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MULTI-VARIABLE PAPERMACHINE CONTROL

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Synopsis Supervisory control of average basis weight and moisture in the machine-direction must be achieved by different control procedures, depending upon the importance of other objectives such as production rate and dimensional stability. Maintenance of close control of refining must be modified, depending upon the number and arrangement of refiners. The control of basis weight, moisture and refining all interact with each other to increase the complexity of the control models required, since the adjustment of a single input variable may influence all three areas of control. Some of the experiences of International Paper's Southern Kraft Division control group in working with these control areas are described.

Introduction

IN A well-operated mill, where careful records of the test results obtained during routine sampling for quality control are kept so that the data may be properly ordered in time, analysis of the records for assignable causes of variation will almost certainly reveal that a large component of the variation can be attributed to differences between shifts. A little investigation of the operating practices of the machine crews will soon reveal the reason for this rather unexpected situation. When one shift crew relieves another, it is customary for the new crew to make changes in the settings of various controls on the papermachine. These changes are made, not because the paper made during the last eight hours has been of bad—or even poor—quality, but because the new crew believes that it can more consistently make paper of uniform quality with the machine adjusted to settings of the controls that they have found serviceable in the immediate past. It is thus demonstrated daily on papermachines not computer-controlled that there are many possible ways of adjusting the flows, speed controllers, temperatures and other variables that will result in acceptable paper.

There is a multiplicity of tests that are routinely run on paper in order to determine its suitability for some purpose. Most of these tests are empirical;

Under the chairmanship of Dr D. B. Brewster the instruments used to perform the test are designed to approximate under carefully controlled conditions some particular stress or strain to which the paper may be subjected. In most situations, it is not possible to describe the properties that the paper must have to give satisfactory test results in terms of fundamental physical or chemical properties of the sheet. A wide range of paper weights, fibre content, chemical additives and so on may usually be found that will give empirical test results within a satisfactory range. Because the sales market for the manufactured paper depends only upon its ability successfully to meet the arbitrary limits specified for these empirical tests and on its price, it is natural to concentrate upon making certain that the test results exceed the minimum values set. Those fundamental properties or empirical tests not specified are permitted to seek whatever level will maintain the important tests at satisfactory values with minimum operator interference.

Analog controllers give an operator important assistance in maintaining the settings of various inputs to the papermachine close to their desired values. Digital computers can in many cases give even more precise control. If an upset in an input occurs, however, requiring that some other input be changed to compensate for the upset, the adjustments made may interact in complicated ways to change the final test results. In the absence of any other method of co-ordinating these compensating adjustments, the operator must decide what inputs to change and by how much. It is small wonder that operators tend to select levels of inputs that they believe to give them the maximum freedom of variable adjustment without causing a major upset in end product test results and stick to them regardless of how well the papermachine may have performed during the previous shift.

One of the justifications for adding a computer to the control hardware used on a papermachine is that much closer control of input levels may be achieved, with consequent savings in raw materials and improvement in product uniformity. Yet, as closer control over individual inputs is achieved, the interactions of changes in input levels become more readily apparent and their influence upon final product test results are not readily detectable. It is the purpose of this paper to enumerate some of these interactions.

Basis weight

THE first papermachine variable to which a digital computer control was applied in the Southern Kraft Division of International Paper Co. was average basis weight. The papermachine made a single quality of paper, tabulating index card stock. The paper was dried to a very low moisture content in a calender dryer. The basic scheme for basis weight control used a continuously scanning beta-gauge to determine the average fibre content of the web and a moisture gauge to determine the percentage moisture content. The average fibre weight was then used to control the opening and closing of the stock valve to maintain a uniform average fibre weight and the average moisture weight was used to control steam flow to the calender dryer section to maintain a uniform average moisture content. The result of holding average fibre content and average moisture content more nearly constant than had been possible was to make average basis weight more uniform. The uniformity in weight obtained was sufficiently impressive to justify application of the computer to basis weight control on the papermachine adjacent to the one first controlled.

The second papermachine manufactured a different product. The grades made on this second machine were unbleached wrapping papers and liner-board. Because such papers fetch a much lower price per ton on the market, it is important to make these papers in the largest volume possible. It is not feasible to bring the paper to a low water content, add back an excess of water, then remove the excess to obtain a permissible level; rather the machine must be operated at the maximum possible production rate. The limiting condition is the amount of steam available for drying the paper. Because of the way in which steam is delivered to the dryers, only a large number of drying rolls could be affected by adjustment of the steam flow and response of dryer temperature to changes in steam flow was very sluggish. It was accordingly decided to control basis weight solely by adjusting the quantity of oven-dry fibre per unit area. Since the moisture content of the sheet was not critical, so long as the maximum permitted was not exceeded, it was thought that this would result in improved control. This did not turn out to be correct. It was found that changes in oven-dry fibre weight resulted in wet or dry areas in the paper, because no adjustment in steam flow was made to compensate for the increased or decreased fibre content and the dryers were operating so close to maximum steam capacity that small changes in fibre content resulted in large changes in the percentage of water retained in the sheet. The control scheme accordingly had to be modified to include some adjustments for moisture before successful control could be achieved.

The two examples mentioned above show the importance of considering as as many aspects of the process as possible. On the first papermachine, uniformity of the product was essential and the value of the paper produced was sufficiently high to make it feasible to operate the machine at less than maximum capacity in order to achieve the required uniformity. The points at which control was applied were ones at which change in level could be effected rapidly, response to adjustments could be detected quickly and sufficient capacity was available to encompass a wide range of adjustments. On the second machine, a second important variable—production rate—had to be considered. Since this variable had to be maintained at maximum, if at all possible, a new control strategy had to be introduced. It appears fairly obvious that the most useful way to control basis weight on this second machine should be by operating it with maximum steam to the dryers, adjust dry fibre weight by controlling the stock valve and maintain uniform moisture content by varying the machine speed. Unfortunately, varying the machine speed introduces complexities into the model, since the lag from adjustment of the stock valve to detection of the change in fibre weight is then variable and the feedforward portion of the model becomes very complicated.

There are other difficulties to be overcome besides those requiring modification in strategy to maintain objectives other than uniform fibre weight. The achievement of uniform fibre weight in the finished sheet requires that the quantity of fibre laid down per unit area be maintained constant. If the proportion of fibre per unit volume in the stock line (consistency) is uniform, the weight of fibre delivered to the wire can be controlled by adjusting the volume of stock delivered to the head box. If the volume of fibre suspension flowing from the head box on to the wire is constant, the fibre basis weight of the sheet produced will vary with the percentage of fibre in the suspension flowing out the slice. In fact, the consistency of the suspension in the stock line is not constant, but shows a periodic fluctuation induced by the consistency controller, a fluctuation characteristic of feedback control loops. This fluctuation leads to periodic opening and closing of the stock valve. As the stock valve opens and closes, the volume of liquid supplied to the head box increases and decreases, changing the pressure that forces the suspension through the slice on to the wire. The opening of the stock valve to admit more fibre to the head box is thus accompanied by an increase in the volume of suspension in the box at the same time that the percentage of fibre per unit volume is increasing. The resulting increase in pressure in the box increases the flow per unit time through the slice of a suspension carrying a higher percentage of solids. The fibre per unit area of the sheet is thus increased both by a change in volume and a change in flow, so the change in weight may be greater than that required. Thus, much more careful control of both consistency and effective head box head is required. It is equally obvious that periodic fluctuations in wire speed because of the action of speed governors will have a similar effect upon fibre weight. All of these factors will, in turn, affect the amount of water retained in the finished sheet and consequently affect total basis weight to a greater degree.

Refining

THE fibre furnish to the papermachine must be mechanically worked to varying degrees to achieve the necessary bonding of fibres together, giving the finished paper the required stiffness, resistance to tear and puncture and other properties. This was the second important part of the papermaking process to which we attempted to apply computer control. In Southern Kraft Division, all papermachines to which we have applied computer control have used either conical or disc refiners for this work. The amount of work done in refining the fibre is ordinarily measured in the laboratory by determining the amount of water that will drain from a slurry of standard fibre concentration in a fixed time or the time required for a standard quantity of water to drain from the slurry. There are numerous conceivable ways of measuring this continuously on the papermachine. Several manufacturers have available continuous freeness testers. The quantity of water draining through the wire per unit time may be measured. It may be possible to relate the water draining per unit time at a single position on the wire to the degree of refining. Alternatively, it may prove more convenient to measure the change in vacuum applied to the wire at a single point or the change in the total vacuum applied to the wire and use one of these variables as a measure of refining. As usual, the choice of the response variable will be dictated by consideration of the ease of measurement, rapidity of response to changes in refining, sensitivity of the response to changes in refining, as well as reproducibility and repeatability of the measurement.

Our first installations for refiner control considered the problem of refiner control as separate and distinct from any other computer control on the same machine, but we soon discovered that such a position was indefensible. Adjustments in stock flow to the wire to maintain uniform fibre weight are accompanied by changes in water flow to the wire. Regardless of what response variable is used to measure degree of refining—water drainage or vacuum change—the variable responds to changes in stock flow for fibre weight control. We therefore found it necessary to incorporate into the refiner model terms to compensate for fibre weight adjustments. Other factors that profoundly affect the variables used for refiner response measurements are the temperature and pH value of the fibre suspension flowing to the wire. An important indirect influence upon the refiner response variable may be the speed of the papermachine, since increasing machine speed will require an increase in the quantity of fibre suspension delivered to the wire per unit time, hence an increase in water drainage per unit time and an increase in vacuum required.

Because of the interaction between the refiner response variable and adjustments made for fibre weight control, we have found it necessary to require that execution of the program for fibre weight control should trigger execution of the refiner control program, rather than permit refiner control action to be taken on a timed sequence basis, independent of other controls, as our original strategy was planned.

The degree of refining of the fibre has an important relationship not only to the ease with which water may drain or be sucked from the forming sheet, but also to the ease with which the sheet may be dried by heating. It is therefore necessary to include in the moisture control model terms associated with the degree of refining done upon the fibre and transfer this information from the refiner control program to the moisture control program. Depending upon the grade of paper being made, it may in some cases be necessary to control the degree to which the pulp is worked by the amount of drying capacity that is available, if it is necessary to run the papermachine at near maximum production rate.

The heavyweight paper grades made by most machines in Southern Kraft Division use mixed fibre furnishes. In almost all cases, this means that a series of refiners must be used to perform the required amount of work upon the fibre. In some cases, separate trains of refiners must be used for pine and hardwood, with retention or mixing chests inserted between different groups of refiners. The time required for a change in work load upon different refiners or refiner groups to be detected by the response variable is then obviously different. It is important in these cases to keep the range of adjustments possible on those refiners nearest to the head box at a maximum, so that a high degree of freedom is maintained for compensating for process upsets. If the upsets are of short duration, no further action is required. If a long-term trend is encountered, requiring a major adjustment to those refiners having the fastest response time, it then becomes necessary to re-establish a then maximum adjustment range on these refiners by redistributing the work load to refiners further removed from the papermachine. This redistribution must be accomplished gradually and the stock in transport carefully tracked so that no upset in freeness of stock delivered to the head box is encountered.

Moisture content

MOST of the comments that can be made on moisture content, from our experience, have already been included parenthetically in the above two control areas. To recapitulate briefly: control of moisture content in the finished sheet is an essential part of basis weight control. On paper grades when the primary consideration is the maintenance of uniform quality, moisture content may be adjusted by controlling the temperature of one or more dryer sections, compensating for adjustment in fibre weight by increasing or decreasing dryer temperature as required. If variations in moisture content tend to become unusually large, it may be necessary to transfer part of the work load on the last dryer section to previous sections in order to preserve maximum freedom of adjustment in the last section. On those paper grades when dimensional stability is of particular importance, careful attention to the drying profile may dictate different and more complex strategies. On those paper grades for which maintenance of production rate at or near the maximum is a primary objective, it may be necessary to control moisture by adjusting the degree of refining, so that drainage rate increase will take the load off the drying sections with which water may be dried out of the sheet by heating. It is therefore necessary to leave communication between the refiner control models and the moisture control models.

The major control areas of basis weight, moisture content and refining encompass the major percentage of control endeavours on the papermachine by Southern Kraft Division of International Paper Co. We are at present involved in attempting to develop a strategy for the control of coat weight and cross-direction basis weight and moisture content, but any comments on total control of these or other areas would be, at this time, speculative.

Discussion

Mr H. B. Carter Would Mr Jolliff please clarify whether or not the Southern Kraft Division operator has some discretion on the head stock factor and carriage?

Mr C. C. Jolliff The operator enters the desired basis weight through a manual station. He enters the desired moisture content in the same way. In controlling refining, he ordinarily keeps control himself until the laboratory tests show paper properties to be within specifications. He then signals the computer to maintain refining at that level.

Dr I. B. Sanborn You mentioned that you have no moisture sensor before the size press. Is that correct?

Mr Jolliff We had a moisture sensor there, but not at the present time.

Dr Sanborn In essence, you predict the change that you have to make in your steam pressure to compensate for fibre changes?

Mr Jolliff That is correct.

Mr W. L. Daniel Has any consideration been given to the different refining effect obtained from refiners on light load from those on heavy load in the total load redistribution program?

Mr Jolliff No, as no difference in refining had been found.

Mr M. A. Keyes Initially, you did some work on the Georgetown installation that involved on-line measurement of wet end table flow patterns. Has this been incorporated in any control schemes?

Mr Jolliff All our controls are based on fact.

A Speaker You mentioned the Box & Jenkins method with the process parameters for basis control, but what methods were used to determine the model parameters used for the controller?

Mr Jolliff The parameters estimated by the Box & Jenkins method were minimising the variance and maximising the likelihood function.

Dr A. R. Farmer Please indicate the extent of the functions performed by the computers at the mills you mentioned. You refer to basis weight, moisture content and refiner control. In fact, what other functions does the computer perform?

Mr Jolliff The six computers installed in the Southern Kraft Division have a number of other tasks, but not all performed in any one mill. So far, we have used computer control on bleaching lines, lime kilns, multiple effect evaporators, recovery boilers and in the controls I have mentioned.

Mr R. E. Johnston In as much as the controllers suggested by the methods of Astrom and the methods of Box & Jenkins are almost the same controller —basically a dead time algorithm—it surprises me that no one has used any of the commercial units available for this purpose. Has anyone here had any experience for using them?

The Chairman This might tie in with a question that I wanted to ask Mr Jones—whether or not CONRAD included the facility for varying the dead time compensation automatically as the process dead time changes? Does the hardware offer the facility of automatically changing the parameter when the machine speed changes?

Mr Johnston No, it would have to be a manual change on the basis of a look-up table.

Dr Sanborn I should be pointed out that dead time in the papermachine does not correspond to an even number of sampling intervals. Hence, one must either truncate or round off when choosing the correct sample lag. With traversing gauges working on average basis weight, this can cause serious errors in dead time compensation. These errors seem to cause no serious problems of control on a practical basis. Thus, we have another illustration of a point that, though apparently important theoretically, is in fact not significant practically.

Would Mr Jolliff please comment on his remark that he needed to readjust the refiner controller each time he adjusted his stuff gate.

I presume because of this that you are unable to adjust the stock valve as frequently as once every 8 s.

Dr Farmer I should like to come back to the question I asked Mr Jolliff originally and his answer to it. Are facilities also provided for management information data processing or production scheduling? Please comment on the justification of the systems installed and the principal areas of pay-off.

Mr Jolliff We have not made a practice of printing out trend lags or other operator guides. Most of the installations have programs available for data collection, which are used as required. Our first installation in Georgetown was a research project of the New York office and did not have to be justified economically. We have had with that and subsequent installations attempted justification after the event because of very poor knowledge of the cost of running on and before the computer was installed. The only time measure of success I believe is the acceptance of computer control by management and ours continues to appropriate money for additional control computers.

Mr O. Alsholm Most of the DDC installations in U.S.A. and in Europe are equipped with almost complete analog back-up. There is no criticism in this statement, as it corresponds to the level of confidence we have achieved so far. On the other hand, our purpose is to make computer installations yield the most economical return possible. Analog back-up is expensive, thus the cheap 'limited' controllers used at Sittingbourne appeal to me, especially as I question the necessity of a complete bumpless transfer, if the computer isolates only a few times per year. Having available both Mr Keyes (who has been involved in most of the recent American DDC projects) and Mr Cyprus, it seems likely that we could get advanced comment on the matter of analog back-up in general, especially on the point of bumpless transfer to analog back-up. Not to be misunderstood, I would like to state that I do not mean the switch between computer control and manual back-up and vice versa.

The Chairman I am interested in CONRAD, which takes ten blocks to do basis weight control. How many words of storage are required for the block and what is the average number of blocks?

Mr R. E. Jones Ten blocks do the basis weight control. This includes, of course, the filtering operation I showed, which is using two of those and one to regulate the loop gain. On this particular installation, we had a storage allocation of 12 words per block of 12 bits each. We are working on a CONRAD package of somewhat greater power, perhaps taking 15 words of 18 bit length, but this will give greater facilities and a larger number of functions.

The Chairman I am sure that this aspect of programming to those involved in installations is recognised as a very important one, particularly this CONRAD approach and the one that Mr Alsholm has used. In Mr Jolliff's paper, there is reference to using machine speed as the manipulated variable for moisture control on a dryer-limited machine. Speed is a very important variable economically and I was rather concerned when he said that it could not be manipulated, because it requires a difficult model and the reason for this was that the head time changed when speed changed. I would like to question this point of view. For regulation purposes, the speed changes would not be great, so one would not expect the dead time to change very much. I consider that the major problem of manipulating speed is that the gain between the speed and the dependent variable moisture content is rather indeterminate; it can be either positive or negative, maybe even zero.

Mr Jolliff Our development group is at present finishing work on a program to maintain the papermachine at optimum conditions for the making of a grade of paper. This will include speed control, of course, but not specifically as a way of controlling moisture content.

Mr Keyes Two comments. One is about adjusting speed as an integral part of a moisture control system. Mr Robert Fritchie while at Albemarle Paper Co., Roanoke Rapids, N.C. implemented a system of this kind. It is particularly valuable for dryer-limited situations such as are encountered on linerboard machines.

My second point is a question for Mr Jolliff on the use of z-transforms for the design of a basis weight controller. As has been pointed out, use of the transforms in the case of dead time assumes that the dead time is an integral multiple of the sampling interval. Has anybody applied advanced or retarded z-transforms to basis weight control system design and, if so, what were the results?

Mr R. E. Jones If I understand the question, it is about the modified transform when the process dead time is not an integral number of sampling intervals. The way we have tackled this is to use the modified z-transform. One of the parameters in the string of blocks in my last figure is not unity, it is a parameter that we call M. The range of M is between nought and unity; its purpose is to handle the fractional part of the dead time.

Discussion

Dr Sanborn To control speed, we do not adjust machine speed for the control of sheet moisture content, but we do consider speed to be the most important variable affecting productivity. If computers are to pay for themselves, productivity must be increased. Hence, speed must be controlled if money is to be made. We have a machine, for example, that in certain circumstances is speed-limited; under other circumstances, it is drying-limited. In this case, we are monitoring the speed and steam valve opening on this machine. If they are both not at some specified maximum value, speed is automatically increased by 10–20 ft/min, provided the drive is capable of such an increase.