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"MODERN CONTROLS FOR PLASTICS & RUBBER EXTRUSION"

JOHN B. MOORE
ELECTRICAL PROJECT ENGINEER - APPLICATIONS

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SENIOR MEMBER I.E.E.E.

There are many new controls for extrusion available today. This paper will address the most important of these. Namely temperature and drive controls.

In order to better understand modern controls, we will first take a brief look at earlier temperature and drive controls starting, back in the late fifties.

Temperature controllers, at that time, were known as "Millivolt" controllers because they accepted a millivolt signal from a thermocouple and amplified it in order to drive a meter movement to indicate temperature. The two most popular methods of control were to attach a "flag" to the indicator needle and as it passed through two induction coils or two photocells, relays would be actuated to turn heat on and off or to turn cooling on and off thus achieving a rather crude control of a plastic or rubber process. Early models of these controllers were strictly on-off as illustrated in Fig. 1., later models added a feature called "Time Proportioning" as illustrated in Fig. 2. This dramatically improved control reaction as you can see.

With the advent of the "Potentiometric" or bridge type controller introduced by Harrel Inc. in the late sixties, two more terms were added to control Algorithms, namely Integration (Auto Reset), see Fig. 3. and derivative (Rate), see Fig. 4. Incidentally, early models of these controllers used resistance temperature detectors (RTD's) instead of the more familiar thermocouples.

In the late seventies, advances in Microprocessor technology heralded the introduction of the Microprocessor based series of temperature controllers used today with all the modern features E.G. PID, overshoot inhibit, separately adjustable cooling gain (Fig. 5.), process and deviation alarms, simultaneous display of set point and measured temperature and small physical size. E.G. 1/8 DIN (17/8 X 3-5/8").

Further developments in Micro Technology and packaging brought about the Multi Zone Micro-Computer based control systems that are widely used in industry today such as Harrel, Barber Colman, Eurotherm, West Instrument and many others. The latest systems being offered today are distributed control systems where a number of varying modules are furnished, each with its own Micro-Processor and power supply. (Eurotherm and Barber Colman) These modules can be added or subtracted from a system at will and large numbers can be accepted under the control of one master and one or more CRT operator stations in order to control multi extruder processes such as co-extrusion, multi extruder processes and feeding and take away equipment.

These controllers are capable of displaying, annunciating and messaging many more alarm functions than discrete controllers (individual). And, when properly applied can prevent and minimize costly shutdowns and scrap generation. Expanding these systems further can control most of a line with a single unit. Fig. 6.

There are two other major benefits from these systems; Recipe storage and communications. Recipe storage can be accomplished by electronic memory, magnetic cards and cartridges. And allow permanent records of ideal running conditions for recall at a later date when running the same end product.

Communications ports are used to "Talk" to and take instructions from computers which can be located remotely or locally. The computer expands memory by providing hard and floppy disk drives allowing many more "Recipes" or "Product Codes". Further, historical data can be accumulated and printed out at will. Most importantly, SPC/SQC charts can be generated for a given process.

The reader may be wondering why so far I have not mentioned programmable logic controllers (PLC's). The main reason is that most extrusion is a continuous process involving mostly analog signals. However, this is changing rapidly.

On most extrusion processes today, there is more and more justification for applying PLC's to extrusion. The most important of these is acknowledgment that an alarm has occurred and that a command has been executed. A PLC is no longer just a relay replacer. They now have process control capabilities, PID capabilities as well as configurable relay logic. An excellent example of this requirement is the "Touch Screen" or other tactile device to communicate commands to a process or accept digital signals to be converted to messages. NRM is presently engaged in research and development combining a process controller, a PLC and an "AT" computer.

When the writer started in this business some years ago, the most popular drives for extruders were the "MG" set, Fig. 7, and the "Eddy Current" drive, Fig. 8. Both were used extensively in the fifties and sixties to provide variable speed and constant torque to machines of all kinds. Then in 1960 along came the variable speed DC drive using thyratron tubes but almost immediately came the SCR (Silicon Controlled Rectifier) sometimes known as a Thyristor. Fig. 8. The first of these drives used three SCR's and three Diodes due to the high cost of SCR's. They developed a DC power output with a high ripple content which caused some difficulties with early DC motors used to seeing straight line DC power. However, as these drives became more popular, the SCR costs dropped sharply and soon all DC drives were full wave six SCR units which presented a much smoother DC to the motors thus extending commutator and brush life. At the same time, with the addition of AC blowers and tach generators to the motors greater speed ranges became available to the processor. Speed ranges up to 20:1 and speed regulation better than 2% became common. Another valuable benefit of a DC drive is it's inherent ability to maintain constant HP as the motor shunt field is weakened. Fig. 9. This allows an extruder to run more than one product. I.E. polystyrene at high speed low torque and PVC at high torque low speed. Typically 1150/2000 RPM.

Relatively new in the extrusion market is the AC variable speed drive, usually accomplished using an inverter and a more or less standard AC motor. Fig. 10.

The main disadvantage of the AC drive is its limited speed range (usually 5:1) and the torque droop at low speed. We have found that so far, for extruder applications, when comparing AC to DC over the normally 20:1, 100% torque conditions; the AC drive is 150% higher in cost than DC and the power unit physical size becomes a limiting factor.

Within the last two or three years, we have seen a vastly increased customer preference for even higher accuracy and more versatile DC drives, hence the introduction of the standard cost digital drive controllers by GE, Siemens, Fincor and Reliance. We are excited about these drives and expect them to move very well.

In conclusion -- thanks to our friends in the space and defense industries, we have been deluged with micro electronics over the past twenty years and thus have been able to apply more space saving and accurate controls to extrusion equipment enabling us to build smaller diameter higher output equipment generating less scrap and with minimum downtime. Also to develop and process more exotic compounds.

PID CONTROL

1. ON/OFF CONTROL - OUTPUT TURNS ON FULL HEAT - OFF OR FULL HEAT - OFF FULL COOL (USUALLY AIR OR WATER). WHEN TEMPERATURE REACHES SET POINT OUTPUT TURNS OFF BUT RESIDUAL ENERGY CAUSES OVER SHOOT THEN LINER SHOOT CONTINUOUSLY, CAUSING CYCLING ABOUT SET POINT AND NEVER STABILIZING.

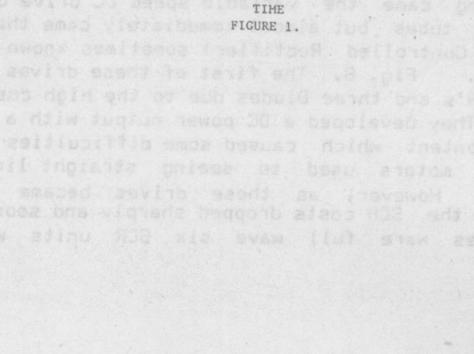


FIGURE 1.

2. P.
TIME PROPORTIONING - INSTEAD OF TURNING FULL ON UNTIL SET POINT IS REACHED THE OUTPUT (HEAT) TURNS OFF AT A PREDETERMINED POINT BEFORE SET POINT IS REACHED. IN FACT IT TURNS ON AND OFF ANY NUMBER OF TIMES UNTIL SET POINT IS REACHED, THEREBY REDUCING THE CYCLIC OVER SHOOT AND EVENTUALLY WILL SETTLE OUT AT A POINT BELOW SET POINT. THIS IS CALLED DROOP AND CAN BE MINIMIZED BY THE OPERATOR ADJUSTING THE SET POINT TO COINCIDE WITH THE INDICATOR-MANUAL RESET.

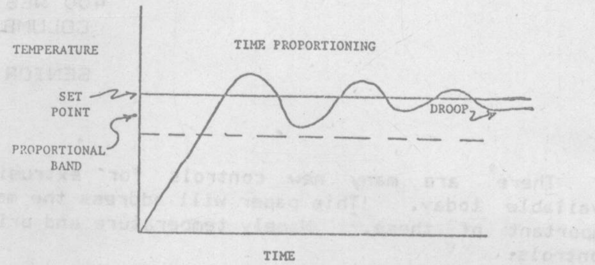


FIGURE 2.

3. I.
AUTOMATIC RESET (INTEGRAL) IS AN AUTOMATIC ELECTRONIC ADJUSTMENT THAT COMPENSATES FOR THE DROOP BEFORE IT EXISTS BY USING AN INTEGRATION THAT DRIVES THE PROCESS TEMPERATURE TO COINCIDE WITH SET POINT. NOTE THAT THIS IS AN EXTREMELY SLOW FUNCTION AND CAN TAKE UP TO 30 MINUTES TO SETTLE OUT AFTER A SET POINT CHANGE. THIS IS PI CONTROL, RESET IS PREVENTED UNTIL THE PROCESS TEMPERATURE ENTERS THE PROP BAND. OTHERWISE EXTREME FLUCTIONS WOULD OCCUR. THIS IS KNOWN AS ANTI-RESET OR OVER SHOOT INHIBIT.

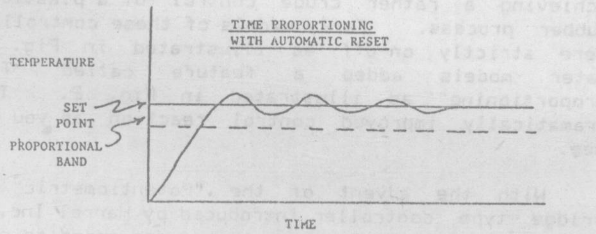


FIGURE 3.

4. D.
RATE (DERIVATIVE) IS AN ANTICIPATORY FUNCTION THAT MEASURES THE RATE OF INCREASE OR DECREASE OF PROCESS TEMPERATURE AND FORCES THE CONTROL INTO A PROPORTIONING ACTION ON AN ACCELERATED BASIS TO SLOW THE ACTION THUS REDUCING OVER SHOOT ON START UP AND SPEEDING STABILITY AFTER A SET POINT CHANGE. THIS IS PID CONTROL.

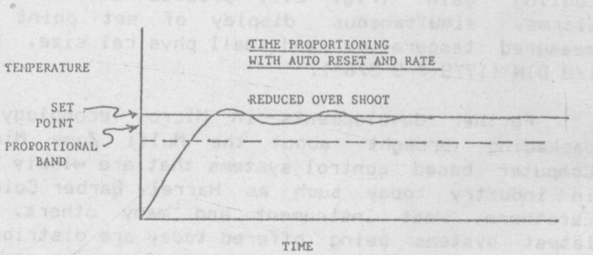


FIGURE 4.

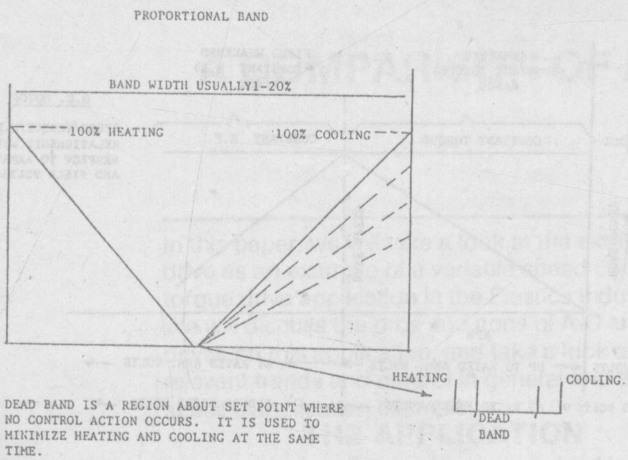


FIGURE 5.

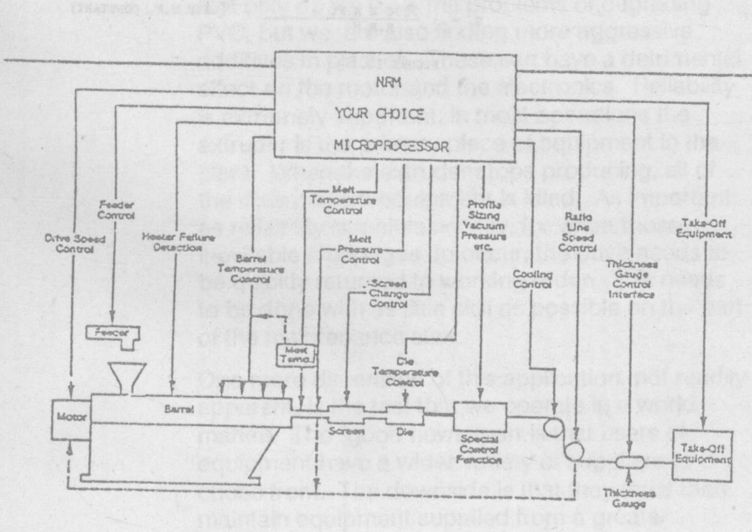


FIGURE 6.

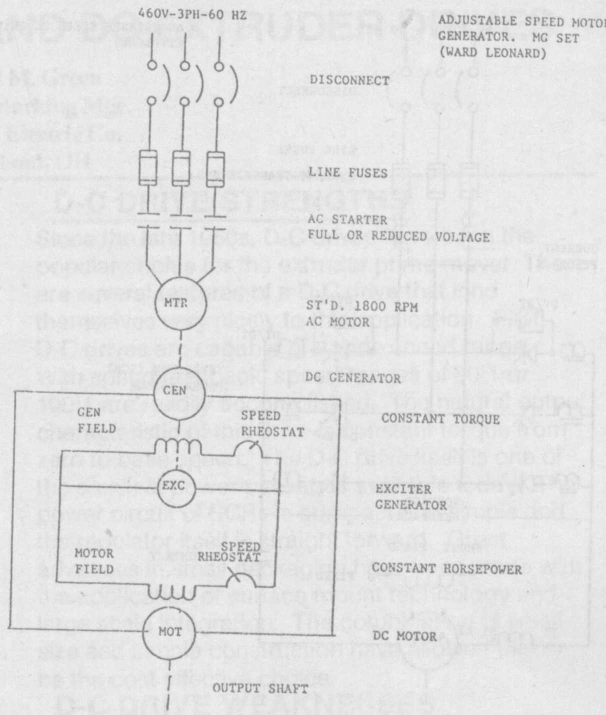
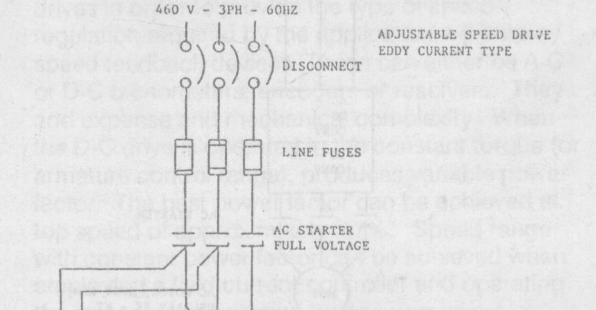


FIGURE 7.



$$\text{DISSIPATED HP (HEAT)} = \frac{\text{SLIP RPM}}{\text{OUTPUT RPM}} \times \text{HP} \cdot \text{LOAD}$$

FIGURE 8.

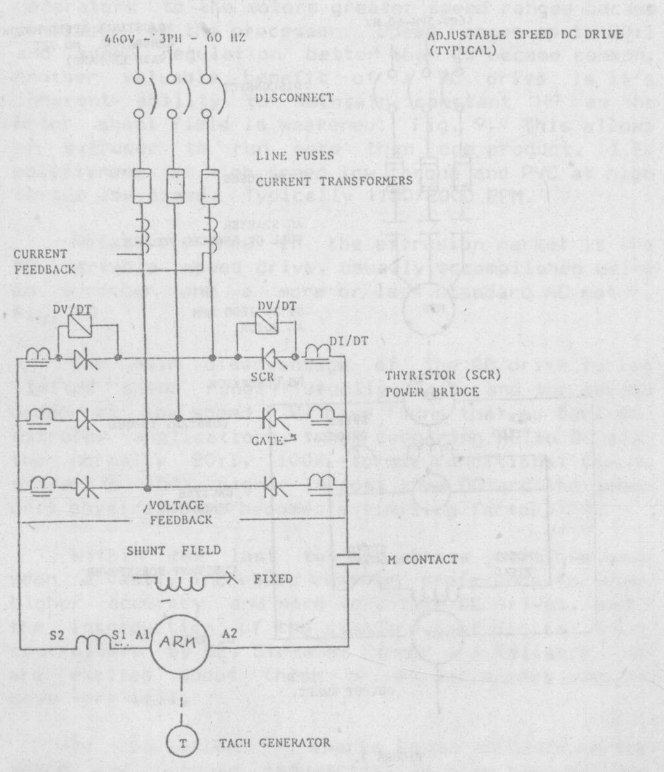


FIGURE 9.

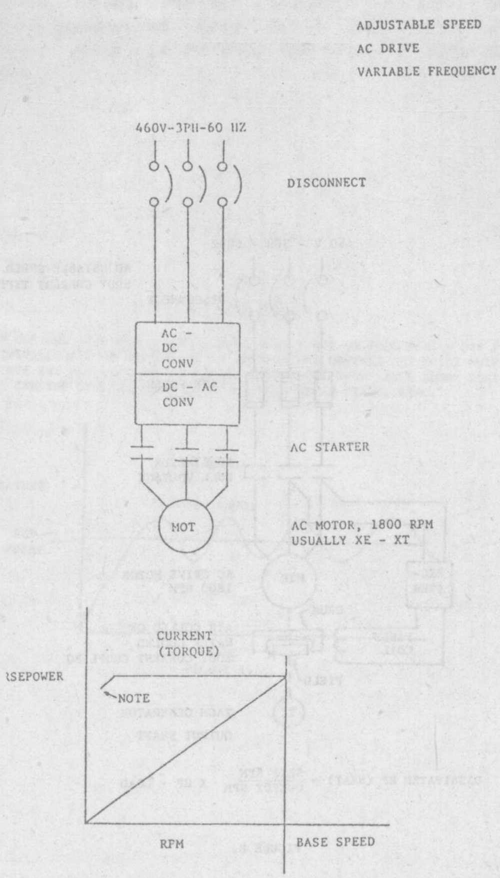
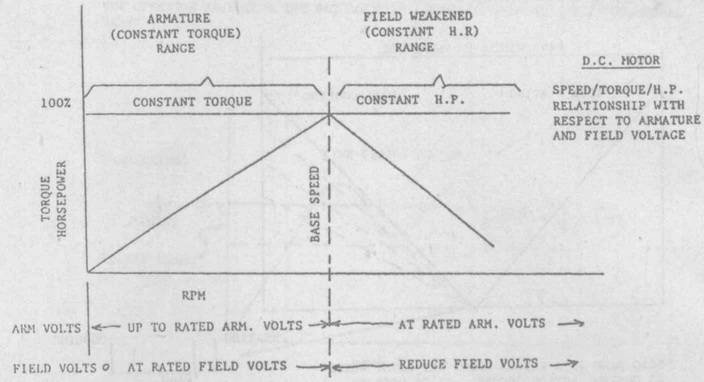


FIGURE 10.



1.) H.P. INCREASES IN DIRECT PROPORTION TO SPEED WHILE DC MOTOR SPEED IS INCREASING DUE TO RISING ARM. VOLTS MOVING TOWARD BASE SPEED.

$$H.P. = \frac{TORQUE \times RPM}{5250}$$ (WITH TORQUE CONSTANT)

2.) TORQUE DECREASES INVERSELY PROPORTIONAL TO SPEED WHILE D.C. MOTOR SPEED IS INCREASING DUE TO FALLING FIELD VOLTAGE BEYOND BASE SPEED.

$$T = \frac{5250 \times H.P.}{R.P.M.}$$ (WITH H.P. CONSTANT)

FIGURE 11.

A COMPARISON OF AC AND DC EXTRUDER DRIVES

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In this paper, we will take a look at the extruder drive as an example of a variable speed constant torque drive application in the Plastics Industry. We will discuss the pros and cons of A-C and D-C drives on this application, and take a look at relevant trends and control in general and a specific application example.

THE APPLICATION

The extruder application is characterized by a constant torque drive requirement of at least 10:1 speed range. Many extruders today need to operate across a wider speed range than this to run a greater variety of product, but for purposes of our discussion, we will limit it to the general case of 10:1. The load is constant torque from minimum speed to top speed and typically requires speed regulation of the 1.0 to 0.5%. The atmosphere around the motor is growing increasingly hostile. Not only do we have the problems of degrading PVC, but we are also finding more aggressive additives in plastics. These can have a detrimental effect on the motor and the electronics. Reliability is extremely important, in most operations the extruder is the primary piece of equipment in the plant. When the extruder stops producing, all of the downstream equipment is idled. As important as reliability is maintainability, for when those inevitable stoppages do occur, the drive needs to be quickly returned to working order. This needs to be done with as little skill as possible on the part of the maintenance staff.

One more dimension of this application, not readily apparent, is the fact that we operate in a world market. The "good news" part is that users of equipment have a wider variety of suppliers to chose from. The downside is that they must then maintain equipment supplied from a greater number of vendors. From the OEM point of view, one can be successful today and export a small amount of equipment. Tomorrow you must export a large percentage of your production to maintain competitive position in the marketplace. This will require that the OEM service and support the drives that are purchased over a much wider geography. Standardization and availability of parts and service around the world will be an increasingly important issue in the decision making process for both the OEM and the user.

D-C DRIVE STRENGTHS

Since the late 1960s, D-C drives have been the popular choice for the extruder prime mover. There are several features of a D-C drive that lend themselves very nicely to this application. First, D-C drives are capable of a wide speed range. With speed feedback, speed ranges of 50:1 or 100:1 are readily accomplished. The natural output characteristic of this drive is constant torque from zero to base speed. The D-C drive itself is one of the smallest power packages available today. The power circuit of SCRs is compact and simple and the regulator itself is straight forward. Great advances in small packaging have been made with the application of surface mount technology and large scale integration. The combination of small size and simple construction have allowed this to be the cost effective choice.

D-C DRIVE WEAKNESSES

The primary weakness of the D-C drive is not a weakness of the drive itself but a weakness of the motor. D-C drives use D-C motors which employ brushes to mechanically commutate the torque producing current in the motor. Brushes are not a performance issue, but are a maintenance one. Properly maintained, a D-C motor will run for a very long time. However, if the brushes are neglected and not replaced when worn, the ensuing reduction in brush pressure on the commutator will result in rapid and catastrophic wear on the commutator. The result will be an expensive and time consuming repair of the D-C motor. D-C drives in order to provide the type of speed regulation required by the application will employ speed feedback devices. These can either be A-C or D-C tachometers, encoders or resolvers. They add expense and mechanical complexity. When the D-C drive is operated in the constant torque (or armature control range), produces variable power factor. The best power factor can be achieved at top speed of approximately .87%. Speed range with constant power factor can be achieved when employing a field current controller and operating the motor in the constant horsepower range. Across this speed range the power factor is constant.

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Before discussing the A-C drives' strengths and weaknesses, let us examine the five different types of A-C drives available in the marketplace today:

- First and simplest is the VVI drive (variable voltage inverter). The output waveform is a six-step voltage waveform approximating a sinewave. Typical speed range is 10:1 (output frequency range). This frequency range will not produce a 10:1 constant torque range because of limitations in the motor. This drive is suitable for low performance applications with single or multi-motor configurations.
- CSI (current source inverter) produces a analogues waveform to the VVI but as a current step. This drive requires matching of the motor impedance to the drive circuit and therefore is applied with single motors only. The drive is inherently regenerative, which is a nice feature for overhauling applications.
- PWM (pulse width modulated) is the most popular output waveform of drives being produced today. The output is a pulse width modulated waveform that, when applied across an inductor (like a motor), approximates a sinewave. Because both the chopping frequency and duty cycle of the pulses can be varied, the drive designer has much more flexibility in producing voltage and current at the motor across a wide frequency range. PWMs can be applied on single or multi-motor applications and can produce low speed motor operation superior to that of VVI and CSI.
- Brushless (A-C or D-C). A brushless motor can be best described as an inside out D-C motor where the field flux is produced by magnets that are attached to the motor shaft and the torque producing flux is produced in a three-phase stator winding and commutated electronically by the drive. Brushless drives are inherently capable of very high performance. The power circuit of the drive is similar to that of the PWM with some additional complexity in the regulator to produce full torque at zero speed and high dynamic performance. The drawbacks of the brushless design are the fact that it requires a special motor with a special rotor (magnets), and shaft position and velocity feedback in order for the drive controller to operate properly.
- Vector control (field oriented control). This is the most promising of all of the A-C drive technologies for ultimately replacing D-C drives. Like the brushless, it is capable of extremely high dynamic performance. It has the additional feature that it uses a standard squirrel cage motor. It does require shaft position and velocity feedback. Like the brushless, it's drive power circuits closely resemble those of PWM and it has a higher complexity regulator. Vector controlled drives are capable of constant torque operation from zero speed to base speed and some are designed with constant horsepower capabilities as well.

A-C DRIVES STRENGTHS

The greatest strength of the A-C drive is the fact that it employs an induction motor. This motor is the simplest electric machine that we know how to build today. There is one moving part and only the bearings are maintenance items. Another plus for A-C drives is the fact that they can be built to delivery constant power factor across the speed range. This is becoming increasingly important as power utilities begin to charge penalties for lagging power factor.

A-C DRIVE WEAKNESSES

The motor is also a major weakness of the A-C drive. In order to product constant torque, constant current (approximately) is required. This means that there is constant heating of the motor regardless of the speed at which it is running. This means, that when applied over wide constant torque range, the cooling of the motor must depend on the speed of the shaft (as is traditionally the case with an A-C motor). We will begin to see A-C motors built with separately driven blowers to deliver constant cooling to the motor at all times. The two drives that are capable of wide constant torque ranges (brushless and vector), require shaft feedbacks. This is difficult to accomplish on today's A-C motors.

Another weakness of the A-C drive is size. A-C drives will generally always be larger than D-C drives by a factor of 1.5 - 2:1. In order to produce adjustable frequency current, first you must rectify the A-C line to a D-C bus (a D-C drive) and then rectify that bus back into variable frequency. Therefore, there are twice as many power components in an A-C drive as in a D-C drive. In the past, the regulator has been approximately twice as complex as that of a D-C drive. Present state-of-the-art electronics allows this factor of complexity to come much closer to 1:1 than 2:1.

Circuits that were difficult to produce with descrete parts can now be accomplished with large scale chips and microprocessors. This has greatly reduced the complexity differences between A-C and D-C drives.

Above and beyond these issues of A-C versus D-C, there are some current trends in drive and control technology that we would like to discuss:

DIGITAL CONTROLS

Digital controls for drives have a number of inherent features that are very desirable for today's environment. It is possible to achieve much higher reliability with digital drives. This stems from the fact that there are many fewer components required to accomplish the same functionality. The difficult functions of the drive are accomplished in software. The microprocessor employed in these drives can be used to perform self-test during manufacturing and later on through product life. The problems associated with analog component characteristic change (drift over time) are not present. Digital controls also allow repeatable settings of key drive parameters. This is important to the OEM when he is reproducing a duplicate machine month after month. It is also important to the user when he is replacing a drive and returning the machine to exactly the same operating performance that it was the day that he received it.

Digital controls, properly designed allow much greater flexibility in application solution than we could achieve with analog hardware. A standard, generic hardware set, can be used in number of different ways with different software. This allows a standard set of parts to accomplish a great number of tasks. The differences are all in the software. Finally, digital controls and microprocessor controls have allowed us to dramatically shrink the size required to do the same functions. This comes from LSI technology (large scale integration) and from surface mount manufacturing techniques which allow much smaller packages for electronic components, smaller PC boards, fewer PC boards, and fewer connectors.

COMMUNICATIONS

As more and more elements of our plastics machines are accomplished with digital products, communication becomes much more important. The best way to interface to a digital drive is with a serial link. However, all serial links are not created equally. Beyond the obvious issues of protocol and baud rate, lies some much subtler yet extremely important issues of integrity, speed and architecture.

By integrity we mean the ability to check for and recover the errors in the communication link. It is not acceptable to start and stop, and change the speed of a drive over a serial link that has no error checking and can not determine whether communications has been successfully completed or not. This generally requires the use of a protocol which includes error checking features. The second issue to consider when looking at a communication link is that of speed. You must evaluate not just the baud rate (which is the raw bits per second) but the actual data transfer speed. You will find that when you install a protocol on your communications link (to insure integrity), that a large amount of time will be dedicated to the error checking and message formatting and that the actual net data throughput will be much lower than the raw data throughput. This will need to be considered when using the communication link to operate several drives in a coordinated fashion. The third issue of communication is that you have to consider both ends of the communication line. Not only the digital drive, but also the master controller or host. For real time control of machinery it is highly recommended that the master controller be designed such that when fault conditions occur that the I/O (input/output) revert to a known state and that during unusual operating conditions or faults, the equipment behaves in a predictable and safe fashion. This is one of the design features that separates industrial programmable logic controllers (PLCs) from commercial office-type computers (PCs).

CONTROL INTEGRATION

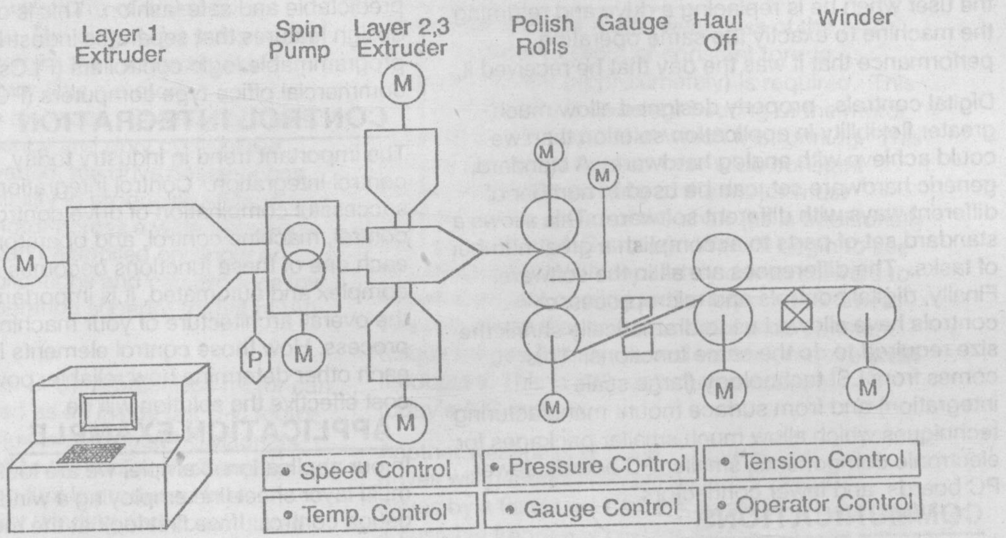
The important trend in industry today, is that of control integration. Control integration is the successful combination of drive control, process control, machine control, and operator control. As each one of these functions becomes more complex and automated, it is important to consider the overall architecture of your machine or process. How those control elements interact with each other determine how reliable, powerful and cost effective the solution will be.

APPLICATION EXAMPLE

In our application example, we are looking at a multi-layer sheet line employing a winder and gauge control. If we first look at the motors involved in speed control, we have the spin pump, the second and third layer extruders, the three polishing rolls and the hauloff. The areas of our machine in temperature control would include the main extruder barrel, the spin pump, the extruders for layers two and three and the three polishing rolls.

Further process controls comes in the form of pressure control in which the pressure of the main extruder is regulated by adjusting the speed of the screw. We are also doing on-line gauge control which could have interfaces to temperature profiles on the dye, dye lip openings, polishing roll spacing and speeds, or a combination of the above. We are performing tension control on the winder motor to ensure that we wind at a constant or tapered tension and produce a consistent roll of good quality. And finally, all of these control loops need to interface to the operator. In this particular example, we have chosen to do that through a CRT and a console, giving him the most information and us the most flexibility in presenting that information to him. A well designed system will integrate all of these controls into a common hardware and software set so that interacting algorithms can be accomplished. It will also allow the operator to make quick and easy use of the system.

In review, we have discussed the pluses and minuses of A-C versus D-C drives when employed as an extruder prime mover. We have discussed the benefits of digital versus analog and the important issues of how your control systems can be integrated. The opportunity before us today as users and builders of equipment and processes is to take advantage of the promise that digital and integrated control systems offer. For done correctly, there are three primary benefits of control integration. First, you will produce better and more reliable processes producing more, higher quality product. Secondly, the overall reliability of our system will be better because we will accomplish the same amount of control with fewer components. The third promise is to make integration cost effective . Properly done, control integration will result in lower machine costs. Interestingly enough, this will be the result of more integration rather than less. For doing each of these pieces individually is expensive. However, a system with proper architecture and good forethought can be assembled to integrate more control for less dollars than could be accomplished with individual control.



AN INTRODUCTION TO
AUTOMATIC PROFILE CONTROL

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Abstract–A brief introduction to measuring the profile variation of an extruded flat sheet and techniques for controlling that profile variation with a flexible-lip die.

I. INTRODUCTION

The purpose of this paper is to look at some of the issues involved in controlling the profile across an extruded sheet of plastic using a flexible lip die. But before that profile can be controlled, it must be measured. If we cannot determine what the profile is, we cannot say if it needs improvement nor when to stop attempting to improve it. There are a few items worth noting on this subject.

II. PROFILE MEASUREMENT

The starting point to profile measurement is to mount a fram across the sheet, move some sort of measuring device across the frame, and get a series of measurements crossing the sheet. But because the sheet is moving as the measurements are made, the measurements are not take straight across the sheet, but are taken on a diagonal across the sheet. This is displayed in Figure 1, where we start measuring at point A on the sheet. Fifteen seconds later the gauge probe has moved half way across the sheet to point B, and has measured in a line from point A to point B. On reaching the edge of the sheet at point C, the profile will show measurements for the diagonal slice through points A, B, and C.

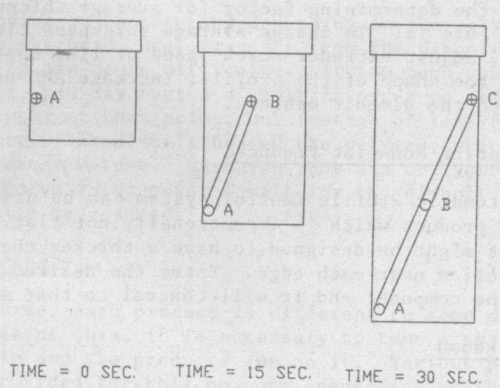

Figure 1 Scanning across the Sheet

Thus, what you have measured is not just the cross-sheet profile, but also any variation that occurred along the sheet during the scan. With a 200 feet per minute line speed and taking 30 seconds to scan across the sheet, the measured profile includes 100 feet of variation in the machine direction.

At this point, we should define a few terms concerning extruded film and its measurement.

Profile–The plot of thickness versus diebolt position. This is the data resulting from one traverse of the sheet.

It is useful to divide variation in the product thickness into its components:

Profile variation–Variation in cross-web uniformity. This is caused, for example, by a non-uniform die opening, non-uniform flow in the die, and non-uniform heating. Automatic Profile Control addresses this type of variation.

Machine-direction variation–Variation in the direction that the sheet travels.

Some variation in the machine direction is random and some is cyclic. We can further divide this category into short-term and long-term:

Short-term Machine-direction variation–This has a cycle less than the time it takes to scan across the sheet, and therefore cannot be controlled. This high frequency variation is caused, for example, by screw design, out of round rollers, and pressure surging. It can be reduced with proper design, maintenance, and persistence.

Long-term Machine-direction variation–This has a cycle longer than the time it takes to scan across the sheet. This can be caused by variations in the material fed to the extruder, including regrind ratios, operating conditions, and variation in process temperatures. It can be controlled by adjusting the extruder screw speed or the line speed.

If we have a hypothetical sheet with no machine direction variation, but one cycle of sinusoidal variation across the web, the measured profile might look like Figure 2.

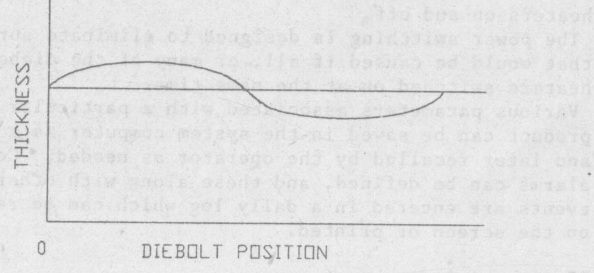

Figure 2 A Sinusoidal Profile

Another hypothetical example could have no profile variation (perfectly flat across the sheet), but machine direction variation is a sine wave. Depending on how fast the sheet is scanned, the measured profile could again look exactly like Figure 2! The number of oscillations that appear depends on the number of machine-direction cycles that occur during the scan time. So when the measured profile from a single scan across the sheet is viewed, realize that part of the displayed variation is machine-direction variation and part is true profile variation.

The obvious first step is to minimize the machine-direction variation, in particular, that part which is short-term. This has been accomplished, with the aid of gauging companies, for many years. Ideally, the short-term variation can be reduced to where it is small with respect to the profile variation. To

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further improve the accuracy of the profile, we can also average successive scans together. The optimum way to do so involves a compromise: Using more scans improves accuracy by reducing the short-term machine direction variation included in the profile, but also includes old data. The best profile data comes from ascertaining the correct amount of averaging through trial and error, taking into account the nature of the machine-direction variation. Two minute averaging will often provide a measured profile that permits effective control.

III. AUTOMATIC PROFILE CONTROL

An Automatic Profile Control system is designed to produce flat product. Flatter product opens the door to material savings, both in terms of reducing scrap and of permitting lower average weights. Other advantages include a more uniform, better looking roll and more uniformity of product characteristics. By installing an Automatic Profile Control system on a line, you can have the same high level of quality every shift on every day. Less operator attention is required, freeing the operator to increase production on the line or to attend to additional lines. This savings in labor can be a significant incentive for Automatic Profile Control.

A. The Components

The starting point for these benefits is a die with a flexible lip, which can be adjusted by a computer. One mechanism for doing this, available from Extrusion Dies Inc., is to apply heat to bolts mounted perpendicularly to one side of the lip. The bolts are spaced approximately one inch apart. As the heat is varied, the bolts' lengths change, the lip is deformed, and the product profile is changed.

A typical system controlling such a die is shown in Figure 3. The Gauging System shown on the left side does measurement and sends thickness data to the Electronics Console containing a 16-bit microprocessor, which communicates with the Solid State Relay Cabinet, where an intelligent controller turns the diebolt heaters on and off.

The power switching is designed to eliminate surges that would be caused if all, or many of the diebolt heaters switched on at the same time.

Various parameters associated with a particular product can be saved in the system computer as a recipe and later recalled by the operator as needed. Certain alarms can be defined, and these along with other events are entered in a daily log which can be recalled on the screen or printed.

B. Control Stratagies

We start with a die with each of the diebolt heaters at 50% power, half ofthe time the heater is on and half of the time it is off. Manually turning the diebolts, we set the die gap to 25 mils along its entire length. Now we start up the line and begin scanning the sheet. The measured profile is sliced into segments, each segment centered on one of the diebolts. For each of these segments, the computer calculates the percentage deviation from the average of the sheet. Control now begins, increasing the power to diebolts where the profile is above average, decreasing power to diebolts where the profile is below average. This is repeated, scan after scan, and the profile variation reduces towards some minimum. On a different line running a different product, we might start with all the diebolt heaters at a different power level. Or, we might use a different starting die gap.

Starting with all the diebolt heaters on for fifty percent of the time allows an equal range of adjustment both up and down. This percentage is then increased to close down the die lip at a particular point of the profile, to make the plastic at that point thinner. Or the percentage can decreased to open up the die at that point. A short time after the power level is changed, the die lip opening will begin to change. One thing which makes control a challenge, is the length of time required to see the entire change, which can run 15 or 20 minutes due to the heating and cooling time constant and profile resolution. The full effect of the last change is never seen before making the next adjustment.

It is critical to correctly map the profile data to the diebolt positions. Diebolt 20's segment of the sheet is not likely to improve if diebolt 20 is controlled based on what is happenning at diebolt 22.

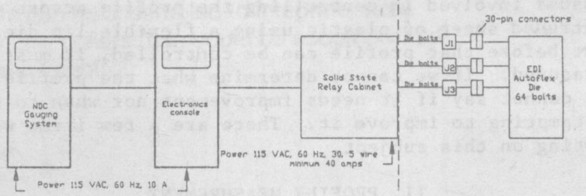

Figure 3 A Typical Automatic Profile Control System

D. Controlling to the Average

The key to understanding Automatic Profile Control is this. Control is always made toward the average thickness. Errors are calculated relative to the average to further decouple machine-direction variation and to facilitate correction of the error. The power level on a given diebolt is adjusted to move the corresponding part of the sheet toward the average thickness of the entire sheet. No attempt is made to move the profile toward the target thickness. That would only cause the die lip to open wider or to close down, and the die lip is not the determining factor for average thickness. So the rule is: To change average thickness closer to target, adjust extruder screw speed or line speed; to change the shape of the profile, increase AND decrease power to the diebolt heaters.

E. Creating Non-flat Products

The Automatic Profile Control system can be used to create product which is intentionally not flat. A product might be designed to have a thicker than average section near each edge. Enter the desired profile into the computer and it will control to that shape.

F. Neckdown

As the plastic exits from the die, it is drawn down to the desired thickness. At the same time that thickness is decreasing, so is the width of the sheet. This shrinkage across the sheet is not uniform, most of it occurring near the edges. See Figure 4. You may find all the material that comes from the first 3 diebolts ends up only 1 inch wide, while 3 diebolts near the center of the die produce 3 inches of the web. If it is necessary to trim off the edges of the sheet, and all the neckdown occurs within the trim width, then neckdown can be ignored. Otherwise some form of neckdown compensation is used to map the thickness readings of the profile to the actual diebolts responsible for them. This allows good control of the edges of the sheet.

G. Interaction across the Die

In adjusting a die, you quickly discover that changing the die lip opening at a single diebolt will cause

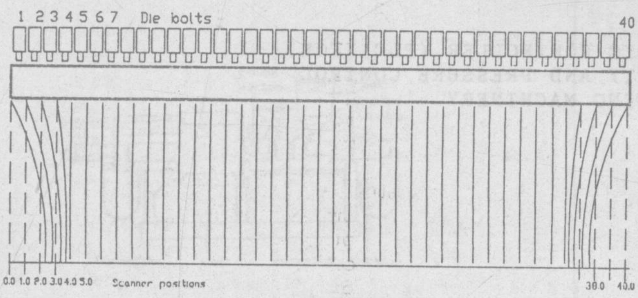

Figure 4 An Example of Neckdown

changes in the profile at that point and also elsewhere. Tightening down on diebolt 18 will reduce the profile at diebolt 18, but also at diebolts 17 and 19. Adjacent Bolt Compensation addresses this overlap of effect.

A second type of interaction is more significant. You tighten down on diebolt 18 and that part of the profile goes down as desired, but now another part of the profile nowhere near diebolt 18 has gone high. This is conversation of mass. Diebolt 18 has blocked part of the flow at that point, but the extruder will push that mass through the die somewhere. This is a prime reason for backing off on a diebolt for every tightening on a diebolt, i.e., keeping the decreases in power equal to the increases in power.

The situation where a diebolt-heater tries to close the die lip entirely or where it backs up away from contact with the die lip each give a situation with no control. Certainly this is not desirable. Periodic regapping of the die, with all heaters at the 50% power level, will undo the effects of excessive manual adjustment of the diebolts, which will help to prevent such situations of no control.

H. Heat Transfer

Depending on the die and depending on the polymer being extruded, heat transfer from the diebolts to the die lip can cause difficulty. If too much transfer occurs, you may heat a diebolt in order to reduce the thickness at that point, but instead of less flow there is more. The diebolt heated the polymer, which flowed in greater volume. Matching your die to your polymer will solve this; power levels for the diebolt heaters can also be reduced.

I. Tuning

Of course, each process is different to some degree. Because of this, it is necessary to tune a system to its die and the products run on it. Various parameters are provided for this purpose, depending on the nature of the control schema being used. It can take several days of running to get a good set of parameters. After that, you can continue experimenting with various changes, running them for a day, then evaluating whether to keep the change or not. Then make another change. It is useful during this tuning to look back at history of bolts, noting what the error has been and what correction was made at each point.

In tuning, it is generally necessary to select a compromise set of numbers. One set might operate well when the line is running smoothly, but not handle upsets well. Another set might be excellent with line upsets, but not do as well as the other set when the line is quiet. Compromise works wonders.

IV. CONCLUSION

The purpose of Automatic Profile Control is to shape the profile of the sheet. To do this it requires adequate measurement of the sheet, with special attention to aligning the measurement data to the positions of the diebolts on the die. The simplicity of the operation is to press down on the high spots, back off on the low spots, and obtain a more satisfactory product.