacts [5, 6]. For example, printing the character E (**Figure 4**), with a printhead (see Figure 2) comprising, say, seven wires aligned vertically and spaced vertically the distance of one pel (picture

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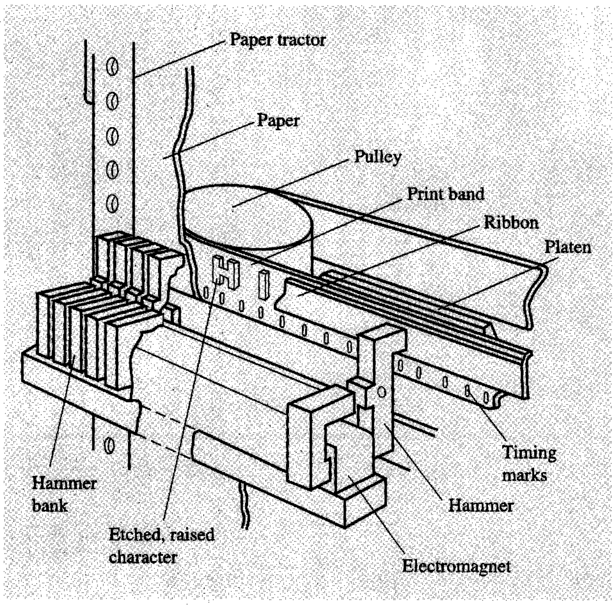

Figure 1

Engraved-band line printer.

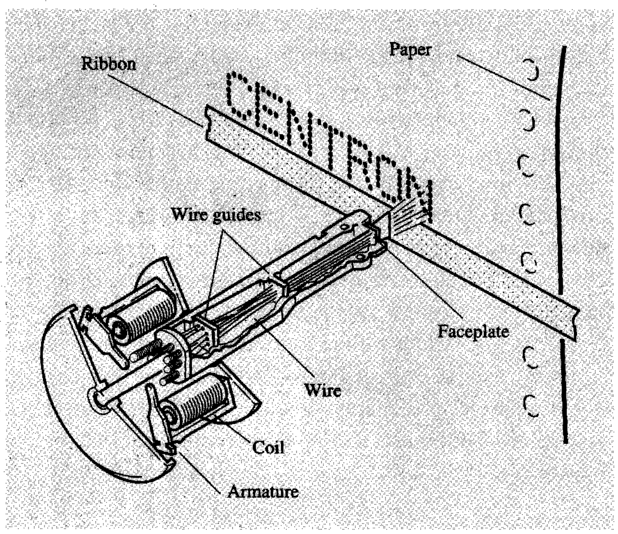

Figure 2

Serial wire-matrix printer.

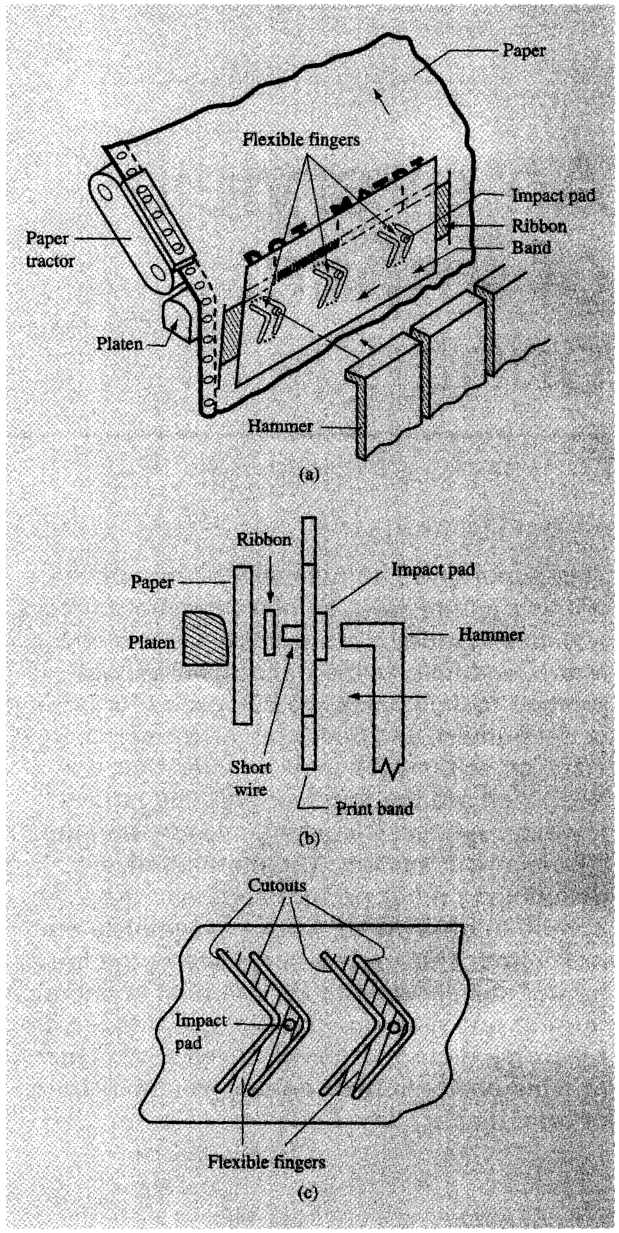

Figure 3

Dot-band (matrix line) printer: (a) Complete structure; (b) side view; (c) front view of two fingers.

element or dot) apart is accomplished as follows. For the first vertical line, the seven wires are fired. The wires compress the ribbon against the paper and platen, creating a column of vertical dots on the paper. When the printhead, which is continually moving, has advanced a horizontal distance of one pel, hammers are actuated for wires 1, 4, and 7. The same action occurs when the next horizontal pel is reached. When the final horizontal pel is reached, wires 1 and 7 are activated. This completes the printing of this character. Characters are printed sequentially. When the end of the printed line is reached, the paper is incremented (advanced) to the next print line.

• *Fully-formed-character line*
In a fully-formed-character line printer, the print or hammer unit is stationary, with one hammer typically corresponding to each print position. The predominant type-element configuration consists of a continuous array of engraved characters, in the form of a print band (Figure 1). The band passes by each hammer. When the character to be printed at a particular position is aligned with this print position, the hammer at this position is activated, compressing the ribbon and paper against the print band and the platen. As can be imagined, printing of the characters of a line occurs in a random manner (dependent upon what characters are aligned when), and printing of the entire line occurs in a relatively short time. After the last character is printed, the paper is incremented to the next line. The ribbon traverses the print line rapidly enough that ink is not depleted locally as a result of successive impacts.

• *Matrix line*
A matrix line printer operates in a somewhat similar manner. Usually, the print wires are aligned horizontally, with the space between successive wires equal to one or more character pitches (the horizontal distance between the center of two successive characters), as seen in **Figure 5**. For the purpose of this example, assume a pitch of one character. Thus, the entire printhead, consisting of these wires and the corresponding actuators, must move laterally one character pitch (actually slightly more, since there is an overhead associated with reversing the direction of the printhead) in order for each horizontal pel to be addressed. For this example, we describe a reciprocating printhead printing a row of E's. With the hammer unit at the leftmost position, each wire is activated, thus printing the top-leftmost dot for each character E. When the hammer/wire unit has moved horizontally one pel, each wire is activated again. This is repeated twice more, until the printing of the top row is completed. The paper is incremented one pel vertically, and the printhead or hammer unit direction is reversed. The process of printing is repeated. This time, however, only the leftmost dot is printed for each character. This process of printing a dot row, incrementing the paper one pel vertically, and reversing the printhead motion is repeated until the entire row of characters is printed. Then, the paper is incremented to the top of the next character row to be printed. For a pitch of $n > 1$ characters, each wire of the printhead prints all of the dots for n characters before the printhead direction is reversed.

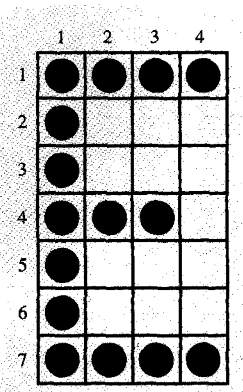

Figure 4

The character E.

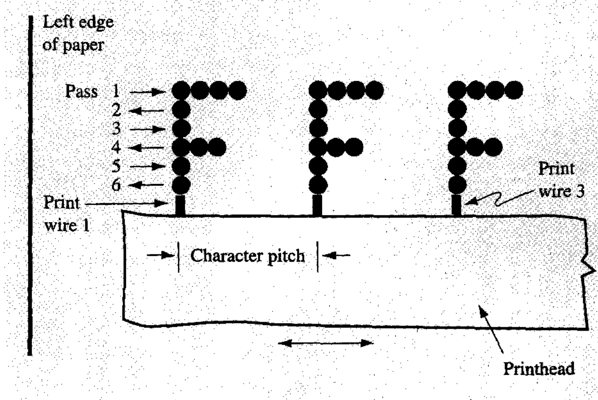

Figure 5

A matrix line printer printing a row of E's.

Subassemblies
In general, the subassemblies that comprise these printers are quite similar in function. The electromechanical assemblies consist of a hammer unit, ribbon system, paper-incrementing system, and type-element-moving system. Each of these systems is driven by electromechanical devices, such as stepper motors, typically under feedback control. The logic that controls these subassemblies is part of the printer's control unit subassembly. Additionally, the control unit converts printer commands from a host computer into mechanism operations. The controller also queries sensors to verify that the printer is functioning properly (i.e., no paper jams, ribbon fold-over, etc.). The printer attachment subassembly allows the printer to be attached to a variety of hosts or networks. A brief explanation of the function of each of the electromechanical subassemblies follows.

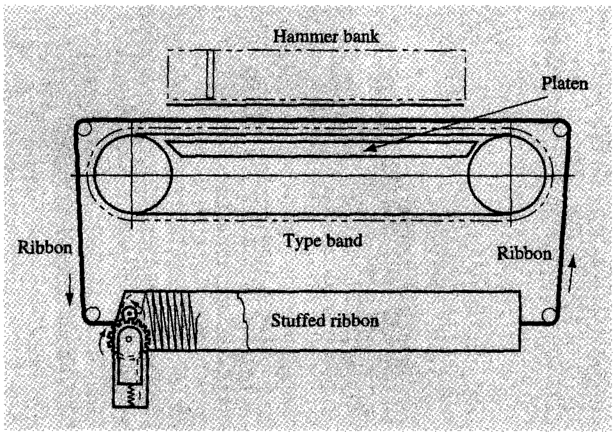

Figure 6

Stuffer ribbon box system.

• *Hammer unit*
For all impact printers, the hammer unit, or printhead, is the most critical subassembly. The performance of the printer in terms of throughput and print quality is directly related to that of the hammer unit. The function of the hammer unit is to supply the energy, by means of an impact, to transfer ink from the ribbon to the print medium so that the result is legible. A variety of hammer technologies, using different electromagnetic configurations, have been successfully employed. Desirable characteristics of the hammer unit are fast cycle time, delivery of sufficiently high print energy, high efficiency (low input power required), relatively short impact duration, accurate impact timing, low operating temperature, and, of course, low cost. For matrix printers, fast cycle time and sufficient print energy are most critical. For fully-formed-character line printers, impact duration, timing accuracy, and sufficient print energy are most critical. Detailed descriptions of some of the hammer unit technologies are given later in this paper.

• *Paper-handling system*
The paper-incrementing system is the second most important electromechanical subassembly in a printer. Paper incrementing is accomplished by a dc servo or stepper motor directly or indirectly connected to paper tractors and/or feed rolls via timing belts and gears. The tractors contain pins on a small band that are engaged into the pin-feed holes of the paper. The tractor pins directly increment the paper. The paper-handling systems for all impact printers serve somewhat the same function, namely, to move paper so that the next line will be printed by the hammer unit at the proper position. For matrix line printers, this typically means moving the paper vertically a distance of one pel. In this case, a premium is paid for very fast increment time. After a line of characters is completed, paper is incremented to the next line to be printed. If the next line to be printed occurs at a distance greater than one standard print line away, a high-velocity paper increment, sometimes referred to as a paper skip, is employed. In addition to paper incrementing, many of the high-speed impact printers have special paper-stacking mechanisms at the output of the printer.

Typically, the distance between the hammer unit and the paper is quite small, and paper shields are used to prevent the folds on fanfold paper from getting caught on the hammer unit during incrementing. Additionally, paper-compressing means are employed to squeeze the layers of multiple-part forms, in order to allow the hammer impact to be more effective in transferring the ink from the ribbon to the paper.

• *Ribbon or inking system*
The basic inking systems for all impact printers make use of an inked ribbon moving past the print hammers. The method for presenting the ribbon in front of the hammer unit varies. The lowest-cost system consists of a supply reel containing the ribbon and a take-up reel, both coupled to stepper or servo motors. The take-up reel causes the ribbon to move past the hammer unit at an appropriate, relatively constant speed [2]. The stepper motor for the supply reel basically acts as a brake in order to better control ribbon delivery. The ribbon speed is such that there is no localized depletion of the ink in the ribbon as it passes the hammer unit. When the supply spool is nearly empty, the ribbon direction is reversed, and the supply spool now becomes the take-up spool and vice versa. A variation of this system uses a stuffer cassette instead of spools. In this device, ribbon is pulled out of one end of the cassette via friction rolls driven by a motor. The ribbon is pulled across the print line in front of the hammer unit and then returned, or "stuffed" back, into the box. (See **Figure 6** [7, 8].) Guidance is usually provided to ensure the proper vertical location of the ribbon [9].

• *Type element*
The type element for a matrix printer comprises the wires connected to the print actuators. For a fully-formed-character line printer, a print band (Figure 1) with characters (type elements) etched onto its surface moves past stationary hammers. The band is wrapped around two pulleys for guidance: One is the driver and the other an idler [10]. They are separated by slightly more than the length of the print line. The print band is driven at constant velocity by a servo motor for most printers. Figure 3 shows a matrix line printer configuration where impact-pad/wire units are attached to a print band that is driven and controlled in a manner similar to that of a

fully-formed-character line printer. These units, or type elements, are impacted by hammers in order to print dots.

Engraved-band line printers

Figure 1 shows the schematic arrangement of a typical engraved-band impact printer. The print band contains repeated arrays of characters on its surface. The character pitch on the band must be somewhat greater than the hammer spacing in order to avoid shadow printing (the partial printing of adjacent characters). The print band moves at a constant velocity past the stationary hammer unit. As described above, when the characters desired to be printed are at the appropriate positions along the print line, the appropriate hammers are fired. The printing of a line is complete when all of the characters on that line have been printed. In the worst case, this is the time it takes for one complete set of characters to pass by a print position. In order to obtain the total time for one print line, one adds to the print time the time required to increment the paper to the next successive line. Thus, the formula for worse-case printer throughput, T, for this technology, in terms of lines printed per unit of time, is

$$T = \frac{1}{\frac{np}{v} + t_{pi}}, \qquad (1)$$

where n is the number of characters per array (complete character set), p is the character pitch, v is the band velocity, and t_{pi} is the paper-increment time for moving paper one print line.

Typically, the number of characters in a set is approximately 50, and the character pitch is about 0.33 cm in order to avoid shadow printing; thus, only two variables remain to control throughput: print-band velocity and paper-increment time. High throughput is obtained primarily by utilizing high band velocity and secondarily by employing very short paper-increment times.

A typical time of 8 ms to move paper the distance of one print line is readily achieved by a dc servo motor. A paper-increment time for one print line as low as 5 ms can be achieved only with multiple, powerful servo motors under sophisticated control schemes. Good print quality can be obtained with print-band speeds as high as 7.5 m/s. Thus, throughput of approximately 2000 lines per minute can be obtained. Higher band speeds are also utilized, with resultant degradation in print quality due to character slur (increase in stroke width because of print-band motion). Additional improvements in effective page throughput can be realized for documents with sparse printing, by providing a paper velocity much higher than normal (3×) during skipping. This is achieved through high-speed paper motion (approximately 2.5 m/s) between print lines that are relatively far apart (greater than 2.5 cm).

High-speed impact line printers print while the type characters are in motion. This requires short hammer contact time for minimized slur and acceptable print quality. The typical time during which the hammer compresses the paper and ribbon against the print band and platen is about 50 μs. Shorter contact times can be achieved with more sophisticated, low-mass hammers. The width of the printed stroke, W, as a function of the hammer contact time can be determined from the following equation [11]:

$$W = rw + avt_c, \qquad (2)$$

where w is the width of the stroke on the print band, r is the static spread factor (about 1.2), a is the fraction of contact time during which ink transfers (about 0.7), and t_c is the contact time (avt_c corresponds to slur). Low contact time is obtained by means of high hammer-impact velocity, low hammer mass, high impact area (character area), and stiff paper/ribbon elastic damping characteristics [12]. Printed stroke widths of approximately 0.04 cm are typical.

- *Hammer unit*

For engraved-band line printers, the hammer unit is the key component, since the print quality and performance depend upon it. Typically, the hammers are spaced at 0.1-in. intervals, with each hammer linked to an individual electromagnet. The printed-character pitch equals the hammer pitch. The print energy of a hammer should be such that during print impact, sufficient ink is transferred from the ribbon to the paper to create a dark, well-printed character. Larger-area characters and thicker paper forms require higher print energy. Basically, S_p, the compressive stress between the hammer face and the ribbon, must exceed S_{min}, the minimum print stress necessary for high optical density (darkness), an empirical quantity. (Reference [13] discusses S_{min}.) The following equation [12] describes S_p:

$$S_p = \frac{C_1 V_h \sqrt{mk}}{A}, \qquad (3)$$

where V_h is the hammer velocity, m is the hammer mass, k is the compliance or stiffness of paper, C_1 is a constant that is related to ribbon-ink-release characteristics, and A is the character area. Nonetheless, there is a balance that must be met so that the print energy does not produce an excessive stress upon the ribbon during impact, which leads to premature ribbon failure as the ribbon fibers are destroyed.

During most of the time that the hammer is in contact with the paper, ribbon, print band, and platen, ink is transferred to the paper. Thus, in accordance with

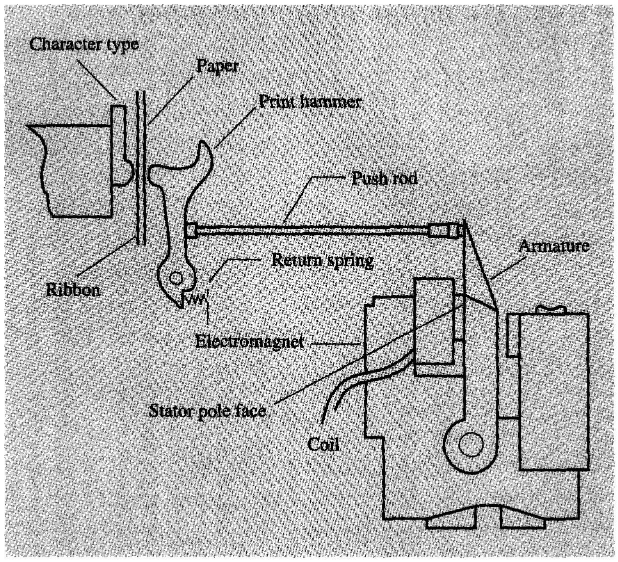

Figure 7

Three-piece actuator.

Equation (2), in order for the stroke width to remain relatively constant, the contact time must be proportionately reduced as the print-band velocity is increased. Contact time, t_c [12], is

$$t_c = C_2\left[\frac{1}{V_h}\left(\frac{m}{kA}\right)^c\right]^q, \qquad (4)$$

where C_2 is a constant relating to paper deformation characteristics, q is a constant ($\approx 1/2$), and c is a constant ($\approx 1/2$). Thus, low contact time is associated with low hammer mass and high hammer velocity.

The time that is required for the print hammer to strike the paper once the armature coil of the hammer becomes energized is called the flight time. During this time, the print band moves at basically a constant velocity, so the distance traveled by the band during this time is the product of band velocity and flight time. Any variations in flight time and band velocity change the impact timing, causing characters to be misregistered or misplaced from their intended location on the paper. This horizontal displacement from the intended position is

$$\Delta x = (v + \Delta v)\Delta T_h + \Delta v T_h, \qquad (5)$$

where Δx is horizontal character misregistration, Δv is the variation in print-band velocity from nominal during hammer flight time, ΔT_h is the hammer flight-time variation, and T_h is the hammer flight time.

Thus, it can be seen that higher band speeds (v), which are associated with higher printer throughput, require tighter control of hammer flight time (smaller flight-time variation). Factors that contribute to flight-time variation include mechanical and magnetic interaction between adjacent positions, changes in input energy to electromagnets due to coil-temperature and drive-voltage changes, and pulse-width variations. Similarly, print-band speed must be tightly controlled; however, feedback schemes are used to compensate for low-frequency band-velocity variations. Additionally, shorter hammer flight times alleviate this problem.

Two types of hammer technologies are commonly used: multistage (three-piece) and one-piece hammers. In the multistage hammer design (**Figure 7**), the armature of the hammer is magnetically attracted to the stator when the coil on the stator is energized, creating the electromagnetic field between the stator and armature. The armature pushes the push rod, which in turn pushes the hammer, until the armature strikes the stator pole face. At this time, the pivoting hammer goes into free flight until it strikes the paper, ribbon, print-band, and platen combination. Since push rods separate the hammer bank and the bulky electromagnetic-actuator bank, the electromagnet can have the large mass or volume required for heat dissipation and development of magnetic energy, while very low-mass hammers that eventually go into free flight can be used. This arrangement requires complicated packaging designs, with cost higher than that for a one-piece hammer. Additionally, not all of the kinetic energy developed in the armature is utilized during print, since the armature strikes the stator pole face. An example of a high-performance hammer in this category is the hammer unit developed for the IBM 4248 printer, rated at 3600 lines per minute. To achieve this speed, a low-mass (0.3 g), high-speed (about 8 m/s) hammer was developed for a type-band speed of 19 m/s.

The one-piece print hammer (**Figure 8**) essentially works in a similar manner, except that the entire mass of the armature effectively strikes the paper, ribbon, print-band, and platen combination. However, the part of the hammer mass close to the impact area and the part close to the electromagnet combine to form a relatively large hammer mass, which is associated with long contact times. Thus, this type of hammer is effective only for lower-speed printers, such as the IBM 3262 [14]. Here, the effective hammer mass, obtained by dividing the rotational inertia of the hammer by the square of the distance from the pivot to the impact point, is 3.6 g. In a one-piece-hammer design, mass reduction is limited because of the necessity for a large armature (that part of the hammer near the electromagnet) required to develop sufficient magnetic energy. However, one-piece technology has been advanced with the flexible hammer technology (**Figure 9**) used in the IBM 6262-12 and 6252 printers [15]. The

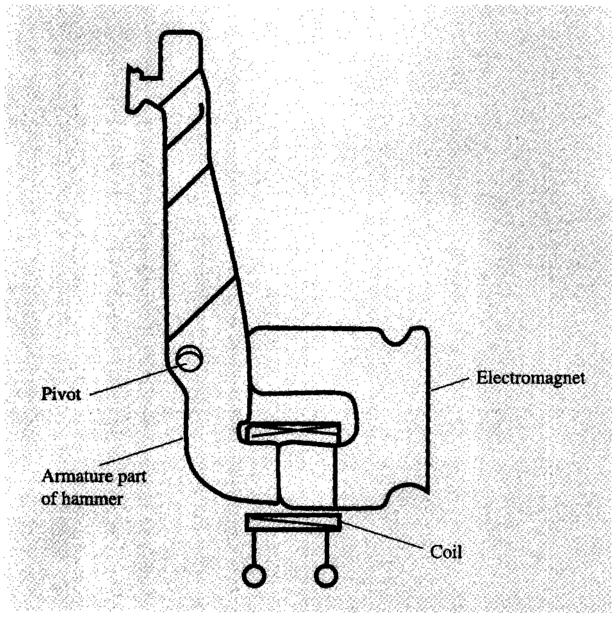

Figure 8

One-piece hammer.

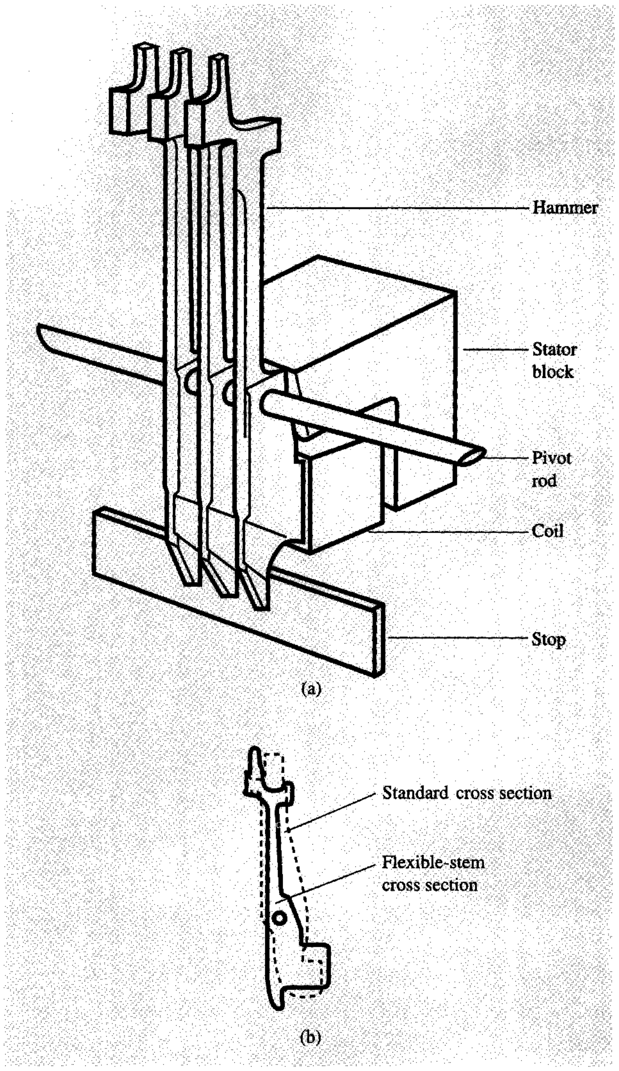

Figure 9

Flexible one-piece hammer: (a) Complete configuration; (b) cross sections of standard and flexible-stem hammers.

concept is to use the cost-effective one-piece design but also adopt a flexible hammer stem to simulate the push rods of a three-piece design. Just prior to hammer impact, the armature hits the armature stop, and the upper portion of the hammer whips forward to strike the paper, ribbon, print band, and platen. The flexible stem decouples the armature mass part of the hammer from the impact mass part of the hammer during impact. The effective hammer mass during contact is thus just the impact part. This effective mass is approximately 0.8 g. Furthermore, the rebound of the armature off the armature stop causes the impact part of the hammer to rebound off the paper. The ultimate result is a one-piece print hammer with very short contact time, producing high quality at relatively high print speed. This hammer also requires improved heat dissipation as well as improved magnetic and mechanical separation between adjacent hammer positions. Magnetic and mechanical separation are necessary so that the actuation of one hammer does not influence the flight time of adjacent hammers. Magnetic shields, shown in **Figure 10**, dramatically reduce the magnetic cross talk between adjacent positions [16] and also act as fins for heat dissipation. This configuration has been implemented in the IBM 6262 and 6252 printers. Mechanical interaction is reduced by means of mechanical isolation in conjunction with increasing the effective mass of the supporting structure.

Packaging schemes with two hamer units separated vertically, allowing two lines to be printed simultaneously, have been used to increase printer throughput. Two-piece-hammer schemes (hybrids of the one- and three-piece designs) have also been used to produce lower-cost, high-performance hammer banks.

• *Type carrier and drive systems*

Chemical etching technology provides inexpensive engraved fully-formatted-character print bands with various character sets, including symbols such as bar-code elements [17]. The print band must be driven at a constant velocity and aligned horizontally to prevent horizontal and

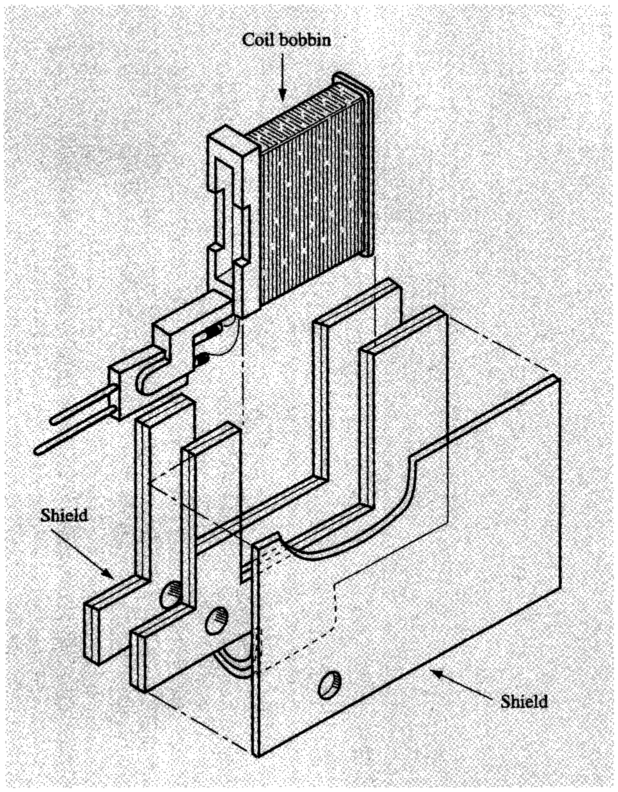

Figure 10

Coil and shield configuration.

vertical misregistration. In some high-speed printers, the bottom edge of the band cannot be supported by a fixed support owing to wear restrictions. Here, the band's vertical location is constantly sensed, and one pulley is automatically adjusted vertically (via a feedback scheme) to maintain a constant vertical band position. For medium-speed printers, the moving band rests on a support bearing, and the two pulleys are allowed to slide vertically along their shafts. This floating-pulley type of support is shown in **Figure 11**. For low-speed printers, crowned pulleys with bottom flanges, as shown in **Figure 12**, are used. The pulley crown causes the print band to be driven down against the flange, vertically positioning the band. Etched timing marks on the print band are sensed and used to determine the band speed and character locations. Feedback schemes are used to keep the band velocity constant.

- *Paper drive*

High paper-incrementing speeds are basically limited by pinhole tears caused by excessive paper acceleration of the tractor pin belt and the inability to stack paper at high

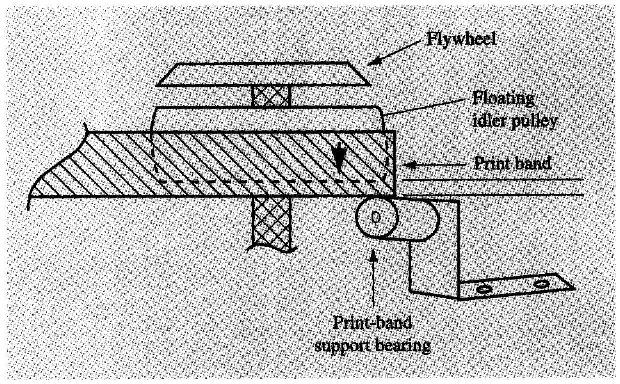

Figure 11

Floating pulley.

incrementing speeds. A special paper-tractor system developed to reduce pinhole damage is incorporated in the IBM 4248 printer (**Figure 13**). Each tractor door has an "endless" tape or forms-retention belt having pinholes that match the pitch of the "endless" tractor-pin belt. The tape holes engage with the pins over the paper pinholes when the door is closed and move with the pin belt. Under the pressure of the cover, the paper is tightly sandwiched between the belt and the tape, and when the pin belt advances, the pins drive the paper and tape in unison. During this time, the tape helps to drive the paper via friction between the tape and the paper surface. This acts to reduce the pin force on the paper, thus reducing pinhole tear under high acceleration. With such tractors, paper speeds of 2.5 m/s can be quickly reached. For medium-speed printers, typical increment speeds of about 1.25 m/s are obtained. The signal used to drive the paper-system motors can be adjusted for forms of varying thickness or mass. Additionally, the timing belts must be sufficiently stiff, and the contact between the tractor pins and the paper must be sufficiently tight for effective control of paper incrementing.

- *Paper stacking*

Power stackers are generally used in conjunction with paper skip speeds above 1 m/s. A power stacker typically consists of feed rolls, a movable table on which the output pages rest, which is kept at the optimal stacking height, and sensors to detect the top of the stack. In addition, some stackers have means of patting down the stack along the perforation folds to allow the paper to stack in an efficient, flat pile. Additionally, some stackers have devices to aid in folding the paper in the correct direction along the perforation [18]. For low-speed printers, passive or gravitational stackers are provided. To facilitate orderly

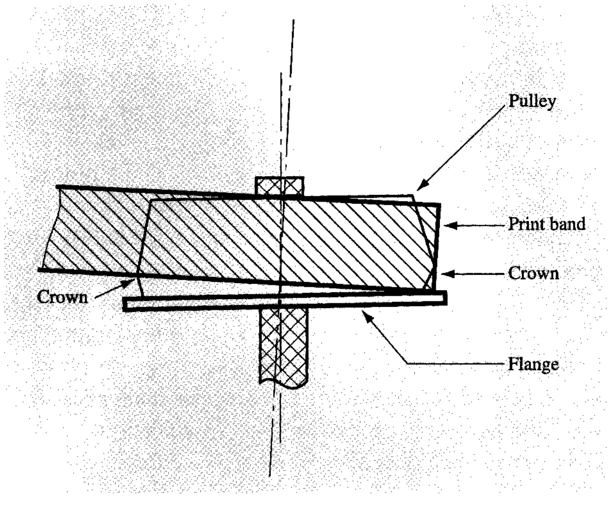

Figure 12

Flanged pulley design.

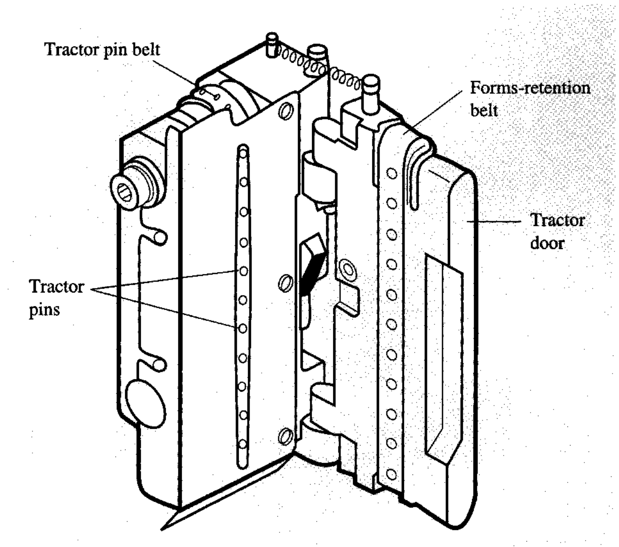

Figure 13

Tractor assembly with forms-retention belt.

folding of paper, chains or other weights have been successfully utilized to force the paper to fold at its perforations [19]. Sometimes, platforms located at the bottom of the stacker are used to compensate for bulges that build up along the paper as a result of pinhole damage (see **Figure 14**). This provides for a flatter stack at the higher stack heights. The vertical distance from the printer paper tractor exit to the paper stack should be kept at approximately the length of three paper sheets of the continuous paper forms being stacked [20].

- *Special applications*

For high-quality text approaching letter quality, polyester-film ribbons can be used. High quality is essential for certain applications such as optical character recognition and bar-code reading. Compared with fabric ribbons, polyester ribbons provide higher character density and more complete character fill as a result of the different ink-release mechanism. A solid layer of ink is attached to a polyester-film backing. During each print impact, about one fifth of the thickness of the solid ink layer is transferred to the paper. Thus, a limited number of impacts can occur before the effective total layer of ink is transferred to the paper. As a result, polyester-film ribbons typically have only a fraction of the lifetime of fabric ribbons.

In addition to printing of multipart forms and heat-sensitive labels, for which impact printers are especially well suited, bar-code printing and condensed printing (more than ten characters per inch) are also appropriate applications [21–23]. Bar code and condensed printing on a band printer utilize a special "interposer," described below, and unique character print bands.

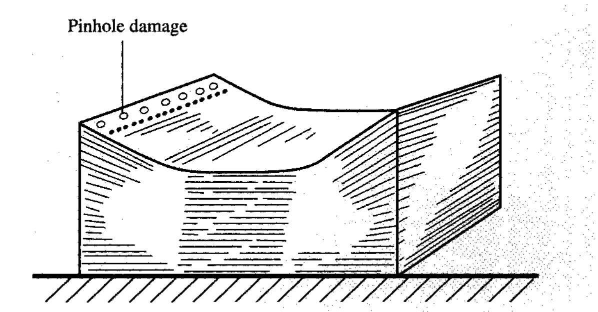

Figure 14

Bulge due to pinhole damage.

Bar codes, which can easily be formed since they make use of only a few line elements, are among the simplest forms of graphics [24]. Engraved-band impact printers appear to be well suited for printing bar codes, since the line elements needed can be readily engraved on a print band. However, there are some inherent difficulties, the major one being the inability to form continuous horizontal lines (necessary for bar codes) without breaks between hammers. Even if the type elements should be made wider than the hammers, the pressure would not

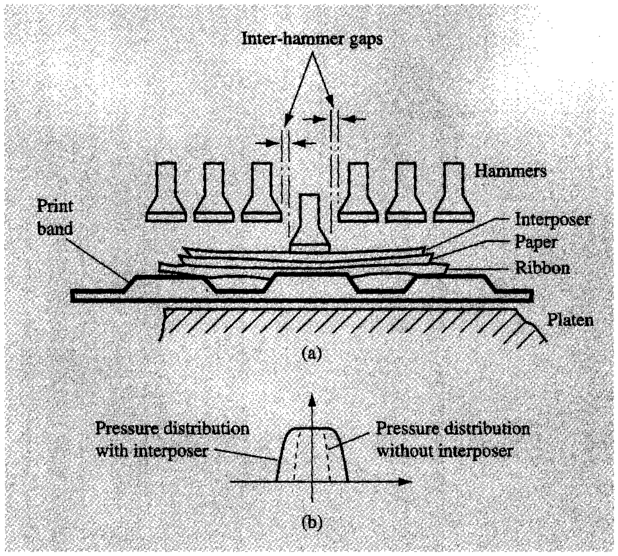

Figure 15

Use of the interposer to print across gaps between hammers: (a) Engraved-band printer with interposer in place; (b) pressure distribution with and without interposer.

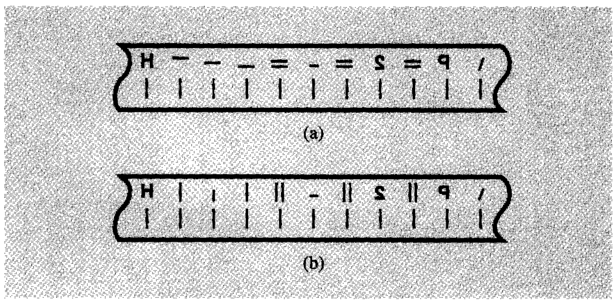

Figure 16

Print band containing (a) ladder bar-code segments and (b) picket-fence bar-code segments.

extend across the entire hammer gap. An "interposer" developed to eliminate these gaps (0.2 to 0.3 mm) is available for use in most of IBM's fully-formed-character line printers [25] [**Figure 15(a)**]. Made of 1.25-mm-thick polyamide sheet, the interposer is placed in front of the hammers when bar-code printing is desired. On impact, the interposer wraps slightly around the hammer and effectively increases the hammer width, adding the necessary pressure to the gap areas [26]. **Figure 15(b)** shows how the pressure is distributed with and without the interposer, demonstrating how the interposer causes the hammer pressure to extend across the gap. The proper curvature of the interposer at the hammer face corner avoids introducing shadow printing when text is printed without removing the interposer. Also, the print quality of text is not affected, as the thin, stiff polyamide layer does not effectively change the overall print-medium stiffness contacted by the hammer. In order to obtain high-quality bar codes, the polyester-film ribbons described above must be used.

There are basically two bar-code configurations, the picket-fence configuration and the ladder configuration. In the former, the bar-code symbologies comprise vertical bars and spaces; in the latter, the bar code comprises horizontal bars and spaces. Bar-code specifications, sponsored by the American National Standards Institute (ANSI) [27], require that the widths of bars and spaces be tightly controlled.

The characters appearing on the print band that are used to print bar codes are bar segments of various widths and positions. The necessary bar segments required to make a bar-code character are printed (and perhaps) overprinted until the desired bar-code character is completed. **Figure 16** shows a physical print-band layout of some bar-code segments for ladder and picket-fence configurations. As can be seen from this figure, the bar-code segments are intermixed with alphanumeric characters, so that text and bar code can be printed simultaneously.

For band printers, the vertical registration of printed characters or bar-code segments is better controlled than their horizontal registration. Thus, printing bar codes with the ladder orientation produces higher-quality bar codes. Bar codes produced in this manner on the IBM 6252 printer receive ANSI bar-code specification grades greater than B. Bar codes printed in the picket-fence orientation on this printer receive grades that are approximately one level lower (C to C+). Lowering the band speed improves this grade, but at the cost of lowering throughput.

One longtime limitation of engraved-band line printers is their inability to print with a character pitch different from the hammer pitch. Condensed printing is desired for some applications in order to print more characters on a given line. This has been accomplished on the IBM 6252 printer by means of a variation to the technology described for bar codes. In this case, the hammers strike an interposer unit made of an etched thin stainless steel plate containing comb-like fingers (**Figure 17**) [28]. The fingers, which have the shape of chevrons, are at a pitch of five fingers per inch, which is double that of the hammers. Each finger has a width that spans two hammer widths, has a face or pad that is approximately the same height as the hammer face, and is free to flex in the direction of hammer motion (normal to the plane of the paper). The gap between adjacent fingers is less than 0.1 mm, and there is a urethane layer on the side of the finger pads that is impacted by the hammer. This configuration is shown in **Figure 18**, for 15-character-per-inch printing. The horizontal location of three successive characters is shown by the letters *a*, *b*, and *c*.

The hammers are arranged so that the character to be printed at position *b* is at the interface between hammers *A* and *B*. For printing characters at position *a*, hammer *A* is activated; for characters at *b*, only *A* is activated (alternatively, only *B* might be activated); for position *c*, *B* is activated. The character arrangement on the print band is such that the character spacing must be in excess of the width of one interposer finger in order to avoid two characters being impacted simultaneously by an interposer finger. As can be seen, every other hammer may have to be activated twice in order to complete a print line, as did hammer *A* in the preceding example. This and the larger spacing of characters on the print band will cause a reduction in the printer throughput. The interposer can be removed when condensed print is not required.

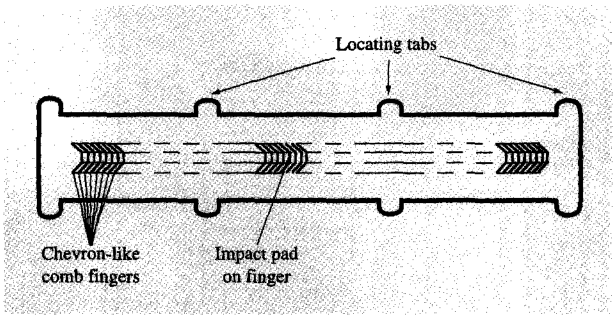

Figure 17

Condensed-print interposer.

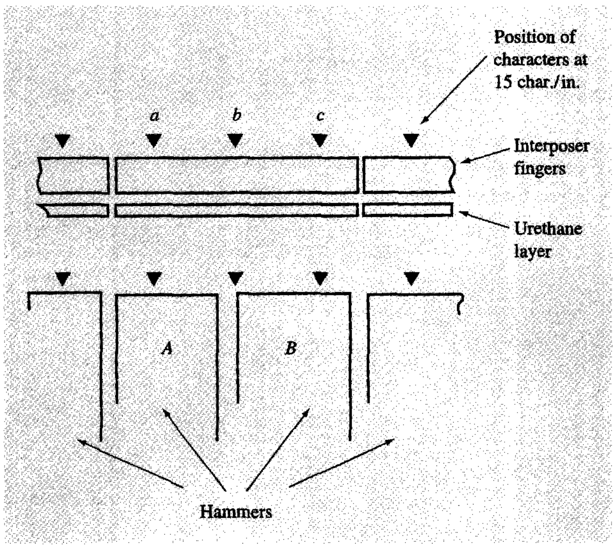

Figure 18

Condensed-print configuration for 15 characters per inch.

Matrix line printers

Basically, the subassemblies for matrix line printers and for engraved-character line printers provide similar function. The electromechanical subassemblies of the latter consist of a hammer unit, a mechanism to shuttle the hammer unit horizontally (in some cases, a band-drive system is used), a ribbon system, and a paper-handling system. The ribbon- and paper-handling systems, in fact, are quite similar to those found in the engraved-character line printers; thus, a very brief discussion will cover these areas.

The general operation of a matrix line printer is described in the Introduction. In brief, a horizontal line of dots is printed, the paper is incremented to the next dot row, and another line of dots is printed. This pattern of printing is repeated until the row of characters or the image is completed; then the paper is incremented to the next row of dots to be printed. High-speed skip is invoked where possible. For most matrix line printers, the printhead shuttles horizontally, printing one dot row as the printhead moves from left to right, and the next as the printhead moves in the opposite direction. The horizontal distance traveled by the printhead is equal to the distance between adjacent hammers plus the additional distance that the printhead must travel in order to decelerate and reverse its direction of motion. The velocity at which the printhead travels between dots, V_p, is

$$V_p \approx fP_h,$$

where f is the frequency at which the hammer is fired and P_h is the horizontal dot pitch.

The printer throughput, T, in terms of lines of text per unit of time is approximately

$$T = \frac{1}{N\dfrac{h}{V_p} + t_i(N-1) + t_1},$$

where N is the number of dots vertically used to construct a character, h is the hammer pitch, t_i is the paper increment time between rows of dots, and t_1 is the paper-increment time from bottom dot row to top dot row of the next character line. This assumes that the hammer-unit direction is totally reversed during the time that the paper is incremented.

Thus, low dot resolution (small number of dots both vertically and horizontally), a large number of print

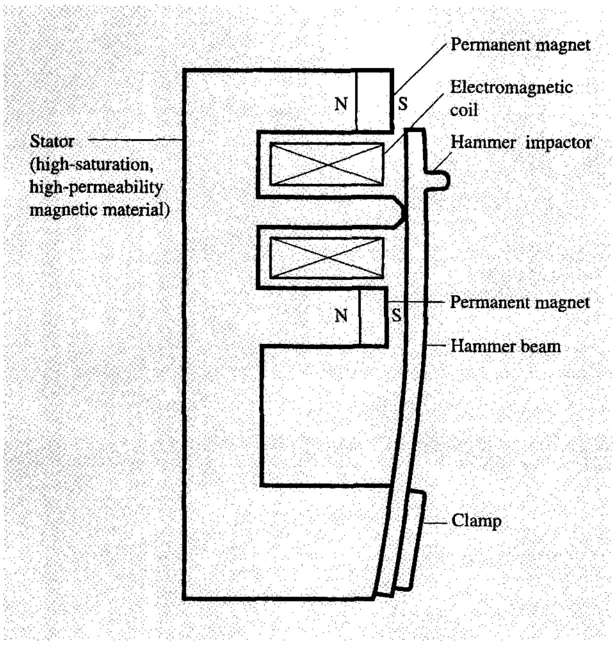

Figure 19

Stored-energy hammer.

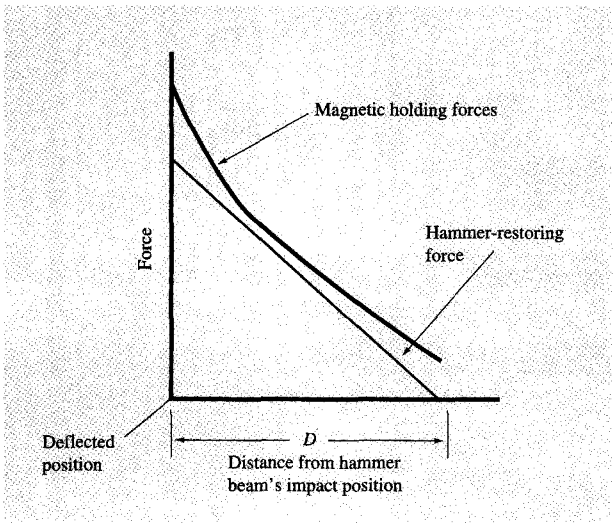

Figure 20

Beam and return magnet forces.

hammers (therefore, a small hammer pitch), a high hammer repetition rate, and a small paper-increment time lead to higher printer throughput.

- *Hammer unit*

A variety of hammer technologies are used in matrix printers: stored-energy, clapper, solenoid, etc. The requirements upon the hammer unit are that it produce an impact force high enough to create dots of high optical density, have a high repetition rate, and have a low hammer pitch. Reliability and low cost are, of course, always requirements.

Stored-energy hammer

A configuration for a stored-energy hammer is shown in **Figure 19**. Initially, the hammer beam is deflected and held by the magnetic path created by the beam and stator structure. When the electromagnetic coil is activated, the current creates a magnetic field that is essentially equal in magnitude but opposite in direction to that created by the permanent magnets. This allows the beam to be released and move more or less in free flight until the impactor strikes the ribbon and paper combination against the platen. The current to the coil is then turned off, and the permanent magnet returns the beam to its initial position. Thus, the print energy is related to the energy stored in the beam when it is in the deflected state. This is approximately equal to the area under the hammer-restoring force curve of the beam, shown in **Figure 20**. Since the magnetic force due to the permanent magnets is not totally canceled (because of magnetic flux leakage), the print energy is somewhat less than the stored energy in the beam. The magnetic force of the permanent magnet must be greater than the beam force to ensure that the beam will return to its initial position when no current passes through the coil. As stated previously, cycle time and impact force are key operating parameters in determining the performance of a matrix hammer. The impact force requirement is similar to that of fully formed characters, except scaled down by the ratio of the area of an average character to that of a dot. The energy stored in the beam of the hammer is converted into the matrix hammer impact energy. The beam geometry and its deflection can be used to determine impact force F [29]:

$$F \propto \frac{DE^{1/2}H^{3/2}b^{1/2}}{L^{3/2}},$$

where D is beam deflection (≈hammer stroke), E represents the modulus of elasticity for beam material, b is beam width, H is beam thickness, and L is beam length.

The beam, part of the magnetic path, is made from a material that has high magnetic saturation and permeability. The operating stress, σ, in the beam is also related to the beam's deflection and geometry:

$$\sigma \propto \frac{DEH}{L^2}.$$

Thus, the same factors that produce high print force also create high stress in the beam.

The permanent magnet holding force must be greater than the hammer-restoring force (Figure 20). This again limits the hammer design. Various methodologies are employed, such as tapered beams to provide uniform stress distribution, rare-earth materials for the permanent magnets, and more efficient magnetic paths to create higher magnetic holding forces.

Finally, the minimum cycle time of the hammer, t_h, is determined by the natural frequency of the beam and by the hammer stroke (distance from the hammer's holding point to the impact point):

$$t_h \propto \frac{L^2 d}{HE^{1/2}},$$

where d is the hammer stroke distance (somewhat less than D). It can be seen that in order to achieve a low cycle time, a small hammer stroke is desired, which is in conflict with having sufficient impact force. The balance and optimization of these conflicting relationships are described in [29]. In general, shorter strokes are used to obtain faster hammer cycle times; however, the stroke must be sufficiently large for the paper and ribbon to move freely. Today, strokes as small as 0.2 mm are employed.

Today, typical cycle times for an actuator are in the vicinity of 300 μs. Additional throughput is obtained through clever hammer-packaging schemes. Banks of more than 130 hammers mounted on a shuttle have been readily manufactured. Some matrix line printers manufactured by Hitachi have hundreds of print hammers. Typically, stored-energy hammer units are relatively efficient, with about 10–15% of the input energy converted to print energy.

Key areas that affect the life of the print-hammer unit are stator-pole-face and wire-tip wear. Using carbide wire tips dramatically reduces wire-tip wear and allows over one billion impacts per wire without significant wear. Pole faces are typically coated with a small layer (0.01 mm thick) of hard chrome. Other materials, such as titanium nitrite, have also been used. This also permits more than one billion impacts.

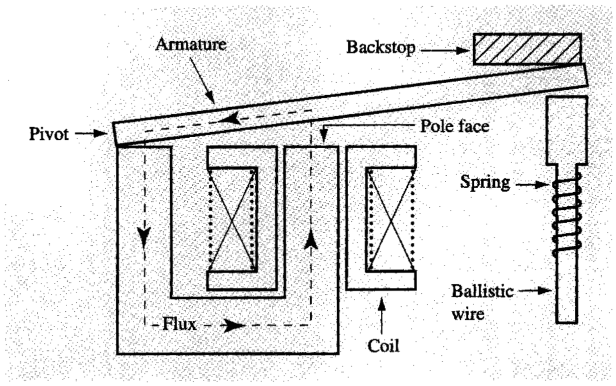

Figure 21

Clapper hammer.

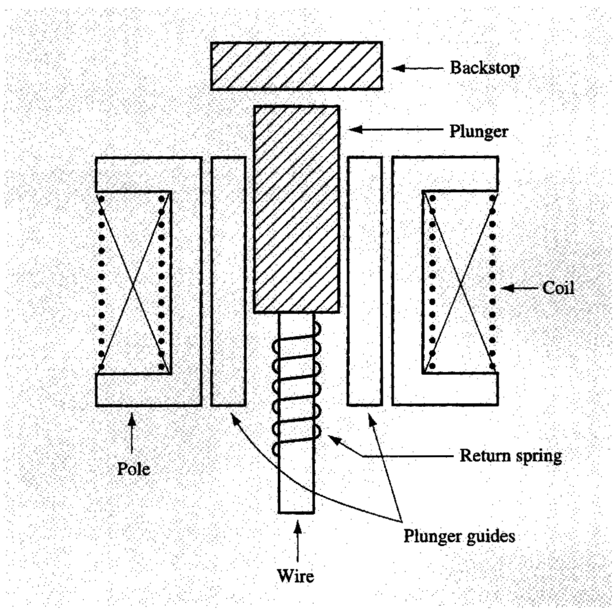

Figure 22

Solenoid hammer.

Clapper hammer

Another predominant hammer technology used for matrix printers is the clapper arrangement (**Figure 21**), in which two moving pieces are utilized, an armature and a ballistic wire, along with a stationary stator. The armature completes a magnetic path and transforms the magnetic energy into the kinetic energy of the ballistic wire. When the coil is energized, the armature is attracted to the pole face, thus propelling the ballistic wire. When the armature hits the pole face, the wire goes into free flight, then strikes the paper, ribbon, and platen and returns to its initial position. The return spring and the damping in the backstop ultimately cause the wire and armature to settle in their initial positions. An efficient magnetic path (coil close to gap, laminated armature, high-saturation magnetic materials), optimized armature configuration (mass, armature stiffness, pivot-to-pole distance, pivot-to-armature-tip distance), optimum materials (backstop

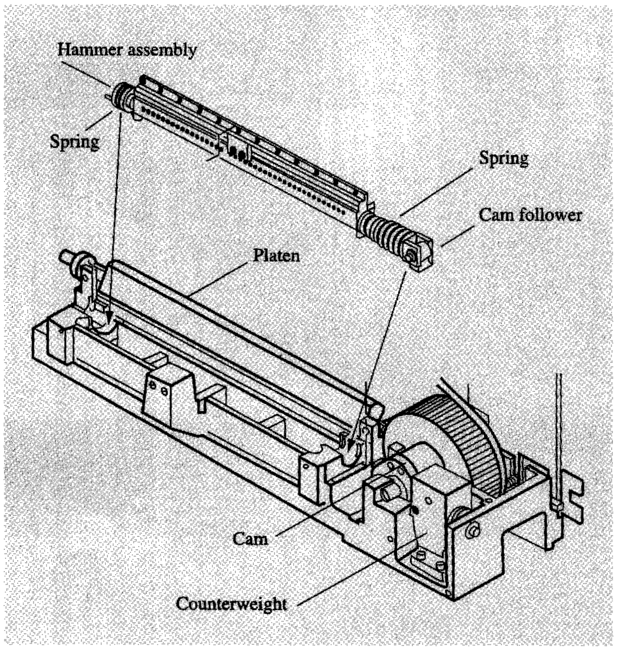

Figure 23

Shuttle assembly.

damping, material on pole face to prevent wear, magnetic properties of pole), and optimized drive-pulse shape are the keys to obtaining high performance and high reliability. Today, hammer cycle times of 300 μs along with a life greater than one billion impacts have been obtained.

Solenoid hammer

Yet another hammer technology employed is that of a solenoid variety, illustrated in **Figure 22**. Here, the wire is attached to the plunger. When the coil is pulsed, the plunger moves in order to be aligned with the pole at a minimum-energy configuration. This arrangement has evolved so that the poles and plungers are toothed, in a stepper-motor fashion, so that higher-acceleration forces are obtained. High performance is obtained by small pole-to-plunger gaps, multiple-toothed poles, efficient damping on the solenoid return, and pulse-shape optimization.

Spot size

As previously mentioned, the hammer print force must be high enough to obtain high print density but low enough to avoid ribbon damage. A typical print wire is approximately 0.3 mm in diameter, so that the printed spot is approximately 0.4 mm. When a smaller spot size is required, a smaller wire diameter must be used. The print impact force must be decreased to avoid ribbon damage, while a fast cycle time is still required. This can be accomplished only through the use of lower-mass actuators, which tend to be less efficient. Wires as thin as 0.15 mm in diameter have been employed in specialized matrix printers.

- *Shuttle mechanism*

For matrix line printers, two techniques are used for moving the dots horizontally: a shuttle system and a print-band system. In a shuttle system (the more predominant approach), the hammer unit is physically attached to a carriage or carrier that is shuttled horizontally. One configuration of a shuttle system consists of a cam directly attached to a motor, as shown in **Figure 23.** The cam is in contact with the carriage on one side and a counterweight (to reduce vibration) on the other. As the motor rotates, the lobes on the cam cause the carriage and counterweight to move in opposite directions.

In a print-band arrangement, as shown in Figure 3, the hammer unit is stationary, and a continuous band of chevron-shaped, flexible fingers, containing very short wires on the paper side and impact pads on the hammer side, passes horizontally by wide-faced hammers. In this arrangement, each hammer is actuated, causing the hammer to strike the impact pad on the print finger in front of the hammer, propelling the print finger toward the paper. The wire on the finger compresses the paper and ribbon against the platen, thus printing a dot. When the print band has moved horizontally the distance of one pel, the hammers can be activated again. In this manner, a line of dots can be printed.

- *Ribbon system*

As previously stated, the ribbon system in matrix printers is essentially the same as that for fully-formed-character line printers. One notable exception is the use of devices to re-ink the ribbon during printer operation, providing high optical density continuously. However, during occasional printing tasks that require sparse printing, excess ink is usually deposited on the ribbon, leading to unsightly smearing. (The solutions to this problem are too complex to be described here.) For bar-code printing (an important application for matrix printers), in order to provide the higher optical densities required by bar-code scanners and wands, special ribbons are used that have relatively high carbon content in the ink.

- *Paper handling*

The paper-handling system in matrix line printers is similar to that for fully-formed-character line printers, with some exceptions: Relatively small paper increments are employed (one pel vertically) in matrix line printers. High-speed automatic paper stackers are not usually employed in matrix line printers, since their print speeds are not greater than 1500 lines/min. High-speed paper skip speeds are utilized, but these speeds are generally less than 0.5 m/s.

Modes of operation

The main advantages of matrix line printers with respect to fully-formed-character line printers are their flexibility with respect to print quality and their graphics/image capability. For printing text, many matrix line printers can be run in three print-quality modes: draft, normal, and near-letter-quality. The difference between these modes has to do with pel density and speed. Characters printed in the draft mode are often only five dots high, with a vertical dot density of approximately 70 dots/in. In the normal mode, characters may have a vertical density of 90 dots/in. and be nine dots high. The horizontal density for both modes is approximately 60 dots/in. For the near-letter-quality mode, dot densities of approximately 150 dots/in. vertically and 120 dots/in. horizontally are used. Print quality in all of these modes is improved by allowing for double or even triple the horizontal addressability. This means that a dot associated with any horizontal location can be printed, provided that the horizontal distance between it and the neighboring dots is no smaller than the base dot pitch, P_h.

Since matrix-printer throughput is directly related to the horizontal and vertical dot densities, doubling dot densities in both vertical and horizontal directions results in a fourfold reduction in throughput. Thus, the print quality and speed trade off.

Additionally, matrix printers can be operated in a graphics mode, which uses dot densities similar to those of near-letter-quality-text mode. Matrix printers are the predominant technology for bar-code printing when the minimum bar dimension is greater than 0.1 mm. The inherent advantages of impact printers, such as ruggedness, ease of printing in harsh environments, and printing on many types of forms, account for this.

Color is rarely utilized in matrix line printers but is found to some extent in matrix serial printers (described later).

Advances in noise abatement for matrix printers have resulted in noise levels below 53 dB. This has been accomplished through hammer-unit design, use of acoustic foam on internal cover surfaces, improved sealing, and use of energy-absorbing materials on impacted surfaces.

Continual improvements in manufacturing have allowed matrix impact printers to remain the lowest-cost printing technology.

Matrix serial printers

As previously described, matrix serial printers (see Figure 2) create characters in a serial manner as a printhead traverses the page. Printing is performed while the head is moving in either direction. The main electromechanical subassemblies are the printhead, ribbon system, paper-handling system, and carriage upon which the printhead and ribbon assemblies are mounted.

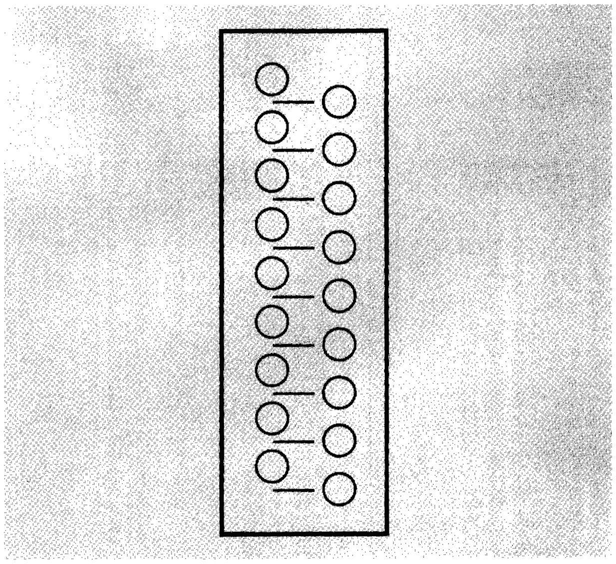

Figure 24

Matrix printer printhead faceplate, illustrating two staggered columns.

The printhead assembly makes use of the same print-hammer technologies described in the section on matrix line printers. The main difference is the packaging of the hammers. The wires emanating from the faceplate of the printhead are tightly packaged. There are generally two columns of wires that are vertically offset from one another by a vertical pel distance (**Figure 24**). The number of actuators or hammers used in a printhead varies from as few as nine (covering the height of one print line) to as many as 48 (covering multiple print lines). In order to have sufficient volume for the electromagnet part of the actuator, a configuration similar to that shown in Figure 2 is used, in which one end of the print wire is attached to the armature and the other end is routed through a wire guide and out the faceplate of the printhead. The armatures and coils are usually arranged in a circle. As with the matrix line printhead, cycle times of approximately 300 μs have been obtained. Short cycle times are obtained by the use of very short distances between the wire tip and the platen (approximately 0.2 mm), stiff armatures, and carefully designed magnetic paths. In many printers, the distance from the wire tip to the platen is accurately and automatically controlled by moving the printhead up to a sensor. The printhead is then backed away from the sensor in a controlled and

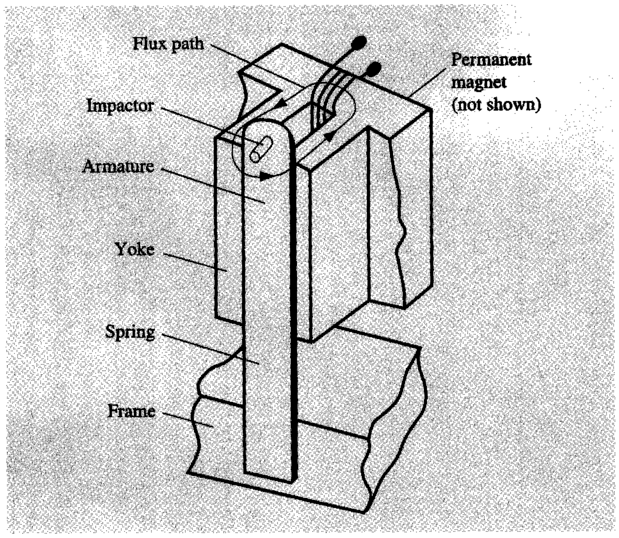

Figure 25

High-speed matrix printer actuator.

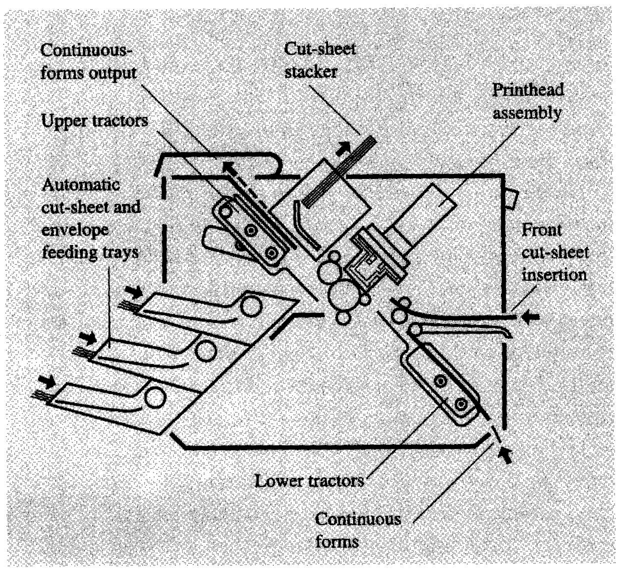

Figure 26

Multiple paper-feed system of the IBM 4247 printer.

measured manner. A particularly fast actuator is shown in **Figure 25**. This actuator makes use of an efficient magnetic path that employs fringe fields at the edge of the armature.

Many matrix printheads have aluminum fins attached to the armature section. The finned structure conducts heat away from the armature area. During the lateral motion of the printhead, ambient air passes over and around the fins, convecting heat away from the finned structure.

If the print wires on the faceplate are arranged in a vertical line, all of the wires can be struck at the same time, maximizing the noise generated. In order to reduce the noise, a different geometrical configuration (often diamond-shaped) can be used. If no two print wires are aligned vertically, the wires strike the paper/ribbon combination more or less one wire at a time. Thus, the peak noise level is reduced, resulting in greater human comfort. Noise levels as low as 52 dB have been obtained, allowing this type of impact printer to be readily used in an office environment.

Some printers are designed with a thermal measuring element in or near the printhead's hammer unit. If the temperature exceeds a certain level (usually because of a very high-density print pattern), the printer electronics will slow the printing rate down until a suitably low temperature is obtained.

The printhead is rigidly attached to a carriage that horizontally traverses the printer (and paper). The carriage is supported by guide bars and is often driven by a leadscrew–motor combination, although a cable–pulley system is sometimes used. A linear emitter arrangement between the printhead and platen is utilized to determine printhead location and velocity. The emitter output is used to control the carriage velocity and the firing of the print hammers. Sometimes the control emitter is located in the motor driving the carriage.

The ribbon-drive system typically consists of a small cassette containing about 7 m of ribbon. The cassette is usually affixed to the carriage, although some configurations have it attached to the frame. The ribbon is pulled out of one side of the cassette and fed into the other side. The drive motor is very inexpensive; in some cases, the ribbon is driven indirectly by the carriage drive motor. A Moebius strip is sometimes employed to improve ribbon life; i.e., a twist is put into the ribbon so that alternating sections of the ribbon are presented to the printhead during successive passes of the ribbon.

Matrix printers were the first to print color graphics. This is accomplished by means of a four-color ribbon (cyan, yellow, magenta, and black) and the subtractive color process. The ribbon can be configured in a variety of ways. Typically, it consists of a horizontal stripe of each color with a border or dam between them to prevent ink migration. To print a line of color, one pass must be made by the printhead for each color. Between passes, the ribbon is moved vertically, presenting a new color stripe in front of the printhead. Only the necessary number of passes are made. For example, if only blue text is to be printed in a line, two passes are made: one with the magenta stripe in front of the printhead, and one with the cyan stripe. Typically, dyes are used in the ribbon, since pigments contain hard particles that tend to wear out the wire tips.

The paper feed systems in many of today's matrix printers are quite sophisticated. **Figure 26** depicts the multiple paper-feeding capability of the IBM 4247 printer. Continuous forms (single and multipart) can be fed in from the bottom of the printer by the upper and lower sets of tractors. With a rearrangement of the tractors, continuous forms can be fed in from the top of the printer as well. In either case, they are stacked in the continuous-forms output area. Automatic cut-sheet and envelope feeding are available from three separate paper feed trays. Individual cut-sheet insertion from the front of the printer is still another mode of paper handling.

Conclusions

The general simplicity of impact printing, i.e., an actuator impacting ribbon and paper to create a mark, translates into low cost and high reliability. Additionally, this printing can take place on the widest variety of forms and with the largest tolerance to environmental conditions (temperature, humidity, dust, etc.).

Advances made in print actuator design over the past ten years have led to an effective quadrupling in printer performance. Additional improvements in function such as bar-code capabilities, condensed print, paper handling, and noise abatement have enabled impact printing to remain an important printing technology.

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