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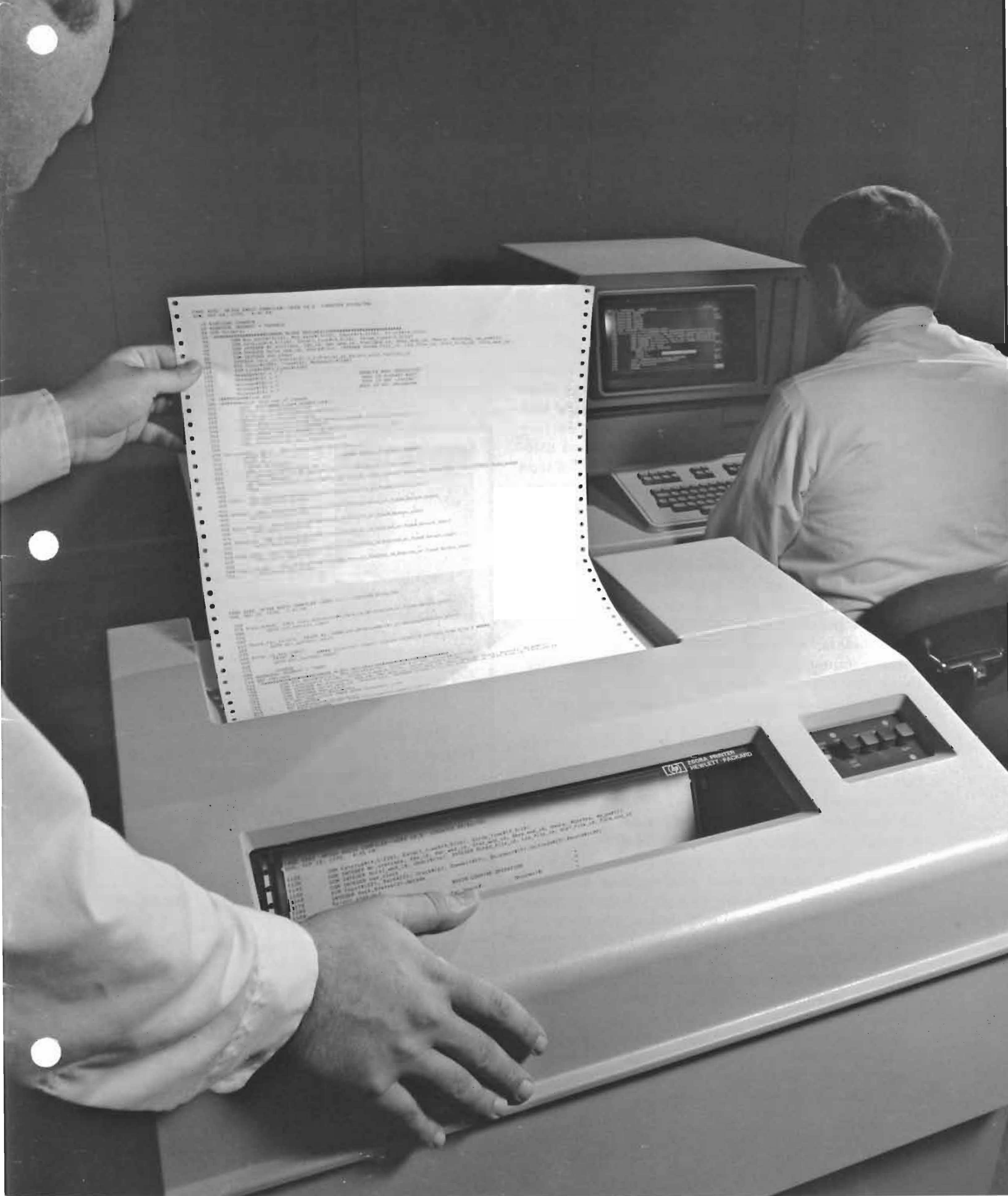


Versatile 400-lpm Line Printer with a Friction-Free Mechanism that Assures Long Life

This medium-speed line printer writes dot-matrix alphanumerics and graphics with a mechanism that has no sliding parts or bearings to wear out. It's also versatile, with a capability for printing with a variety of character sets.

by F. Duncan Terry

THE TRANSFER OF INFORMATION from a computer to a printed page can be done with any of several different techniques at various speeds in a variety of modes. For most small computer systems, especially those directed towards the scientific and small business markets, the impact printing technique is favored because it allows printing on multicopy forms using standard paper. Impact printers commonly used in small systems print with speeds ranging from 120 characters per second to as high as 1000 lines per minute.

Described in the previous articles in this issue is a serial-character printer (Model 2631A) using a horizontal-scan, dot-matrix, impact printing technique capable of printing at speeds of 180 characters/second. This article describes a new medium-speed line printer (Model 2608A) that uses a combined horizontal- and vertical-scan, dot-matrix technique to achieve print speeds of up to 400 lines per minute, equivalent to nearly 800 characters per second. With this speed, the new printer (Fig. 1) can fulfill the majority of printing needs in the small computer field. It also offers the system programmer a new dimension in system interaction with a line printer.

Basic Operation

The printing technique used in the new printer is similar to that used in the HP Model 2607A Printer but a new mechanism was designed to achieve higher speed and greater ruggedness. The basic printing operation is the energizing and release of a cantilever steel tine (hammer) by an electromagnet (Fig. 2). To print a dot, the magnet draws the tip of the hammer away from the paper and then releases it. When released, the hammer snaps forward and a tungsten-carbide sphere welded near its tip impacts the ribbon against the paper and platen, printing a dot 0.45 mm (0.018 inch) in diameter.

To print a complete character, the hammer and magnet are moved horizontally five dot positions, and dots are printed in the positions required by that

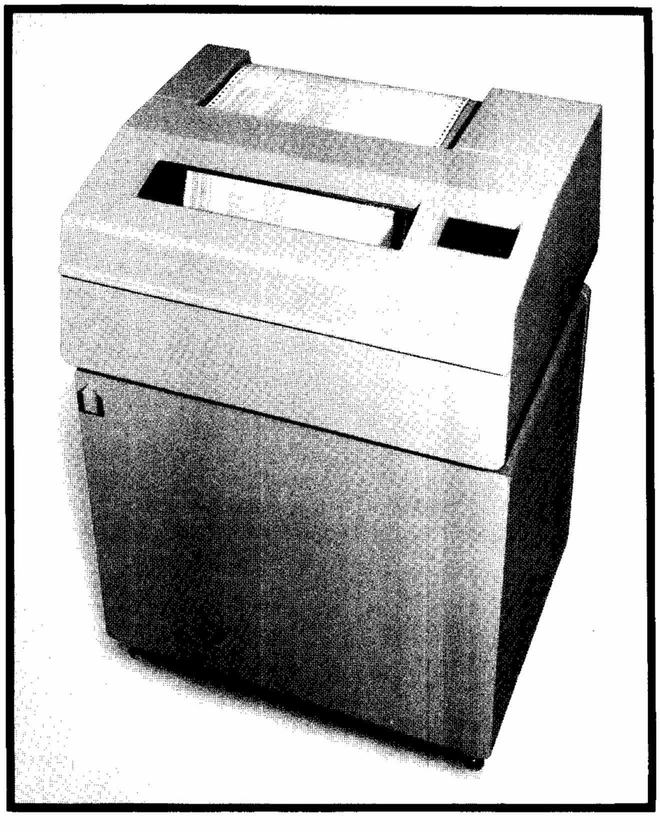


Fig. 1. *Model 2608A prints 132 columns of characters on standard 14-inch wide computer paper at speeds up to 400 lines/minute when printing upper case only with a 5 × 7 dot matrix, or to 320 lpm when printing upper and lower case with a 5 × 9 dot matrix. As many as 16 different character sets can reside within the printer, any two of which may be used within any line, and the normal dot matrix can be expanded for special print characteristics. Forms with as many as six parts can be printed.*

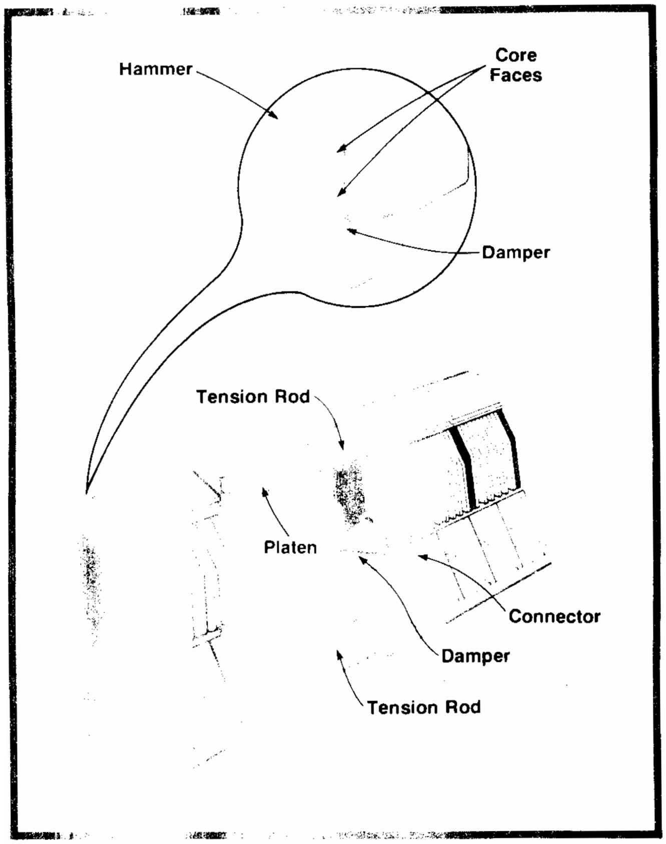


Fig. 2. *Print hammer mechanism. Eleven modules holding twelve hammers each are clamped together by two tension rods to form a rigid bar that is moved back and forth by a linear (voice-coil) motor.*

character in that particular row of the dot matrix. The paper is then advanced 0.353 mm (0.0139 inch), the hammer and magnet reverse direction, and the next dot row of the character is printed. Seven rows of dots complete an upper-case character (Fig. 3). For lower case characters, two more dot rows print the descenders, if required.

The mechanism has 132 hammers, spaced on 2.5-mm (0.1-inch) centers, that move horizontally as a unit. Any combination of hammers can be fired simultaneously, depending on the information being printed. The paper is pulled through the machine in discrete steps, one dot row at a time, and after each advance, the hammer and magnet assembly moves horizontally to print all the dots in that row for all the characters on that line.

New Directions

This technique has proven to be versatile, reliable, and cost-effective. It has, in fact, proven to be capable of generating some of the most uniform and readable multicopy print from any type of printer because each dot is printed with the same intensity, a characteristic that is most noticeable when several carbon copies are being made. This is in contrast to full-font printers where a low-density character, such as a period (.), receives the same impact force as a high-density character, such as the number sign (#), with resulting variations in print intensity.

It was felt, however, that the basic mechanism had a potential for higher speed and also for printing graphics. In addition, the use of a microprocessor for control could add a high degree of versatility. Therefore, a major redesign was initiated. To take full advantage of the basic reliability and flexibility of this method of printing, extensive analysis of the printing action was undertaken, leading to major design changes and improvements in the mechanism. The electronics were completely redesigned.

During the design phase, the project focused on three main objectives.

The first was to fully exploit the fundamental advantages of the print mechanism.

High reliability is characteristic of the print hammers because each is a simple mechanical spring with no bearings or sliding parts to wear out. This concept was extended to the horizontal movement of the hammer assembly, which is now mounted on metallic flexures, achieving a virtually frictionless print mechanism. Print uniformity is enhanced by moving the electromagnets horizontally with the hammers rather than moving the hammers only. This maintains a uniform magnetic field and reduces the problem of cross-talk between adjacent characters at the extreme excursions of the hammer assembly. It also allows the hammers to move a greater distance so dots can be placed in the between-character spaces for printing graphics. Also, the hammer assembly is now moved by a friction-free voice-coil-type linear motor, which allows the stroke length to be changed easily for printing graphics. Print speed was more than doubled by

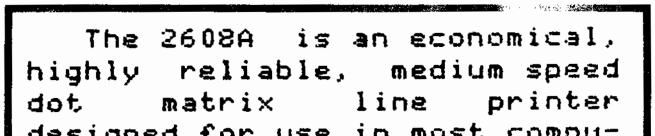

The 2608A is an economical, highly reliable, medium speed dot matrix line printer designed for use in most computer applications. Printing at 400 lines per minute, utilizing a high resolution matrix, offering special user features such as graphics, multiple character sets, 16-channel VFC and double size characters, the 2608A is a printer designed with today's systems in mind, rugged enough for EDP applications, yet quiet enough to be

Fig. 3. *Dot-matrix printing performed by the Model 2608A Line Printer is reproduced full-size here.*

driving the hammers near their resonant frequency, by improving the hammer damping characteristics, and by using better materials.

The second was to enhance system flexibility in a cost-effective manner.

Microprocessor control made it feasible to offer multiple character sets, double-sized characters, full-scan graphics, overstriking for underlining or creating APL characters, and a 16-channel vertical format control (VFC) that is fully electronic and can be initialized either from ROM or by software. Self-test routines exercise all features of the printer to give assurance that the printer is functioning properly. A number of status indicators are now available to the host system.

The third was to enable the printer to fit in a wide variety of environments.

The compact appearance disguises the fact that the new printer is a rugged, workhorse machine. Low acoustical noise (72 dBa standard, 68 dBa optional) allows its use in systems that are to be placed in sensitive environments. The 100-metre (∼100-yard) ribbon, capable of printing 30 million characters, is contained in an easily changed, smudge-free cartridge. Modular construction minimizes maintenance costs.

These and other characteristics are described in more detail in the article that follows.

Acknowledgments

Many thanks are due Jim Barnes, R and D manager, who guided and supported the project from its inception, and to Don Bowman, who was project leader until transferring to production. In addition to contributions from those mentioned in the following article, significant contributions were made by Tom Baker, who did major portions of the mechanical design and Randy Mazzei, who did the industrial design. Ralph Tenbrink and Al Olson worked out the difficult manufacturing processes. Lamar Goats performed the reliability verification testing and Gary Gapp did the product performance testing. Other contributors were John Meredith, Mike Harrigan, Ross Casey (mechanical), Tom Holmquist (electrical), and Darrell Cox (ribbon).

F. Duncan Terry

With HP since 1969, Duncan Terry was responsible for the design of the 2630 family of printers and the 2608A line printer. Prior to joining HP's Boise Division, Duncan designed logic state analyzers at HP's Colorado Springs Division. The author of several papers on nuclear radiation and electronics, he is also named inventor on two patents relating to test instruments. Born in Lander, Wyoming, Duncan received his BSEE degree in 1962 and his MSEE degree from the University of Wyoming. Duncan is married, has two daughters (ages 14 and 11) and in his off hours, he spends his time camping, hunting, hiking and working on home electronics.

SPECIFICATIONS

HP Model 2608A Line Printer

PRINTING

TECHNIQUE: Impact

CHARACTER FORMATION: Dot matrix, 5×7, 5×9, 7×9.

GRAPHICS MODE: 924 dots per line at 70 dots per inch × 72 dots per inch vertically. In the graphics mode, the printer interprets each data byte as eight horizontal dot positions and prints dots where 1's occur e.g. 323_8 = 11010011 = ●● ● ●●).

LINE LENGTH: Up to 132 characters.

PRINT SPEED

MATRIX SIZE	LINES PER MINUTE
5×7	400
5×9	320
7×9	250

40 dot rows per second with the maximum 924 dots per line in the graphics mode.

LINE FEED RATE (6 or 8 lines per inch): 15 ms.

FORM FEED RATE: 357 mm (14 in) per second.

VERTICAL FORMAT CONTROL: Electronic control, 16 programmable channels. Standard channel definitions and assignments are available from internal ROM, or forms may be defined and channels assigned by an external data source.

FORM WIDTH: 130 mm (5 in) to 385 mm (16.16 in) edge-to-edge.

PAPER WEIGHT:

SINGLE PART: 20 lb up to 100 lb.

MULTI-PART: Up to 6 copies with 12 lb paper and 7 lb carbons (0.61 mm maximum pack thickness). Multipart forms and card stock should be tested for satisfactory feeding, registration, and print quality.

POWER: 100, 120, 220, 240 Vac +5%, −10%, 48-66 Hz, 700 VA typical, 1500 VA max when printing; 225 VA non-printing.

SIZE (including stand): 1042 mm H × 680 mm W × 555 mm D (41 × 26½ × 22 in)

WEIGHT (including stand): 97 kg (215 lb).

ENVIRONMENTAL

TEMPERATURE

PRINTER: 0 to 55°C (32 to 131°F) operating; −40 to 75°C (−40 to 167°F) non-operating.

RIBBON: 10 to 50°C (50 to 122°C) in use or in storage.

RELATIVE HUMIDITY: 5% to 95% non-condensing. Forms should be tested at high humidity for satisfactory feeding and handling. At low humidity, forms should be tested to determine if static build-up should be eliminated for proper stacking.

AUDIBLE NOISE (using ISO 3744 as measurement standard): 72 dBa operating, 55 dBa in standby. Optional sound cover reduces operating noise level to 68 dBa.

CONTROLS AND INDICATORS

POWER ON indicator
ON LINE/OFF LINE button and indicator
FAULT CONDITION indicators
  PRINT MECH PLATEN RIBBON
  PAPER OUT TEST FAIL
FORMS ADJUST UP/DOWN buttons
POWER ON/OFF switch on rear panel
POWER ON CONDITIONS
  6 or 8 LPI
  PRIMARY LANGUAGE (1 of 16)
  SECONDARY LANGUAGE (1 of 16)
FORM FEED button
LINE FEED button
6/8 LPI button and indicator
RESET button
SELF TEST button and indicator

INTERFACE:

STANDARD: Differential line driver compatible with the HP 26099A interface board for 2100 and 1000 series computers, and the 30209A interface board for 3000 series computers.

OPTIONAL: HP-IB, HP's implementation of IEEE Standard 488-1975 and ANSI MC1.1.

OPTIONS: Sound cover. Language options include Arabic, Cyrillic, Katakana, and Draw; character options include APL, French, Ferman, Swedish/Finnish, Norwegian/Danish, Spanish, British, Japanese ASCII, Roman extension.

PRICE IN U.S.A.: $9250.

MANUFACTURING DIVISION: BOISE DIVISION
11311 Chinden Boulevard
Boise, Idaho 83707 U.S.A.

Optimizing the Performance of an Electromechanical Print Mechanism

by Everett M. Baily, William A. McIlvanie, Wallace T. Thrash, and Douglas B. Winterrowd

THE SPEED OF ANY MECHANICAL SYSTEM is usually limited by effects that result from controlling the acceleration and/or deceleration of critical parts. Finding the causes of certain effects and minimizing them so printing speed could be increased was a major design goal for the Model 2608A Line Printer.

Details of the print hammer mechanism in the 2608A are shown in Fig. 1. The longer beam (or tine) is the hammer and the shorter beam is the damper. To print a dot, the electromagnet is energized, pulling the hammer back against the core face. This stores enough energy in the hammer so when the electromagnet is de-energized, the hammer flys forward and strikes the paper through the ribbon with enough impact to leave a crisp dot. The hammer then rebounds and collides with the damper on the return stroke, reducing excessive residual motion of the hammer.

Between release and impact, the beam moves freely at a rate determined by its natural resonant frequency, which is about 400 Hz. The principal advantages of allowing the hammer beam to impact the platen at its natural frequency are speed and the relatively low power required—if the core is energized again to print an adjacent dot, the hammer will already be moving towards the core face.

The disadvantage is the tendency for the hammer to "overstrike", that is, to rebound from the damper and print an unwanted dot. In earlier implementations of this printing technique, this problem was handled by making the print speed slow enough to place overstrike dots roughly in coincidence with the printed dot.

One way to allow an increase in print speed would be to increase the resonant frequency of the hammer beam. The relationships involved are:

$\omega : h/l^2$, where ω = the resonant frequency;
h = hammer thickness;
l = hammer length.

$\sigma : hy/l^2$, where σ = stress;
y = displacement.

$E : \sigma^2 lh{:}y(h/l)^3$, where E = strain energy.

To raise the resonant frequency, either the thickness can be increased, or the length can be reduced. Because of a number of material-availability, processing, and tolerance problems, the hammer thickness is limited to a practical value. Since a certain amount of strain energy needs to be imparted to the hammer for good print quality, reducing the length of the hammer would increase the stress, raising it above the maximum permissible for good fatigue life. Thus, there are practical limits to raising the resonant frequency.

Another way would be to improve the damping mechanism so overstrike would be eliminated altogether. Specifically some means had to be found to limit residual motion in the hammer to something less than that needed for a visible overstrike.

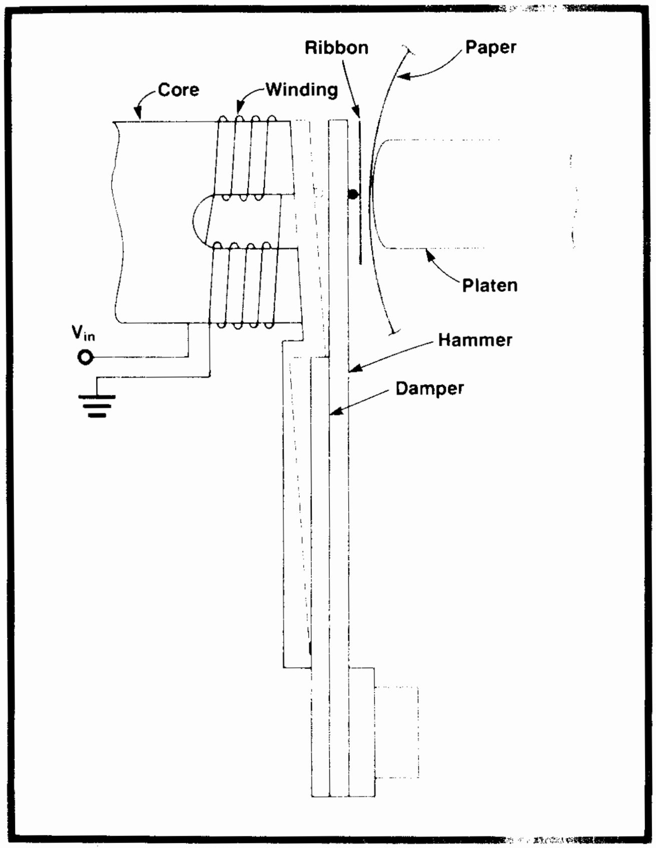


Fig. 1. *Details of the model 2608A's print mechanism. To print a dot, the electromagnetic core is pulsed, pulling the hammer back against it and then releasing it to fly forward, printing the dot.*

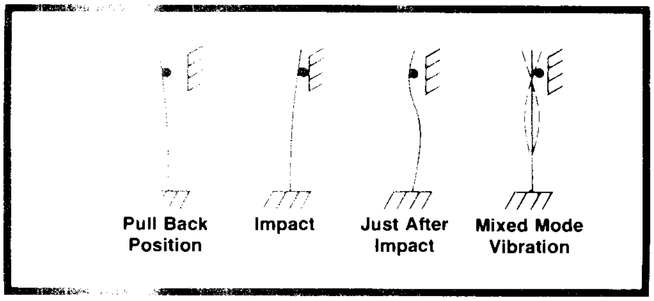


Fig. 2. *Basic hammer motion. Impact redistributes energy in the fundamental resonance mode to higher modes.*

Analyzing Overstrike

The main variables affecting residual motion are impact location, expressed as a percentage of hammer length, and the damper-to-hammer length ratio. Other variables are thickness and width but these had already been determined by overriding criteria.

Ordinary steel rules make useful large-scale models for observing the residual motion of a hammer. As shown in Fig. 2, the impact location, which acts as a temporary node point, is in the vicinity of the natural second node point for a cantilever beam. The action of impact redistributes the residual energy in the hammer beam into higher modes, reducing the amplitude of the fundamental motion. Experimentally it was found that the optimum impact location from the tip is 13% of the hammer length, 9% above the second node point. Furthermore, the model suggests that maximum damping occurs when the second-mode frequency of the hammer is a multiple of the dominant fundamental mode of the damper (not shown in Fig. 2). Experiments showed that the optimum multiple is 2. With this configuration, overstriking would be minimized over a practical range of parameter variations.

In going from the scaled-up thin-section model to an actual size thick-section model, however, performance was not the same. There was enough residual fundamental motion after impact to cause occasional overstriking. Sensitivity to parameter variations was much greater too. These performance differences might be explained by the rate at which energy in the hammer is dissipated, primarily in the form of acoustic energy coupled to the air. As the equations show, the strain energy increases as the cube of the thickness, but since energy dissipation into the air is proportional to frequency, which increases linearly with thickness, the damping ratio goes down in proportion to thickness. Intuitively speaking, the thicker hammer is stiffer and less affected by its surrounding medium.

It was therefore proposed, and confirmed by experiment, that the introduction of a magnetic damping pulse would obtain the results desired. The pulse is timed to occur as the hammer rebounds from the damper and is on its way towards an overstrike.

Further Analyses

The complexity of hammer motion led to further studies using a high-speed camera (40,000 frames/s). This provided excellent qualitative information, but quantitative data was hard to derive so the next step was to design a computer model of the hammer mechanism and simulate the dynamic processes digitally. This allowed us to simulate different combinations of operating conditions and parameters.

A finite element technique was used for the analysis. The hammer and damper beams were modeled as one-dimensional beam elements, i.e., only one degree of deflection and rotation were allowed at each node, and the deflection due to shear was neglected.

According to the simulation, the hammer imparts energy to the damper when they collide, but the collision propels the hammer back towards an overstrike. Experimentation with the location of the impact point, the ratio of the fundamental frequencies of the hammer and damper, and the gap separation between

Acoustic Design of the Model 2608A Line Printer

With as many as 132 hammers impacting the paper and platen during printing, it was inevitable that the Model 2608A's printing mechanism would generate some noise. In fact, prototypes demonstrated 90+ dBa sound-pressure levels. To make the printer a welcome participant in an office environment, a noise abatement program was initiated.

Because of the rigidity required in the printing mechanism, no attempt was made to apply any vibration isolation to the working parts. Instead, attention was directed towards attenuating acoustic radiation from openings in the printer's enclosure. Hence, the access cover was designed with a labyrinthine-foam seal around the edges. The stand is foam lined and totally enclosed, except for vents near the floor for cooling air input. The paper box is contained within this stand so noise leaving the machine by way of the paper inlet slot is attenuated by the stand. The cooling fan inlet is also in the stand and the cooling vents are at the rear, away from the operator.

An optional removable shroud encloses the paper outlet at the top of the machine and effectively moves this sound escape outlet to the rear of the machine.

To prevent the taut paper from acting as a soundboard where it leaves the platen, a plastic cover clipped on to the top of the core bar presses into the paper just above the platen (see the diagram in the box on page 26). This not only damps paper vibration, but it also reduces the area of paper affected by hammer action.

Although the resulting external sound levels are highly room and geometry dependent, they are in the range of 72 dBa. With the optional shroud, the sound level is 68 dBa, about the same as an electric typewriter and quieter than many nonprinting computer peripherals.

-Lynn Hessing

them confirmed that the combination of parameters found empirically was the optimum for suppressing overstrike.

The magnetic damping pulse was also implemented in the simulation. The simulation showed that the timing was critical; firing the pulse too late would provide insufficient damping, and firing it too soon would delay but not prevent overstrike. Simulation showed that for a given amount of magnetic core force, a pulse fired 3.3 ms after the print pulse and sustained for 0.5 to 0.7 ms would be most effective in suppressing overstrike. This was close to the optimum values found experimentally.

Driving Circuits

With the hammer design optimized, design of the hammer drive circuits could be completed. The design goal was efficiency with cost as a tempering factor. The number of drive circuits (132) dictated that each drive circuit have minimal complexity.

The approach chosen was to use a single high-power pulsed source and to use silicon-controlled rectifiers (SCRs) to switch the current to the appropriate hammer drive coils. The SCRs are driven at the TTL level by a shift register.

Pulsed drive was chosen so SCRs could be used. Since these are inherently latching devices, turn-on information needs to be present only at the beginning of the power-pulse cycle. This makes the remainder of the cycle available for loading the next dot information into the shift register.

The optimum drive voltage for the hammer coils is 18-20V for 1.5 ms. The coil current peaks at 1.5A, and since any number of coils up to 132 may be energized simultaneously, the total power-pulse current can be as high as 200A. The energy losses in generating, filtering, and switching 200A at 20V would have been prohibitively high using conventional techniques, not to mention the size of the necessary filter capacitors. The method chosen was to use a coarsely-regulated (±5%) 270V dc supply and an iron-core step-down transformer. Two power Darlington transistors switch the 270V to the transformer to generate the power pulses. The power switching thus takes place at a relatively low current level (<15A).

A block diagram of the core driving circuit is shown in Fig. 3. The dot control information is transferred from the microprocessor in serial form and held in an input register until the logic circuits shift it into the trigger register. As soon as the power pulse has been initiated and the indicated hammers fired, the dot information is shifted out of the trigger register into the damping register. At the same time, the previous dot information held in the damping register is shifted back into the trigger register. A delayed trigger is then applied to SCRs controlling those coils that were energized during the previous dot position but not the present one. This provides damping for those hammers now rebounding from the damper beams. The delayed trigger has no effect on SCRs that are fired in both the present and previous dot positions because they would be turned on already.

Mechanical Construction

The magnetic cores for the hammer drive are made of Hyperco-50 (vanadium permendur), a material that

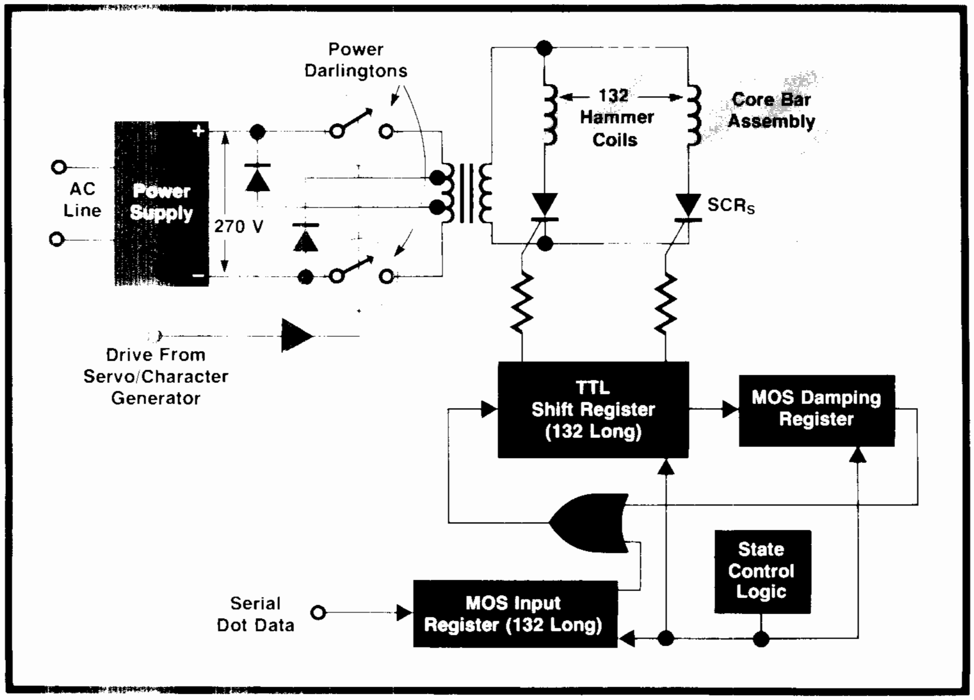


Fig. 3. *Block diagram of hammer drive circuits. A power pulse is applied to all hammer coils simulateously but only those coils that are switched on by the SCRs will be energized.*

provides one-third higher flux density than ingot iron. Since the same magnetic field intensity could be supported with less of this material than of iron, the weight of the hammer-core assembly was reduced by using this material. Because of its relatively high fatigue strength, this material is also well suited for the hammers.

The core assembly, or core bar as it is known, is subject to thermal expansion, since its temperature can vary as much as 150°C. Heat is generated by I^2R losses in the coils, and by eddy currents and hysteresis losses in the cores. Improved efficiency was built in by rigidly mounting the magnetic cores and the hammers in a single assembly that moves as a unit. The rigid mounting permits a minimum-reluctance air gap. Although this reduced the required drive energy from 0.07 watt-second per dot to 0.03 watt-second, the dots are now printed at a faster rate with a corresponding increase in heat.

Heat build-up within the core bar presented a problem since the core bar is asymmetric, does not heat uniformly, and is composed of such diverse materials as aluminum, steel, and potting compound. To combat this, the core bar is designed with eleven aluminum modules clamped tightly between two end caps by two tension rods, forming a rigid structure. Each module holds an assembly containing twelve cores and hammers, as shown in Fig. 4. This structure allows the various materials to expand at different thermal-expansion rates without causing out-of-tolerance warping of the assembled core bar.

Heat generated in the core bar is dissipated mainly by fins located on the back of the bar. Air is blown upwards through the fins and out the top of the printer through the paper exit, with a small amount going through the hammers. Calculations show that the fins can dissipate a maximum of 185W and an additional 60 to 90W can be dissipated by other surfaces, assuming a practical air flow of 0.3 to 1 m^3/minute and an allowable wire temperature of 200°C. This is adequate for removing the heat when printing alphanumerics. However, when printing dense dot patterns in the graphics mode, heat can be generated at rates up to 620W. For this reason, the number of dots printed is monitored electronically and print delays are imposed if the dot density averaged over a

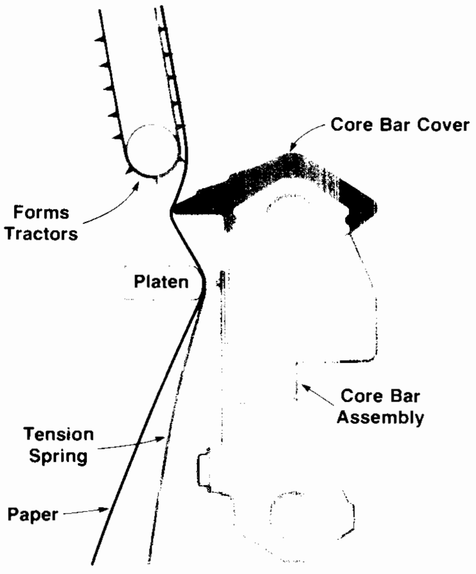
Precise Paper Movement

Good print quality in a dot-matrix printer requires accurate placement of the dots for each character. As described in the accompanying article, servo control of the core bar motion in the Model 2608A Line Printer positions the dots accurately in the horizontal direction. Precise movement of the paper is required to position the dots accurately in the vertical direction. Not only must the paper be moved precisely but the movement must be made and stabilized within 5 ms if print-speed requirements are to be met.

It was found early in the project that step motor drive through a belt-and-pulley arrangement introduced too much inertia into the system to achieve smooth acceleration and deceleration of the paper. Therefore, a custom-made, four-phase step motor that advances 2° per step is used so it can be directly coupled to the tractor drive shaft.

Open-loop control of the step motor achieves the simplest and least expensive method of control. However, to assure that the rotor detent position is reached reliably for worst case loads, more than sufficient torque for overcoming inertia and friction is needed. To improve the motor's rated torque, a two-level voltage drive is used. A 600-μs overdrive pulse from a high-voltage supply causes an initial rapid increase in winding current (to 5A) that is sustained by a low-voltage supply for the remainder of the drive pulse. By this means, torque was increased 25% over a single-level drive while mechanical resonance problems were minimized.

Extensive studies with an electro-optical tracking system on early versions of the printer revealed that hammer action caused the paper to vibrate against the platen. To reduce this motion, the platen face was curved to match the bend radius of the paper, providing better adhesion as the paper is tensioned around it. Tension is provided by a thin (0.010-inch) stainless-steel, cantilever, paper-tension spring that contacts the paper along the entire width of the platen just below the print line. A plastic cover along the top of the core bar protrudes into the paper path to force the paper to conform to the radius of the platen face, as shown in the drawing.



With this paper path, the step motor drive moves the paper 0.0139 inch for each dot row and completes each movement within 5 ms without overshoot or other aberrations, giving excellent print quality.

-Robert Deely
-Lynn Hessing

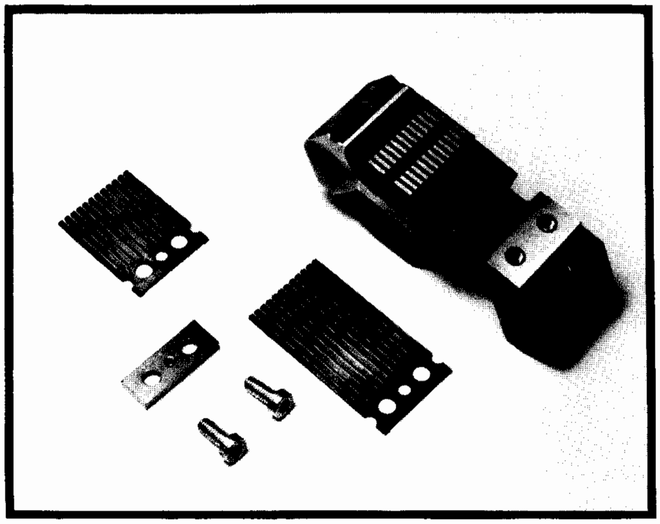


Fig. 4. *One core-bar segment holds twelve hammers, dampers, and cores. The cores are held in place by potting compound that permits the cores to expand thermally at a different rate than the aluminum module.*

page exceeds 37%.

Mechanical Tolerance

A tolerance study revealed that consistent print quality is obtained when hammer-to-paper spacing is 0.038 ±0.08 mm (0.015 ±0.003 inch). Hammer variations alone take up 0.08 mm of the allowed 0.16 mm spacing tolerance. This means that straightness tolerance over the 335-mm (13.2-inch) length of the core must be 0.08 mm, assuming variations are negligible. The core-bar assembly has an initial straightness tolerance of 0.05 mm, and this is maintained by the tautness in the tension rods.

Core Bar Motion

The core bar is attached to the printer casting by two stiff flexure springs that allow lateral motion while precisely maintaining the hammer-to-platen spacing (see Fig. 5). The rest position is aligned with the center dot column of the character matrix. With this configuration, energy stored in the flexure springs by core bar movement left or right aids the linear motor in providing the forces necessary to reverse the core bar direction at turnaround.

As illustrated in Fig. 6, the linear motor housing is also attached to the printer casting by stiff flexure springs. These isolate drive force vibrations from the casting. Although the flexures permit some movement of the linear motor, the closed-loop motion-control system assures precise and controlled movement of the core bar with respect to the platen, independent of motor housing motion.

The lateral motion of the core bar is tightly defined by the action of the hammers. Since these operate at a fixed repetition rate (400 Hz) close to the hammer resonant frequency, the core bar must move across the character spaces at constant velocity to assure equally spaced dots. In addition, core-bar turnaround must be completed in an integral number of dot cycle times. It is also desirable to make the velocity rate of change

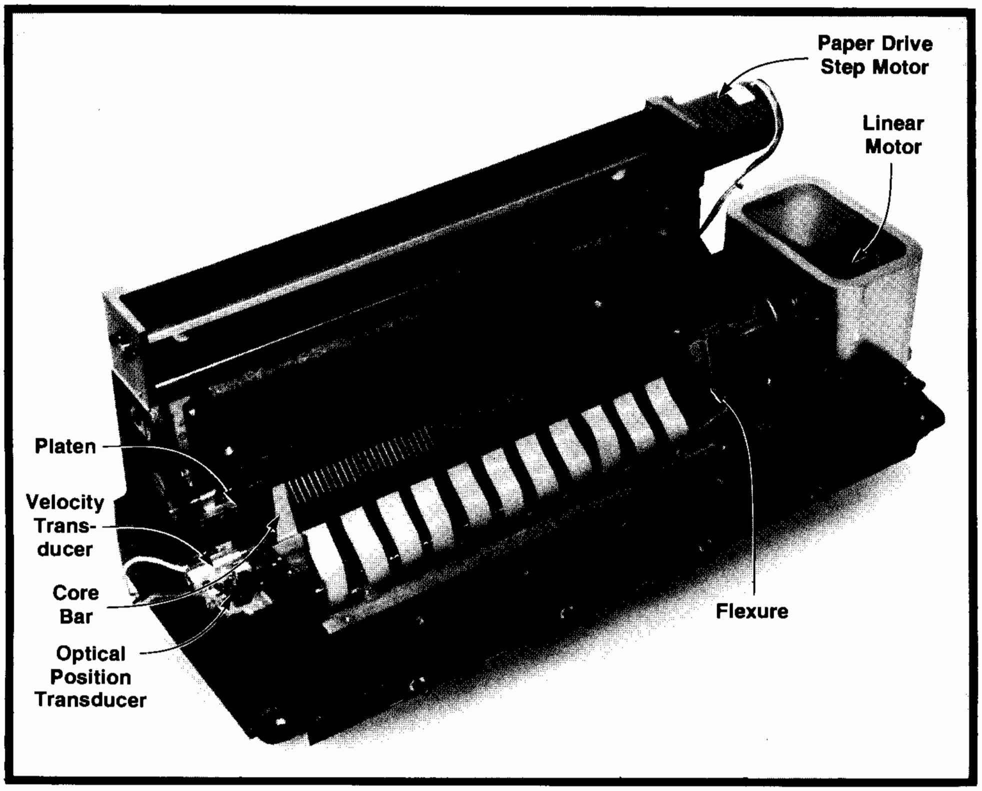


Fig. 5. *Partially assembled printer mechanism.*

constant during turnaround to minimize the magnitude of the forces acting on the bar. Hence, the desired core-bar velocity profile is as shown in Fig. 7.

To achieve the desired motion, the core bar is embedded in a closed-loop motion control system, diagrammed in Fig. 8. The actual velocity of the core bar is obtained from a velocity transducer that has its stationary part fixed to the print mechanism base and its movable part fixed to the core bar. The transducer output is compared to the desired velocity profile obtained from a waveform generator and the error between the two signals is forced to zero by the motion-control system loop. Thus, the actual velocity closely matches the velocity profile waveform.

The equation of core-bar motion is:

$$V_{in}\cdot K_a\cdot K_m=M_1\ddot{X}+C_1\dot{X}+K_1X$$

where X = core-bar displacement
V_{in} = drive amplifier input voltage
K_a = drive amplifier constant
K_m = linear motor force constant
M_1 = core bar mass
C_1 = effective viscous friction
K_1 = flexure constant.

With this as the model describing the core bar and drive components, a compensator that provided appropriate loop dynamics was designed using classical root-locus design. The compensator used a third-order pole at the origin to achieve a system capable of following the input velocity profile ramp on turnaround (classical type-2 control system) and three zeros were included in the left half plane for stability.

When this compensator was added to the system and the loop closed, however, the system proved to be unstable. It was found that the model did not give an accurate representation of the core bar over the total range of frequencies involved. Although the core bar oscillates at about 30 Hz during the printing of alphanumerics, its motion has a high harmonic content because of the nonsinusoidal nature of the velocity profile. At frequencies above 400 Hz, the core bar, which at that time was a ribbed steel bar with the cores and hammers mounted along the top, no longer behaved as a rigid body but was subject to some twisting and bending. The twisting and bending motions were coupled into the velocity transducer.

Frequency response plots of the core bar system were made with an HP Model 5451B Fourier Analyzer to determine what additional compensation would be needed to stabilize the loop. These plots disclosed the existence of several resonance peaks that rendered the system uncontrollable for the response speeds of interest. An accelerometer probe was then used with the Fourier analyzer to find the sources of the resonances. Therefore, changes were made to the core-bar design. The changes were iterative in nature with each change followed by further probing with the accelerometer and analyzer to determine the extent of the resonance attenuation achieved.

As a result of this process, several modifications were made. For example, the coupling structure between the linear motor coil form and the core bar was strengthened to prevent excessive flexing. The print mechanism base, originally made of half-inch aluminum members bolted together, was replaced by a one-piece, ribbed aluminum casting, and the core bar was redesigned with the cast-aluminum modules shown in Fig. 4 for increased rigidity. Finally, the velocity transducer was relocated to a point where any twisting or bending modes of the core bar would have minimum effect. The frequency response plots also indicated a need to improve the linearity and speed of response of the drive amplifier.

With these changes, plus the addition of lead-lag and roll-off compensators to the electronics, the desired stability was achieved.

Position Control

For proper synchronization between hammer operation and core-bar motion, it is necessary to generate

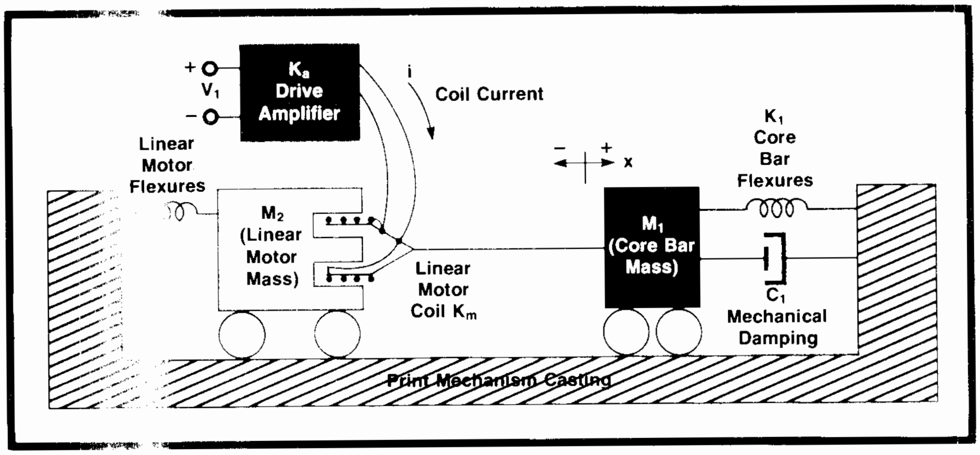


Fig. 6. *Mechanical diagram of the core bar and linear motor.*

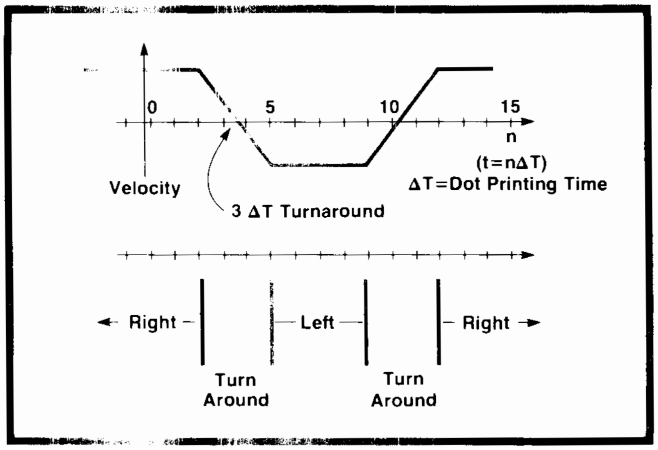


Fig. 7. *Velocity profile of the core-bar for obtaining even spacing of the printed dots and a constant rate of change during turnaround.*

information pertaining to the core bar position. This is done by applying the output of the velocity transducer to an op-amp integrator and applying the resulting position waveform to a bank of comparators that have equally spaced reference voltage levels. Each time the waveform crosses a comparator reference level, the resulting output edge triggers a pulse generator, signifying that a dot column has been encountered.

A second position circuit is included for controlling the stationary "home" position of the core bar when the printer is in the STANDBY mode. An LED and a phototransistor are mounted on the base casting with a vane attached to the core bar passing between them. The vane partially blocks the LED light when the core bar is in the home position so the output of the phototransistor is proportional to core bar position over a narrow range. This signal is switched into the motion-control feedback loop during STANDBY to place the core bar in the home position. An initial adjustment of the vane is made so the home position coincides with the mechanical rest position of the flexures.

The output of the position integrator is also included in the home-position feedback loop. The integrator provides an accurate, dynamic position-feedback signal for returning the core bar to the home position in situations where the core bar is remote from the home position with the photo-detector circuit in a limiting state. A block diagram of the composite motion and position control system is shown in Fig. 9.

When the core bar is operating in the oscillatory print mode, the output of the phototransistor is used to generate a short pulse each time the core bar crosses the home position. This pulse closes a switch in parallel with the position integrator capacitor to provide a momentary reset, preventing any slight offset in the velocity transducer circuit from causing the position waveform to drift with time.

Microprocessor Control

The printing of the dots is synchronized with the motions of the core bar and the paper by the machine's microprocessor. This is a control-oriented, eight-bit, NMOS microprocessor designed and manufactured by HP's Loveland Instrument Division. A second function of this microprocessor is to control the conversion of the ASCII-coded input characters into the dot patterns required for printing these characters.

The core-bar position control system provides position information to the microprocessor. Using this information, the microprocessor decides when to reverse or stop the motion of the core bar, when to advance the paper, which portion of the dot patterns to use, and when to fire the print hammers.

The core bar is moved according to the largest matrix to be used in a given line. In the alphanumeric mode, there are three sizes of dot matrices— 5×7, 5×9, and 7×9— according to what is being printed. For example:

E	g	_ (underline).
5×7	5×9	7×9

If upper-case ASCII only is being printed, seven dot rows with five dots per row in each character are printed at a speed of 400 lines per minute (lpm). If a lower-case character is included in the data stream, then nine dot rows per line are printed and the speed is 320 lpm. If underline is added, nine dot rows with seven dots per row in each character position are printed and the speed is then 250 lpm. In the graphics mode, core-bar motion across seven dot columns is used and printing proceeds at a rate of 40 dot rows (0.572 inches) per second.

The ASCII-coded characters sent to the printer by the external system are processed through the inter-

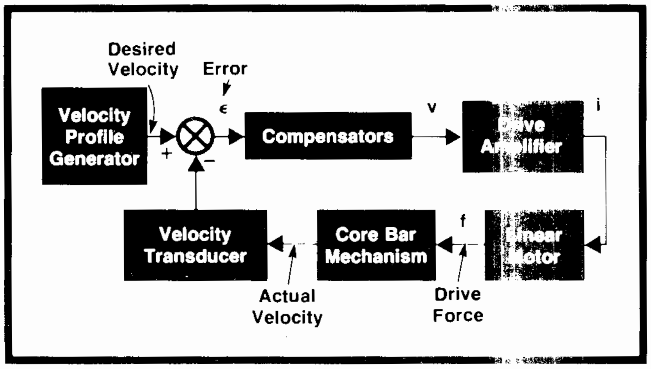


Fig. 8. *Closed-loop motion-control system forces the core bar velocity to match the velocity profile.*

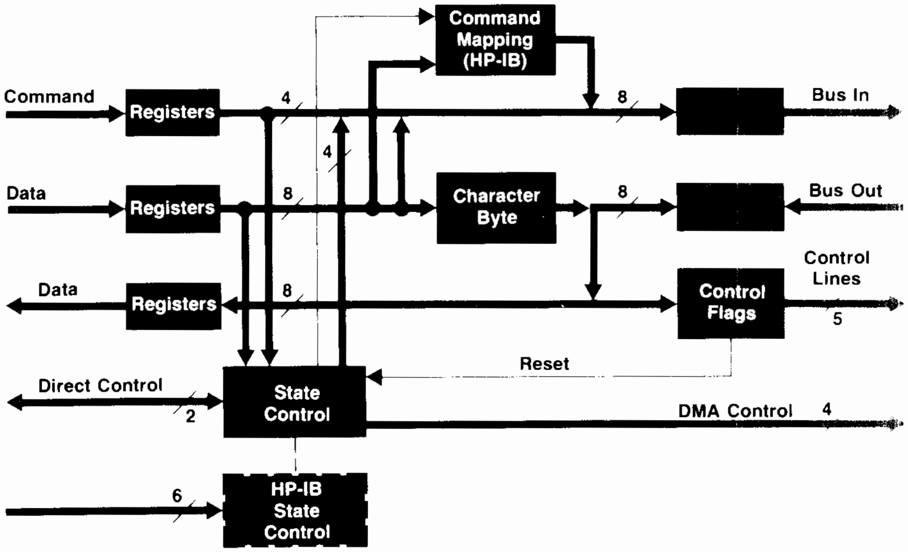
Interface I/O for a 400-lpm Printer

The design of the interface I/O for the Model 2608A Line Printer is in keeping with the general philosophy of flexibility in the printer's electronics. The selection of which functions are to be performed by the I/O and which by the main processor in the printer allows the communications flow between the printer and the host computer to be relatively independent of the main processor control.

The standard interface to the host computer is a TTL-level, direct-coupled, differential, parallel bus with eight line pairs carrying input data, eight carrying output data, four for commands, and one line pair in each direction for control. Except for the control lines, these connect to registers in the I/O, as shown in the diagram below.

Another function of the ASM is the processing of control code bytes that are to be acted upon by the printer. Character data bytes are scanned for the shift-out, shift-in, and backspace characters and these operations are performed, unless the printer is in the transparency (print control codes) mode.

The HP interface bus I/O is implemented with a CMOS SOS integrated circuit developed specifically to provide a logical interface to the interface bus defined by IEEE-488-1975. The HP-IB has bidirectional buses and control lines so information on these lines is sorted out by the HP-IB IC and applied to the appropriate unidirectional bus feeding into the standard parallel I/O, as shown in the diagram. The I/O's state control for the HP-IB has two serial linked ASMs.



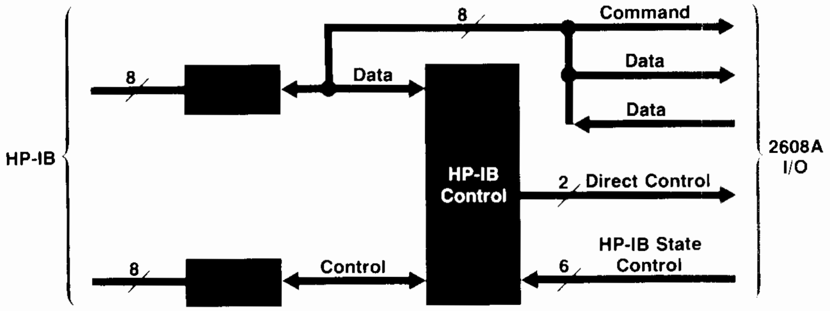
The heart of the I/O control is the algorithmic state machine (ASM) shown in the diagram. Strobe logic within the ASM syncs the asynchronous incoming information to the printer's clock. Incoming information is decoded to determine whether it is data or information related to a command. If it is character data, the ASM takes control of the bus into the main processor RAM by turning off the processor clock (stealing processor cycles) during the processor fetch phase. This gives the ASM direct access to the main processor's RAM by way of the processor's *outgoing* data bus. The ASM stores the character data at the appropriate address, returns control to the main processor, and then waits in its idle state for the next data or command byte. Input data burst rates up to 500K bytes/second can be handled this way.

Printer command bytes with I/O flags and data bytes associated with commands are routed onto the main processor's incoming bus.

The HP-IB I/O also enables three additional control codes to be acted upon by the printer. These are carriage return, line feed, and form feed.

The flexibility of the I/O system design allows adaption to other interface requirements. The standard interface is easily changed to a positive- or negative-true TTL interface. A serial interface is being designed.

--Stanley G. Peery



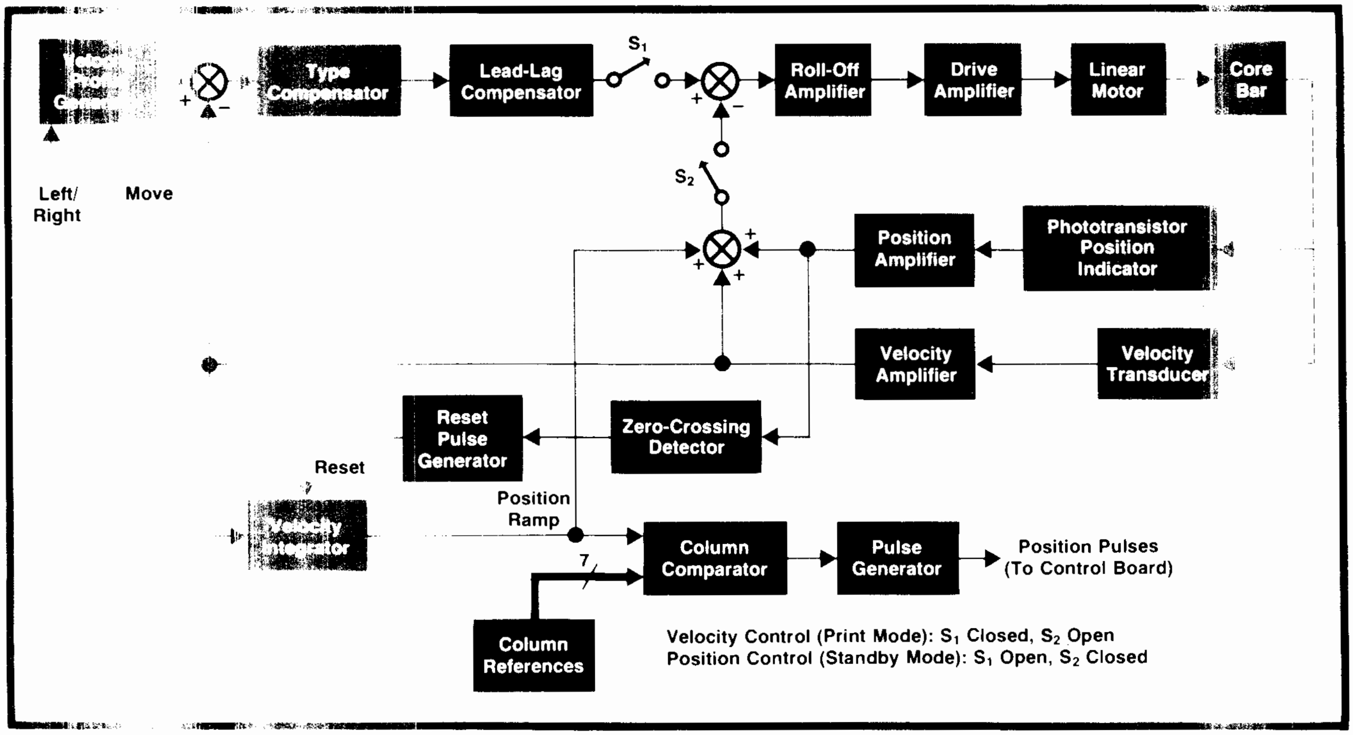


Fig. 9. *Combined motion and position system.*

face board and stored in a buffer RAM (read-write memory) using direct memory access (Fig. 10). Actually, there are two buffers so characters can be loaded into one while the microprocessor converts characters stored in the other into dot patterns.

Dot-pattern conversion is performed with the use of a table stored in ROM. Inputs to this conversion are:

1. 7-bit ASCII-coded character;
2. 1-bit code extension (i.e., shift in/shift out);
3. 4-bit language code (16 languages possible);
4. 3-bit dot-row number;
5. 3-bit dot-column number.

This implies a virtual memory space of 256K bits. However, because many characters are duplicated in the languages, the printer's actual memory space is 40K bits with 16 languages.

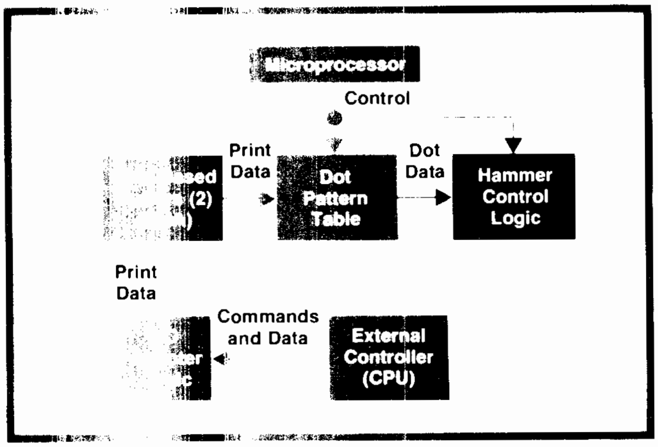


Fig. 10. *Block diagram of the microprocessor control system.*

The microprocessor moves the ASCII-coded character data directly from RAM to the dot pattern generation table. From there, it goes to the hammer control logic. This decoding is done once for every dot in each of the 132 character positions per line.

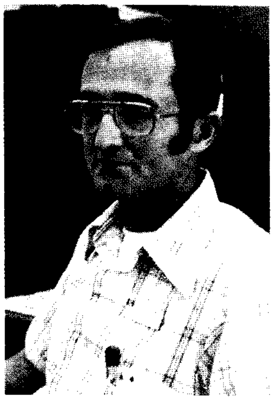
In the graphics mode, each eight-bit byte sent by the external system is presented to the hammer-control logic as eight contiguous dots with the 1's printed and the 0's left blank. Since there are 924 (7×132) dots per dot row, 116 (924÷8) data bytes are needed to describe one row. Thus, to turn the printer into a convenient, user-oriented graphics device, external software is required. Such software has been written for use with the Graphics-1000 software on the RTE-IV operating system for the HP 1000 series computer system.[1] The Model 2608A Printer can thus be an AGL-compatible plotter supported by the 1000 system.

Acknowledgments

The computer simulation of hammer motion was developed by C.S. Chan.

Reference

1. R.K. Juncker, "Higher-Performance HP 1000 Computer Systems, "Hewlett-Packard Journal, October 1978.



Everett M. Baily

Everett Baily received his BSEE degree in 1961 and MSEE degree in 1964 from the University of Idaho and PhDEE from Stanford University in 1968. An HP employee since 1974, Everett was production engineer for the 7970 Tape Drive before undertaking the design of the electronic drive circuitry for the 2608A Line Printer. Prior to joining HP, he was a professor of electrical engineering at the University of Idaho. Born in Twin Falls, Idaho, Everett now lives in Boise, Idaho, with his wife and daughter, 11 and son, 9. In off hours, Everett likes to hunt, fish, camp, take photographs and work at restoring his Model A Fords. He is also a United Way volunteer, is active in a local church group, and is vice chairman of the Boise IEEE chapter.

Wallace T. Thrash

Wally Thrash began work at HP's Boise Division as a senior lab technician, working in the investigation of the feasibility of the 2608A Printer, and later in design of the hammer-drive circuits and linear-motor drive amplifier for the 2608A. Before joining HP, he worked as a lab technician for a disc memory manufacturer. Born in Sacramento, California, Wally is completing his degree in applied physics at Boise State University. Married with two children (ages two and four), Wally lives in Boise, Idaho, and enjoys building his own microcomputer as well as camping, snow skiing and partridge and grouse hunting in the Idaho uplands.

Douglas B. Winterrowd

Doug Winterrowd received his BSEE degree in 1973 and MSEE degree in 1974, both from Montana State University. He joined HP shortly after graduation and has since worked on design of the main control electronics and firmware for the 2608A line printer. Born in Conrad, Montana, Doug is married and lives in Meridian, Idaho. Like many other Idahoans, Doug spends much of his leisure time hiking and crosscountry skiing.

William A. McIlvanie

Bill McIlvanie is a 1972 BSME and a 1974 MSME graduate of Washington State University. An HP employee since 1974, Bill was development engineer for the hammer mechanism on the 2608A Line Printer. He is also named inventor on a patent for a rock drill, a project he undertook while doing graduate work for WSU. Bill is single, lives in Boise, Idaho, and enjoys a variety of outside interests including skiing, fishing, golfing and playing on a Boise city league softball team. He is also fond of listening to classical music.

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