Media Path for a Small, Low-Cost, Color Thermal Inkjet Printer

The DeskJet 1200C media path is heated for media independence, requiring development of a new grit drive roller and pinch wheel combination. A new stepper motor was developed to attain the target speed and accuracy. Media flatteners and precise gearing with an antibacklash device contribute to accuracy.

by Damon W. Broder, David C. Burney, Shelley I. Moore, and Stephen B. Witte

The media path is the part of a printer that moves media past the print cartridges, stopping and accurately locating the media for printing. The media path also constrains the media in a plane a fixed distance from the print cartridges. A media path should advance media accurately and quickly, be quiet, be inexpensive, hold the media flat, and keep the media the correct distance from the print cartridges.

Fig. 1 shows an overview of the media path of the HP Desk-Jet 1200C printer. Media stacked in the input tray (1) is individually picked by a media pick roller (not shown) and driven around the curved preheat zone (2) where it is preconditioned (moisture is driven off and the temperature is raised). When the page reaches the pinch/drive rollers (3), the main drive system (4) takes over from the pick roller drive (not shown). Once in the print zone (5) the media is heated further and ink is sprayed onto the page. The heating, soaking, and drying causes the media to move out of its plane, but the media control shims (6) help hold it flat for better print quality. The page is then incrementally advanced and printed upon until the entire page has been printed. Finally, the page is fed out into the output tray (7) and the process is ready to repeat.

Design Approach

For the office printer market, the DeskJet 1200C is designed to support a wide variety of plain papers, to be HP LaserJet printer compatible, to print text very quickly, to print high-quality graphics, and to be cost competitive. These characteristics forced the design team to face the following challenges:

- Constrain plain papers flat even though plain paper tends to cockle and curl in various directions when ink is sprayed on and heated.
- Print to 50-dot row margins for LaserJet compatibility, even though such small margins allow very little control over media flatness.

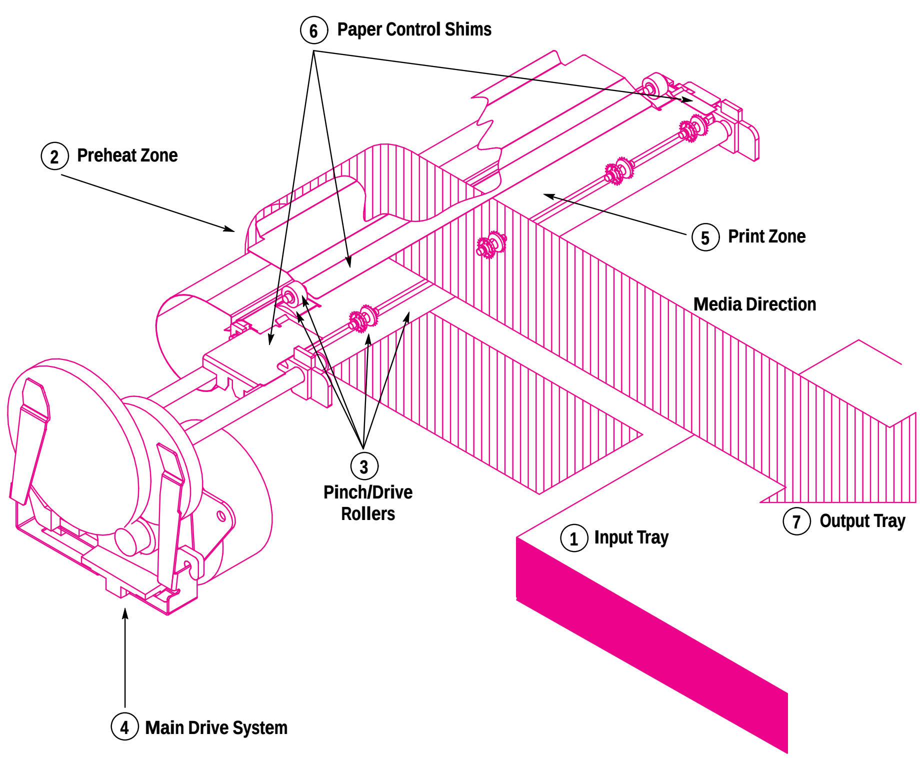

Fig. 1. Overview of the media path of the HP DeskJet 1200C printer. Media stacked in the input tray (1) is individually picked by a media pick roller (not shown) and driven around the curved preheat zone (2) where it is preconditioned (moisture is driven off and the temperature is raised). When the page reaches the pinch/drive rollers (3), the main drive system (4) takes over from the pick roller drive (not shown). Once in the print zone (5) the media is heated further and ink is sprayed onto the page. The heating, soaking, and drying causes the media to move out of its plane, but the media control shims (6) help hold it flat for better print quality. The page is then incrementally advanced and printed upon until the entire page has been printed. Finally, the page is fed out into the output tray (7) and the process is ready to repeat.

- Move media very quickly through the print area while maintaining high placement accuracy for good graphics print quality.
- Keep the price low.

The parts of the media path (Fig. 1) that drive and meter the media include the stepper motor, the drive pinions, the drive gears, the antibacklash device, the shaft bushings, the adjustable plate, the drive rollers, and the pinch rollers. While driving the media these components work together to ensure fast, accurate movement of the print media, which in turn provides the best possible throughput.

The stepper motor provides the fastest response available in an inexpensive motor. Although stepper motors aren't always the most accurate type of motor, the accuracy of the system can be optimized by designing the system so that the motor always moves in multiples of four half steps. Moves of four half steps cancel out all of the error caused by manufacturing variation except the locations of the stator teeth which are formed out of the sheet-metal case of the motor. Used in this way, the stepper motor can provide very fast and accurate moves and is well-suited for driving the media in an inkjet printer.

The gearing system in the DeskJet 1200C is designed to optimize the accuracy of the media drive. A single-reduction drive is used because there are fewer components in the gear train, so this type of drive is more accurate. However, accuracy is not the only reason to use a single reduction. The size and spacing of the drive rollers relative to the print cartridges and heater also pushed the design towards a single-reduction gear train. The DeskJet 1200C relies on a heated media path to dry the ink as it is being printed. To make room for the heater while maintaining control of the print media, the drive rollers had to be much smaller than other inkjet printers had typically used. By using smaller drive rollers, we were able to use a single-reduction gear train.

The spacing of the drive rollers was a critical issue in the design of the DeskJet 1200C. The spacing is constrained by the size of the print cartridges and heater. Thus, we had to trade off room for the heater and print cartridges against control over the leading edge (the star wheels hold the media down against the output drive roller) and print quality in the bottom margins (the main drive roller is more accurate than the output drive roller). As the space between the rollers increases, there is a longer span of media at the top of the page to control with the star wheels and a longer space at the page bottom where the media is driven by the output roller.

A major problem in reducing the shaft spacing was reducing the size of the drive roller. Drive rollers in inkjet printers have typically been rather large elastomer-coated shafts, 40 to 70 mm in diameter. To shrink the roller to a size we could use ($<$20 mm) we had to find a different process, one that was new to inkjet printing. We decided to try the grit drive system used in several HP plotters, which consists of a grit-coated metal drive wheel and an elastomer pinch wheel. By using a grit system, we could minimize manufacturing errors associated with the size and shape of elastomer rollers and reduce the size to one we could use. Of course, we then faced many problems adapting the grit drive system to a heated media path system.

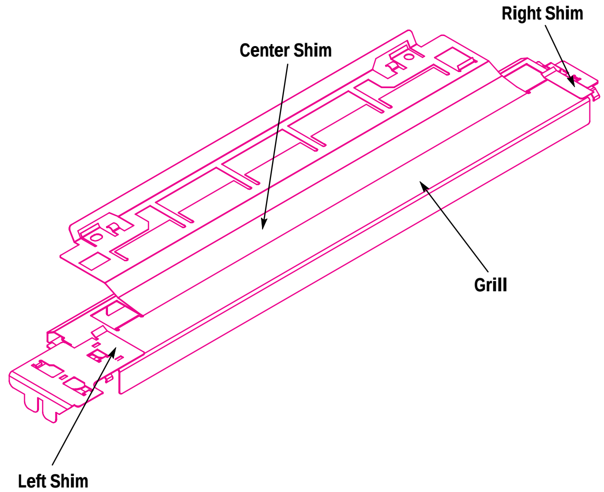

Fig. 2. A grill and three shims hold the media flat in the print zone.

The media path must also hold the print media flat. The environment in the print region is somewhat hostile to paper. The ink soaks the paper, and the heater boils the water out of the paper and dries it out. The DeskJet 1200C is intended to print on any office paper with nearly equal print quality. The heater and the ink design help achieve media independence, but at the same time, the heater and ink wreak havoc with the fibers that make up the paper. The fibers, predominantly cellulose, swell with ink and the paper expands. Then, as the paper is heated and dried, the fibers shrink and the media contracts. None of the expansion and contraction is uniform from one side of the media to the other, so the media tends to move out-of-plane. To print with high quality, the distance from the print nozzles to the print media must be accurately maintained. We hold the media flat against a grill (which covers the heater) with three shims—center, left, and right, as shown in Fig. 2. The fixed right shim constrains the right edge of the media and acts as the zero reference point for printing. The adjustable left shim adjusts to A and A4 sizes while constraining the left edge of the media. The center shim helps keep the media flat against the grill and helps keep the media from crashing into the print cartridge. The center shim also allows printing very near the bottom edge of the media—as close as 5 mm.

As the paper advances out of the print region, we also hold it down with the star wheels. These systems provide good control over the media, keeping it constrained in a plane at a fixed distance from the print nozzles.

Heated Media Path

The DeskJet 1200C was envisioned to support a broad range of media: not just A and A4 sizes, but also glossy paper, transparency film, and virtually any paper on the market (at one point we were even printing on paper bags). With such a wide range of media as the goal, and the added challenge of fast throughput, it became evident that the DeskJet 1200C would need a heated media path to meet these goals with any kind of reasonable print quality.

The heated media path of the DeskJet 1200C (see Fig. 3) is composed of two main components: the preheater and the main heater. The preheater is a flexible polyimide heater that serves as the inner guide for the media. As the media is

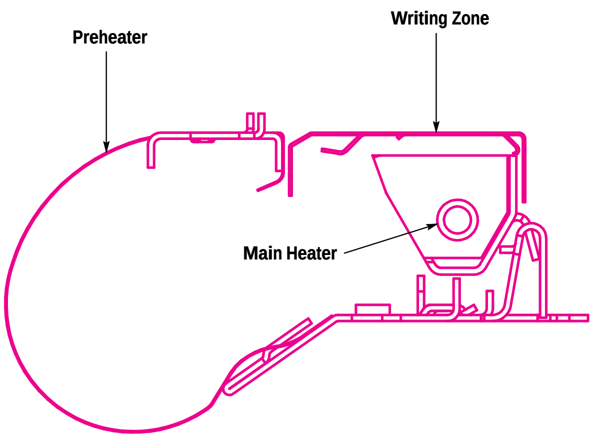

Fig. 3. Heated media path.

fed up into the main heater and the writing zone, it is wrapped around the preheater. This contact allows the preheater to precondition the media so that when the media reaches the writing zone it is much more dimensionally stable. Much of the paper fiber shrinkage that occurs with heating happens before the paper reaches the writing zone.

The main heater consists of a Kanthal wire and a quartz tube. Current drawn through the wire causes it to heat up and emit infrared radiation. The radiation and convective heat from the bulb help evaporate the water from the ink in the writing zone. This increase in the evaporation rate of the ink allows increased throughput and improved print quality over a much broader range of media.

Drive Roller Development

The DeskJet 1200C media advance is controlled by a high-pressure nip concept (drive roller and pinch wheel) located near the left and right media margins (Fig. 4). As mentioned earlier, this gives a clear advantage in space conservation and design simplicity over other inkjet products using large-diameter drive rollers and low-pressure nip concepts.

A traction surface designed to tolerate thermal shock with a low thermal expansion needed to be developed. The low-cost, high-quality advance mechanism goals also required a reliable manufacturing process that would produce 100% in-specification parts.

The traction surface characteristics were initially defined from a customer satisfaction viewpoint:

- The combination of nip pressure and drive roller roughness could not mar transparencies or leave tracks in plain paper.
- The traction surface had to push the media with no slippage.
- Banding had to be controlled much more tightly than before to meet print quality expectations. This meant that the traction surface had to advance the media consistently a constant distance for a given arc of rotation, that is, the pitch diameter had to be as tightly controlled as technology would permit. The printer's performance could not be adjusted to compensate for poor control of this specification in manufacturing. Print quality swath banding has a 1:1 correlation with this assembly.
- The cost had to be low and the process compatible with high-volume manufacturing.
- The materials selected had to survive with no degradation of their properties within the thermal operating environment of the printer.

A fundamental design goal for the Deskjet 1200C drive roller assembly was to develop a roller surface that would not slip on any media type. This was approached from a mechanical friction and traction point of view. Lab tooling adequate to characterize the traction surface had to be developed quickly. The reality of our schedule required high-risk decisions with data lagging by several months.

Concurrent development was started for lab tools, prototypes, and metrics simultaneously. We had to allow the development of the drive roller assembly to slip out of phase with the rest of the project and get convergence by the time of the production build.

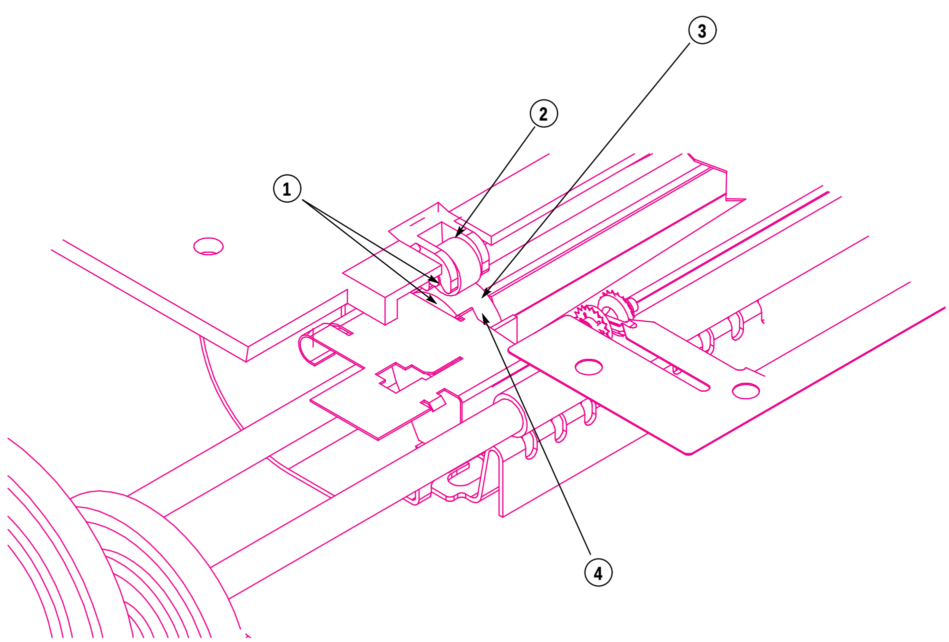

Fig. 4. Drive roller and pinch wheel. (1) Nip area (drive roller and pinch wheel), one of two in the printer. (2) Pinch wheel. The pinch wheel rolls on the media above the drive roller to apply normal loading of the media into the traction surface of the drive roller. (3) Drive roller. Rotary motion of the drive train is converted to linear media motion. The surface must not slip or leave tracks in the media. (4) Pitch diameter is twice the radius from the drive axle center of rotation to the contact zone between the media and the traction surfaces.

Stepper Motor Simulation Model

The model used to simulate a permanent magnet stepper motor for the simulations described in the accompanying article originated from a classic control systems point of view. The model includes simple position and velocity feedback control algorithms. Fig. 1 is a block diagram of the model.

A nonlinear block in the model allows the nonlinear characteristics of the stepper to be included. This block makes the stepper torque output match the desired torque for a given error signal.

The resultant nonlinear system was linearized by running it at a very high sample rate of 40,000 samples per second. At this sample rate, speeds, positions and currents are changing very slowly. Hence linear control systems analysis is valid.

The model was used to compute velocity profiles with several different motor resistances, inductances, and so on. The lowest-resistance motor available in a permanent magnet motor at this time was an 8-ohm motor. Fig. 2* shows that the simulated velocity clearly does not reach the desired 1400 steps per second. This motor fails and stalls in the real system. In Fig. 3,* the simulated velocity of a 2-ohm motor is shown. In this successful run, it appears that the motor has no trouble reaching the desired 1400 steps per second. This motor was built and is now the motor being used in the DeskJet 1200C printer.

The currents in a failing stepper motor are shown in Fig. 4* and the currents in a stable, running stepper motor are shown in Fig. 5.* In the failing stepper motor, the currents do not even reach their normal operating levels before they are switched again. The characteristic hook in the graph of these currents reflects reality very well for the case of insufficient voltage used to drive the motor.

Stephen B. Witte
Development Engineer
San Diego Printer Division

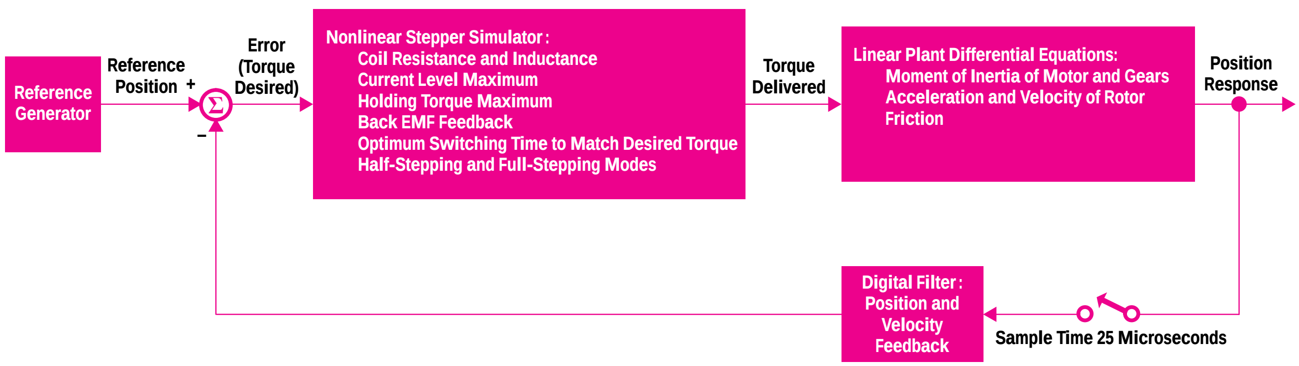

Fig. 1. Block diagram of the theoretical stepper motor model.

* See top of next page for Figs. 2, 3, 4, and 5.

The term traction was used to define media slippage with the drive surface to avoid preconceptions of friction behavior. (Paper has a composite surface of fibers and fillers that cause its frictional characteristics to be nonlinear with normal forces beyond a relatively low surface shear stress.)

The characterization efforts revealed interactions with printer components not previously considered. Affected components were redesigned and the traction surface successfully developed in concert with these components. Analytical tools to measure system and component performance were developed or enhanced by this project. This greatly improved correlation of print quality goals with measured performance and design specifications.

High-volume processes at multiple suppliers for this assembly were characterized with proven process margins. Supplier inspection processes were improved to fit part requirements and inspection metrics.

Media Motor and Antibacklash Device

The goal for selecting the Deskjet 1200C media axis drive was to design a motor and gearing system that is simple and compact and has better speed and accuracy than we had ever achieved before. Not only did this new gear drive system have to have improved performance, but it also had to be less expensive.

One key element of the media drive system is the motor selection. The HP PaintJet, PaintJet XL, and PaintJet XL 300 printers use a hybrid stepper motor to drive gear trains that control two roller media drive systems. These systems have relatively high inertia and are limited in speed. They also have multiple idler gears for the purpose of transferring position control to a different location in the machine. For the HP DeskJet 1200C printer, a decision was made to use a double-pinion approach to eliminate the idler gears.

For low cost, we believed that a permanent magnet stepper combined with an antibacklash device would be as accurate as the hybrid stepper system. The key issues were: How do we design a low-cost anti-backlash device? and, How do we get the speed and torque that we need out of this low-cost stepper motor?

To determine whether the permanent magnet stepper would work, a theoretical model was developed that allows the simulation of the motion of a stepper motor from a standing

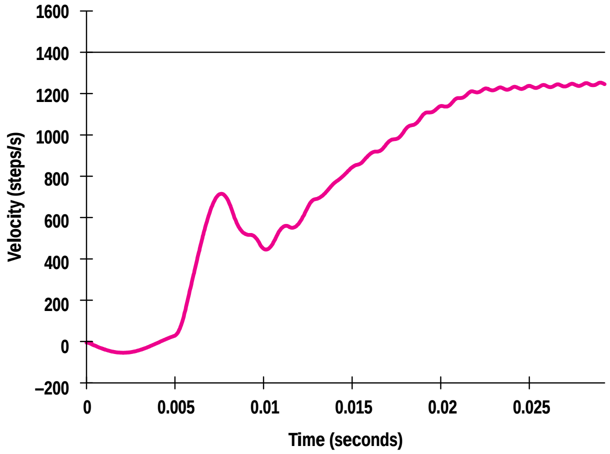

Fig. 2. Simulated velocity profile of a failing motor (8-ohm).

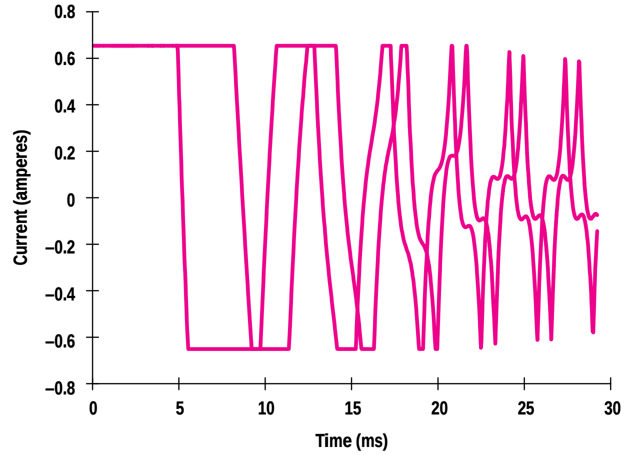

Fig. 4. Simulated currents in a failing motor.

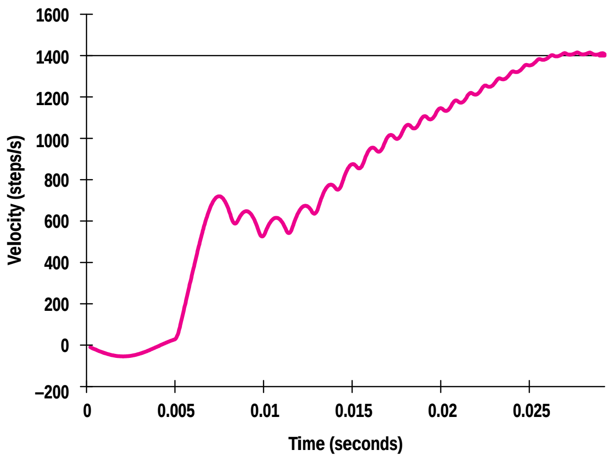

Fig. 3. Simulated velocity profile of a good (2-ohm) motor.

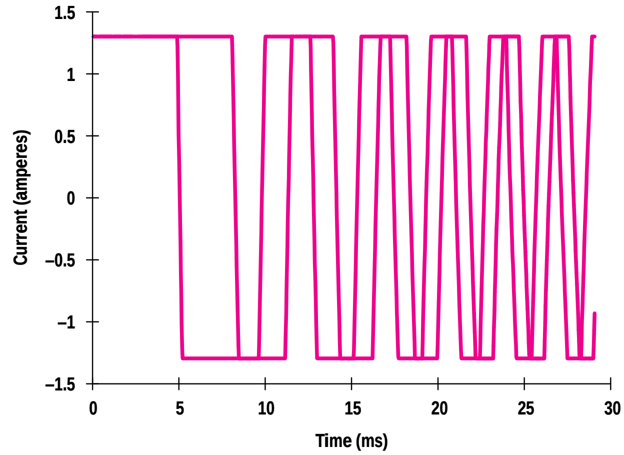

Fig. 5. Simulated currents in a stable, running stepper motor.

start through high speed and back down to a stop (see "Stepper Motor Simulation Model" on page 75). This model includes the motor, system inertia, inductance, motor resistance, and friction. It also dynamically calculates back-EMFs and motor currents.

This simulation predicted that a motor with a resistance of one or two ohms could run significantly faster than previous DeskJet motors. Speeds of 2000 full steps per second (2500 r/min) were predicted as possible high-end speeds where older permanent magnet motors had not been run much faster then 600 to 1000 steps per second.

A motor vendor was located that would be willing to wind the motor coils with a heavy-gauge wire and prototype motors were assembled. These motors performed at the predicted speeds and astounded the motor R&D engineers themselves! They previously had not built permanent magnet steppers with this kind of speed capability. This vendor developed manufacturing processes to produce these low-resistance coils in production and ultimately won the contract to provide HP with these motors for the Deskjet 1200C printer.

Fig. 5 shows the complete motor, gears, and backlash system.

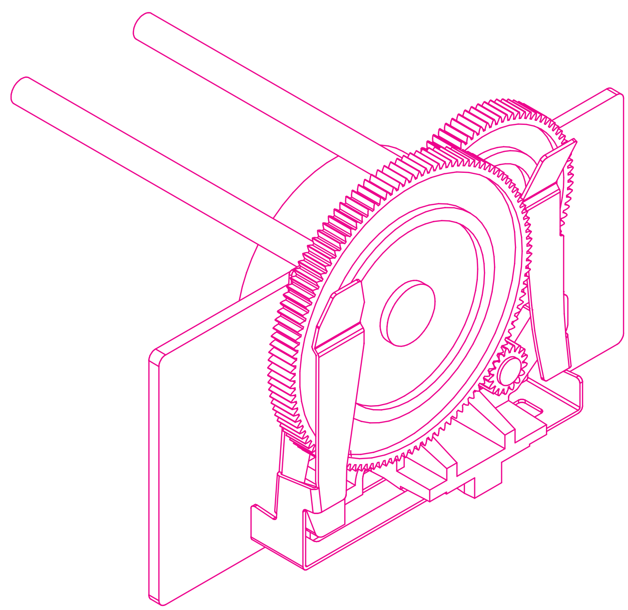

Fig. 5. The complete motor, gears, and backlash system.

Reducing Stepper Noise. Once we had the speed that we needed, we had several more hurdles to pass. It was necessary to control the motor and make it start and stop precisely without the noises that normally come from stepper motors. When the first DeskJet 1200C lab prototypes were built, people were very concerned about the stepper noise. Hardware was developed that allows the dynamic response of both the motor and the gear-driven shaft to be measured. This hardware was combined with personal-computer-based software that makes the process of smoothing out the step profile of the motor relatively easy. Because the designers had been clever enough to make it easy to download step times to the printer, it was possible to try out different combinations of step times quickly and observe the response of the motor and drive shaft visually (in addition to hearing it). The dynamic response was successfully smoothed out and the system became much quieter. At the same time, we were also anticipating problems with overshoot.

Controlling Backlash. Fig. 6 shows the function of the anti-backlash device. The purpose of this sheet-metal spring is to keep the teeth of the gears meshed tightly even if the motor backs up slightly. If the gears were to become unmeshed, the resultant accuracy error would be twice as much as all other error sources combined.

The DeskJet 1200C media axis completes a 1/3-inch swath advance in under 58 milliseconds. (For comparison, the PaintJet XL300 completes a 1/6-inch swath advance in about 200 milliseconds.) Hence, it was expected that it would be difficult or impossible to prevent gear backlash. However, we came up with a way to reduce this backlash. The idea is to use a piece of sheet-metal steel that pinches the gears, adding friction so that when the motor stops and backs up, the gears follow it backwards. This steel antibacklash device has three springs built into one component. The first spring applies a controlled pinch force on the gear. The second spring is stretched forward every time the motor moves forward and provides the restoring force or antibacklash function. The third spring provides a thrust load that keeps the plastic gears pushed against the motor mounting plate.

Motor Pinions. One of the most difficult challenges on the HP DeskJet 1200C printer was to achieve an overall accuracy goal that was as good as the PaintJet XL300 over twice the distance of that printer. It turns out that one of the key components in the DeskJet 1200C mechanism is the quality of the motor pinions. We chose to hob the pinions instead of molding them because their relatively small size makes hobbing relatively low in cost. Also, hobbing is substantially more accurate. Gear accuracy is commonly measured in the industry, and the key measurement is called total composite error or TCE. This measurement is very similar to runout and essentially behaves the same way as runout. However, while it is easy to measure runout on a motor-driven smooth shaft, it is difficult to measure the TCE of a pinion after it has been mounted on the motor shaft, especially with a stepper motor. To measure the TCE of a pinion after it has been mounted on the motor shaft, it is necessary to turn the motor very smoothly and slowly at only a few r/min. So, first we designed the stepper motor (which is by nature very oscillatory) to go extremely fast, and then we tried to drive it at very slow speeds. We were only able to make the motor move at slow speeds by using two function generators constrained in a phase-locked loop to be 90 degrees out of phase, then connecting their amplified outputs to the phases of the motor. Effectively, this became a sine-wave drive for the stepper, and it did successfully drive the permanent magnet

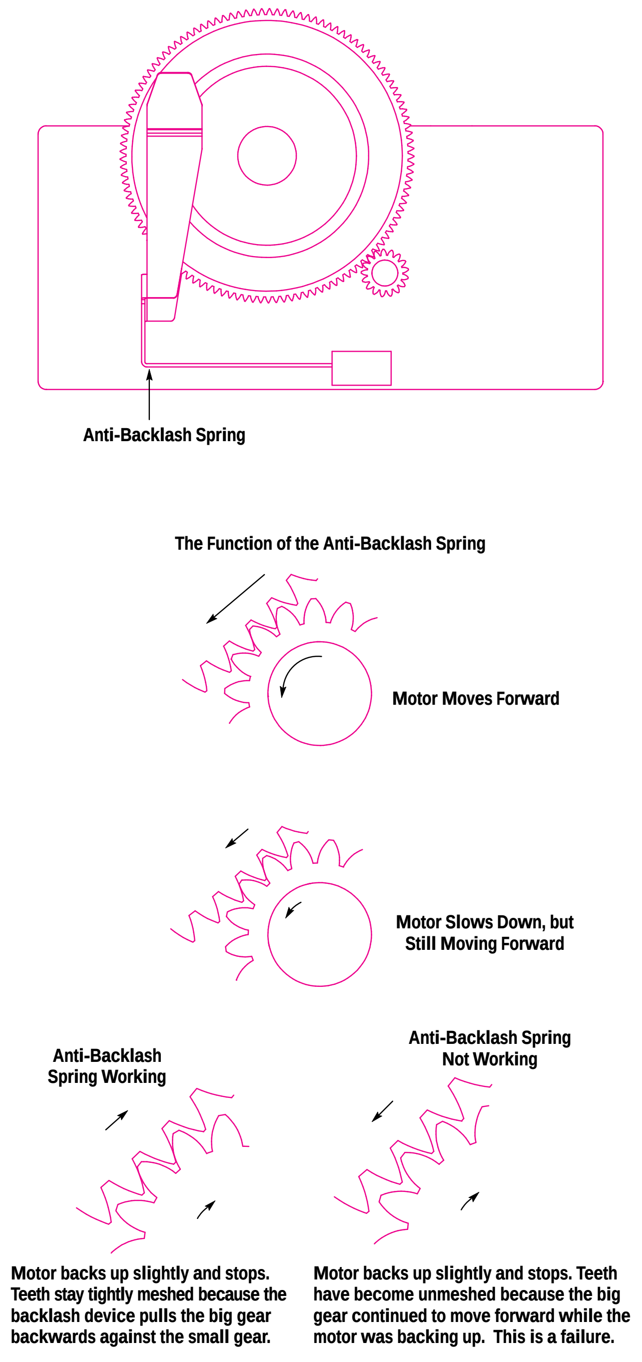

Fig. 6. Controlling the backlash. The large drawing at the top shows the function of the antibacklash device. The purpose of the backlash sheet-metal spring is to keep the teeth of the gears meshed tightly even if the motor backs up slightly. If the gears were to become unmeshed, the resultant accuracy error would be twice as much as all other error sources combined. The middle drawings show the motor moving forward and the motor slowing down but still moving forward. The two drawings on the bottom show the backlash spring working (left) and the backlash spring not working (right).

stepper at slow speeds. For the first time we could measure pinion quality after the gears had been mounted on the motor shaft. With this measurement ability, we were able to work with the vendor and resolve tricky problems such as damaging the pinions and bending the motor shafts while mounting the gears on the shafts. The resultant print quality of the HP DeskJet 1200C printer is good enough that few swath advance accuracy problems have occurred in production.

Media Drive Accuracy

The media advance accuracy is an important metric of the performance of the media drive system. As media moves through the printing region it is stopped, printed on, and then advanced to the next printing location. The distance it moves each time depends upon the print mode and what is being printed. Print quality for both text and graphics depends on advance accuracy. However, graphics print quality is more dependent on advance accuracy because there is no blank space in which to hide the advance error. Every advance made during graphics printing has the potential to show a print quality error, whereas during text printing it is possible to avoid splitting text between advances and thereby avoid showing advance error.

In the early stages of development the design team needed an estimate of the drive accuracy of the printer. A mathematical model was constructed that simulates an advance made by the worst-case components in the worst possible orientation. This model provided a good guide to what sort of tolerances we needed in our manufacturing processes, but was too conservative to simulate what we expected most advances to look like. The next model built was a Monte Carlo model that chooses components from simulated distributions and orients the parts randomly, much like a manufacturing process. When this model is run for a large number of cases, a good approximation of the expected mean and standard deviation of an advance is produced. Once the mean and standard deviation are known, process control of advances is possible. The goal of the modeling effort was to simulate advances and establish tolerance limits on advance accuracy. This goal was achieved and the process limits were confirmed by measuring drive components, building machines, and measuring their swath advances.

The DeskJet 1200C project was able to use tools previously developed for media advance measurement for other printers. The best tool we found is an optical vision system which, when given a specific plot, measures a series of advances and reports the data. For our purposes, predominantly graphics print quality, measuring 32 nozzle advances provides all the information we need about the drive system. The 32-nozzle advance data can easily be extrapolated to the other advance distances we are interested in.

Fig. 7 shows media advance measurements down the length of a page. This data was processed to find the mean and standard deviation, which were compared with the model. First, components were measured and used to build a set of machines. Then the swath advance of the machines built with these components was measured. Finally, the statistics of the measured swath advance were compared with the results from the model with the measured components as inputs. Fig. 7 also shows the results of the simulation: the distribution of swath advances predicted by the model. As can be seen, the measured advance fits within the predicted distribution and the mean and standard deviation of the predicted distribution agree well with the measured mean and standard deviation. Thus, we confirmed the accuracy of our fabrication processes, the simulation model, and the printers we manufacture.

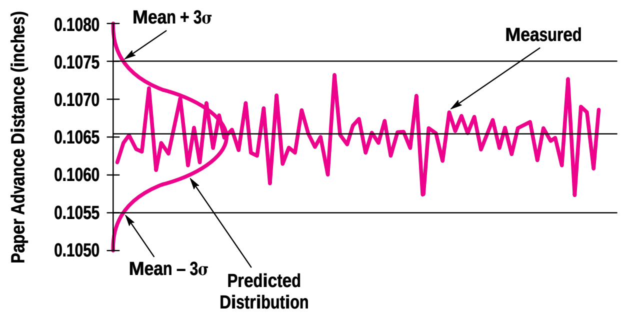

Fig. 7. The measured media advance down the length of one page of a single machine is shown along with the predicted accuracy calculated with measurements of the drive components as inputs to the model, which is shown as a distribution. The actual output of the model is the mean and standard deviation for a given machine.

Acknowledgments

As with any large development effort, there are innumerable people without whose contributions this product would not exist or function as smoothly as it does. We would like to thank Gerold Firl, Mike Green, Joe Milkovits, Tim Zantow, and Tom Halpenny for their contributions to the media path. We would like to thank Ron Kaplan for his valuable assistance in the early characterization and tooling development, Frank Nasworthy for his expertise in designing the pinch wheel, Steve Witte for his assistance with the hardware connectivity and programming skills, Damon Broder for his overall support of the paper advance system, Jeff Wilson and Dennis Culver for their design and fabricating assistance in tooling design, and our staff of lab technicians—Tau Ngo, Nhuong Nguyen, Robert Schmidt, Damon Johnson, and Danny Zepeda—for their many long hours of testing. Thanks also to Steve Gaddi for his support of paper advance testing.