Modal-based cross-directional control

ANDREW P. FEATHERSTONE AND RICHARD D. BRAATZ

ABSTRACT

Knowledge of the fundamental modes of sheet or film production processes is essential for reliable automatic control of cross-directional profiles. Any automatic controller that attempts to suppress disturbances associated with misidentified modes will increase profile variability. This work describes an algorithm for a modal-based controller design. The proposed algorithm is robust because it is immune to inaccuracies in the fundamental modes. This robustness derives from the fact that it only performs input moves in spatial frequencies associated with modes that are identified with confidence.

Application:

How to design cross-directional control systems that consistently reduce product variability.

Sheet and film production processes include paper machines, adhesive coaters, and blown-film extruders. Cross-directional control in these processes is essential to product quality and production efficiency. However, a series of plant audits showed that cross-directional control systems for paper machines often exhibit poor performance. Problems with these control systems are described in some detail in the literature *(1)*. These audits revealed that only about one-third of all controllers running in the automatic mode actually reduced process variability compared with control loops that were manually tuned.

The objective of the present work was to determine the causes of poor performance in cross-directional control systems. It seemed unlikely that the control algorithms were the sole cause of the high profile variability, since these control algorithms have been successfully applied to other processes for decades. This motivated a detailed study of the relationship between model accuracy and controller performance.

A sheet/film production process can be represented by its fundamental modes. It was determined that accurate identification of the steady-state sign of a particular mode is required for effective control of that mode. If the amount of on-line data available for sheet and film processes is limited, then the steady-state sign of a significant number of modes will be identified incorrectly. Any controller—no matter how well designed—that attempts to suppress disturbances associated with misidentified modes will increase profile variability. This phenomenon can completely explain the behavior sometimes observed with existing cross-directional control systems, i.e., that the closed-loop variance can be larger than the open-loop variance *(1)*. A robust controller design procedure is proposed that is immune to inaccuracies in the fundamental modes. This robustness derives from the fact that it only performs input moves in spatial frequencies associated with modes that are identified with confidence.

PROCESS DESCRIPTION

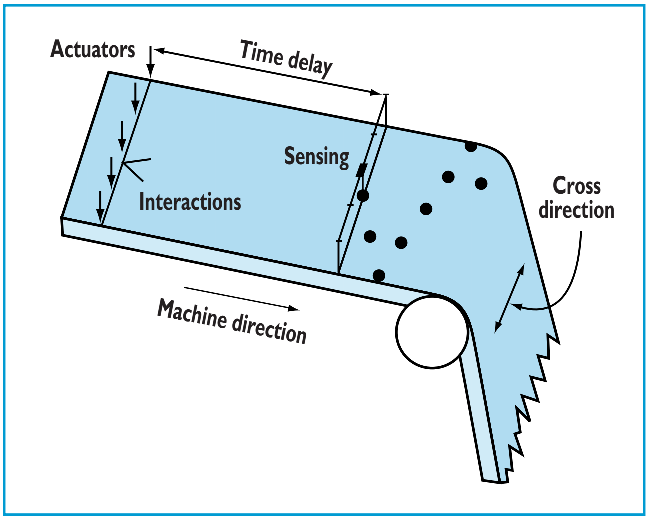
Sheet and film can be produced as either flat or circular webs. **Figures 1 and 2** show generic web-forming processes for sheet and blown film, respectively. Products produced as flat webs include newspaper, cardboard, plastic sheets, and bumper stickers. Tubular blown-plastic film is produced as a circular web that can be cut to yield a flat film or used in tubular form for bag and sack products. Thin-film lines (film thickness <100 µm) produce a wide variety of materials, such as laminating, thin-shrink, form-and-fill, bag, and general packaging films *(2)*. Heavy-duty film lines produce heavy-duty sack, refuse-sack, heavy-duty shrink, and carrier-bag films *(2)*.

Devices used to adjust cross-machine direction (CD) profile properties include choke bars (restricter bars), flexible lips, steam sprays, and air jets. These devices permit local adjustments along the width of the machine. Sensors are located downstream in the machine-direction, some distance from the point of actuation. Profile properties of interest include basis weight, caliper, and moisture content. A general characteristic of sheet and film processes is that the measurements are taken at a much slower rate than most of the process dynamics. The dynamics in the mappings of each actuator move (in response to a downstream sensor reading) are approximately the same *(3)*.

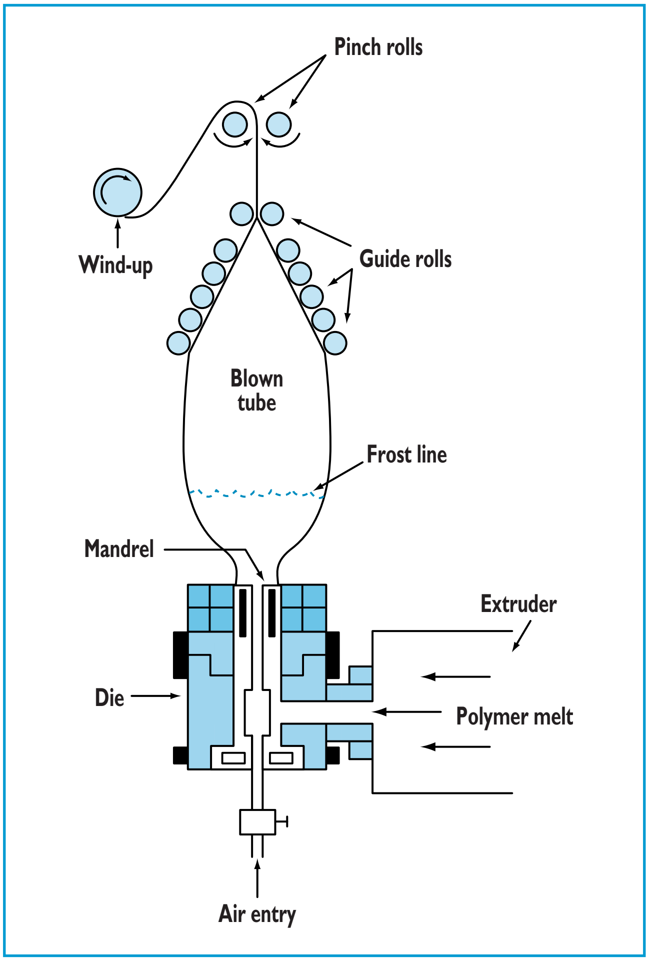
MODAL DECOMPOSITION

For sheet and film processes, the mapping between n actuators and n sensors can be represented by a transfer-function matrix, which can be written in terms of its modal decomposition *(4, 5)*:

$$P(s) = U\Lambda(s)V^T = \sum_{i=1}^{n} \Lambda_{ii}(s)\, U_i V_i^T \quad (1)$$



1. Generic web-forming process



2. Generic blown-film process

where U and V are real orthogonal matrices, U_i is the ith column of U, s is the Laplace transform variable, and $\Lambda(s)$ is a diagonal transfer-function matrix whose ith diagonal element is $\Lambda_{ii}(s)$. Virtually every sheet and film process model reported in the literature has this modal decomposition *(3)*, which can be computed using standard matrix algebra *(6)*.

Each $\Lambda_{ii}(s)$ represents a fundamental mode of the sheet/film, and U_i and V_i represent spatial directions associated with the ith fundamental mode. For example, the spatial directions for a blown-film process with 45 actuators and measurement lanes are shown in **Figs. 3 and 4** *(6)*. Figure 3 shows the first through fifth V_i sectors, while Fig. 4 shows the 21st and 22nd V_i vectors (for this particular process, $U_i = V_i$). These vectors represent different spatial frequencies described by the model.

MODAL-BASED CONTROL

The steady-state sign of a fundamental mode $\Lambda_{ii}(0)$ must be accurately identified for disturbances in the direction of U_i if it is to be controlled with acceptable closed-loop performance *(6)*. A controller design based on a model with incorrect steady-state signs for some of the fundamental modes will suffer increased variance in the corresponding directions U_i.

The proposed identification procedure is to use least squares to estimate each $\Lambda_{ii}(0)$ and basic statistical analysis to compute confidence intervals for each estimate *(6)*. The proposed modal-based controller is selected to have the structure

$$K(s) = V\Lambda_K(s)\,U^T \qquad (2)$$

which is suitably robust and provides desirable performance properties *(5, 7)*. The constant matrices U and V act as steady-state decouplers of the process dynamics. Each $\Lambda_{K,ii}(s)$ is designed to control the corresponding fundamental mode of the process $\Lambda_{ii}(s)$, as long as the steady-state sign of the mode is known with confidence (otherwise $\Lambda_{K,ii}(s) = 0$). The controller $\Lambda_{K,ii}(s)$ for each mode can be designed using any suitable controller design technique.

RESULTS

The identification and control methodology is applied to the cross-directional control of a simulated blown-film extruder.

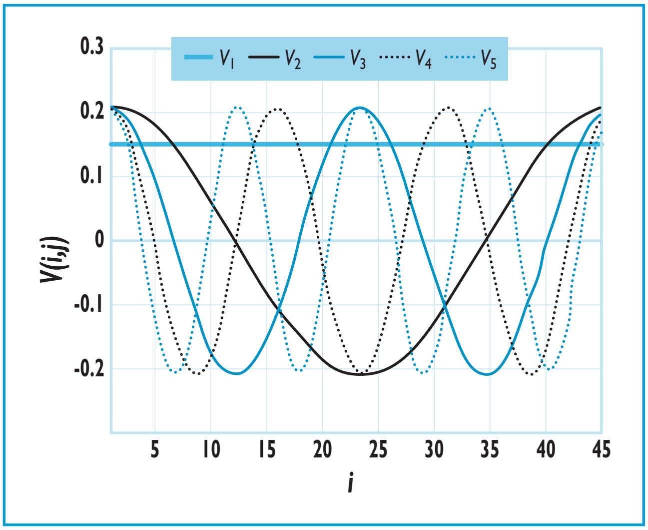
Process identification

The measurement noise in each sensor lane is assumed to be independent and have a variance of 0.04. Following standard industrial practice *(8)*, five step input tests were performed in a number of actuator locations, which are separated so that the resultant bump response profiles are expected not to overlap. For the blown-film process example, the step input was specified as

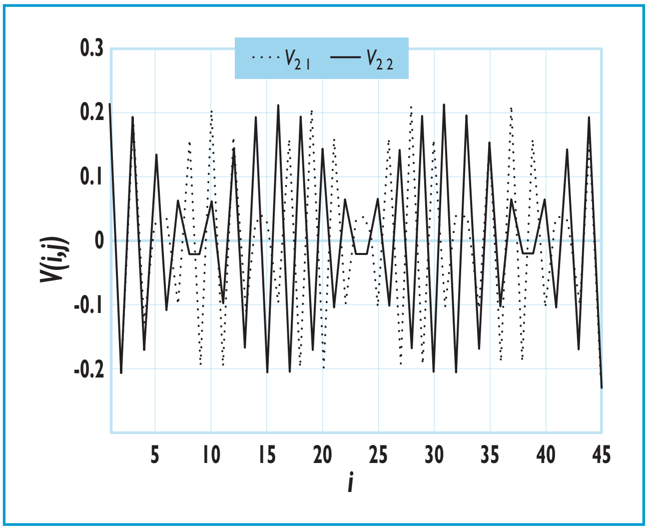
$$u_s = e_{10} + e_{20} + e_{30} + e_{40} \qquad (3)$$

where

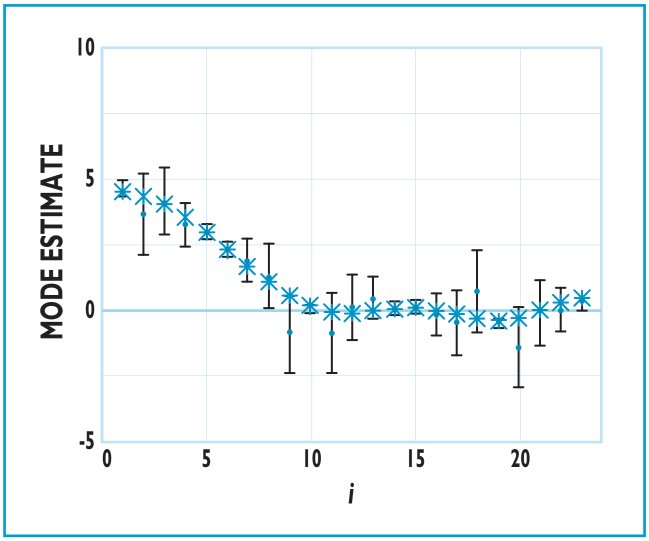
$$e_k^T = \left[0\ \ldots\ 0\ 1\ 0\ \ldots\ 0\right]^T \qquad (4)$$



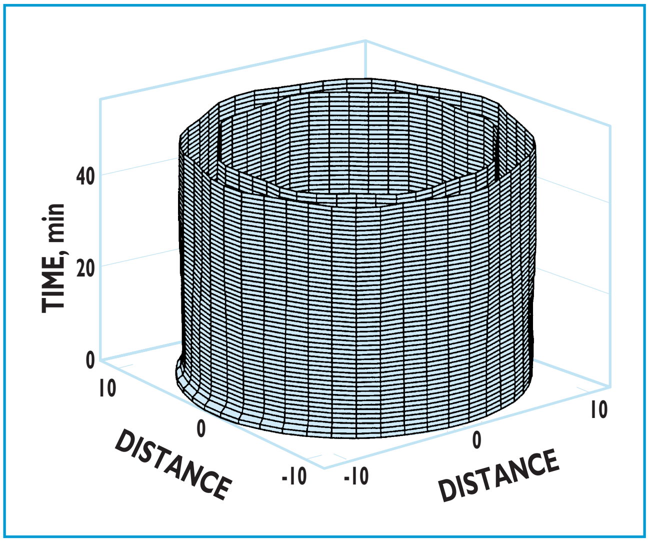
3. *Plot of first five* $\mathbf{V}_i$ *vectors for the blown-film process example*



4. *Plot of the 21st and 22nd* $\mathbf{V}_i$ *vectors for the blown-film process example*



5. *Steady-state plant modes (*✳*) and the 95% confidence intervals associated with each estimated steady-state mode* $\Lambda_{i,i}(0)$



6. *Time-domain profile response using the model-based controller under CS-1 [Note that nominal film thickness is not drawn to scale relative to the bubble radius; the film was assigned a nominal thickness of 2 and a bubble radius (measured to the median of the film width) of 10.]*

with the 1 in the *k*th position. The process transfer function $P(s)$ was fit to the input–output data using least squares. The modes and estimates of their accuracy were computed from the steady-state interactions matrix, the results of which appear in **Fig. 5**. From Fig. 5, it is apparent that (a) the steady-state signs of many of the fundamental modes are incorrectly identified and (b) most of the fundamental modes have large confidence intervals. In fact, the steady-state signs of only ten modes are identified with confidence, while six of the remaining modes are actually identified with the incorrect steady-state sign.

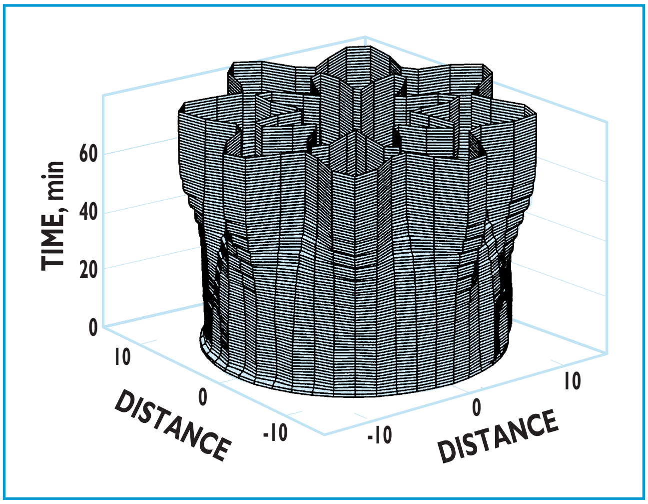
Profile responses

The physical constraints on the manipulated variables at each time instance were included in the time-domain simulations *(3, 9, 10)*:

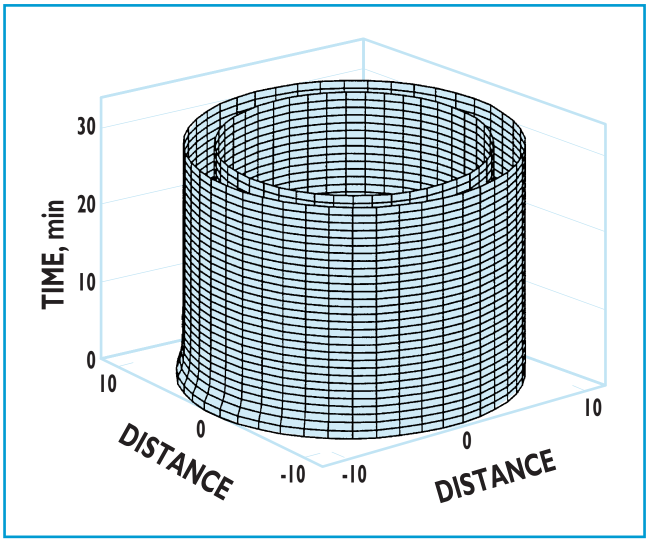
$$-u_h \le u_i \le u_h, \quad \forall i \text{ (min–max constraint)} \qquad (5a)$$

$$-l_b \le u_{i-1} - 2u_i + u_{i+1} \le l_b, \quad \forall i \text{ (second-order bending moment constraint)} \qquad (5b)$$

For the profile responses, Constraint Set 1 (CS-1) assumes that uh = 1 and lb = 2, which is applicable for a rigid slice lip. Constraint Set 2 (CS-2) is described by uh = 10 and lb = 10, which represents a more flexible slice lip. More relaxed constraints would also be appropriate for actuators such as steam sprays or cooling air jets.



7. Time-domain profile response using the model-based controller based on the model from five standard step experiments under CS-2 [Note that nominal film thickness is not drawn to scale relative to the bubble radius; the film was assigned a nominal thickness of 2 and a bubble radius (measured to the median of the film width) of 10.]



8. Time-domain profile response using the modal-based controller. Because the inputs generated by the modal-based controller easily satisfy the tightest constraints (with a maximum deviation of 0.2449 and a maximum second-order bending moment of 0.0654), the profile response is the same for CS-1 and CS-2. [Note that nominal film thickness is not drawn to scale relative to the bubble radius; the film was assigned a nominal thickness of 2 and a bubble radius (measured to the median of the film width) of 10.]

Figures 6–8 show the closed-loop profile responses to a disturbance using both model-based and modal-based controllers. Figures 6 and 7 show the profile response using an industrial-standard model-based control algorithm *(10)*, while Fig. 8 shows the profile response for the modal-based controller. Note that these figures are not drawn to scale, since the actual film thicknesses are very thin and would be difficult to visualize. The standard deviations for the initial disturbance and for the final profiles are listed in **Table I**.

The effect of the misidentified steady-state signs of the fundamental modes on the performance of the model-based controller is seen in the profile responses in Figs. 6 and 7. The model-based model gives poor performance, the severity of which depends on the extent of the constraints. The profile responses in Figs. 6 and 7 drift away from the desired uniform profile thickness, but they remain bounded because the actuator moves are bounded by the constraints. For a real blown-film extruder, the responses would cause the film to break. The industrial-standard model-based controller under the weaker constraints (Fig. 7) yields worse performance than would have been obtained without the controller.

The poor performance—similar to the results from the control system audits reported by Bialkowski *(1)*—is due to incorrectly identified steady-state signs for some of the fundamental modes in the model. The misidentification of mode signs results in a model-based controller that excites the spatial directions associated with these modes. Note that the poor performance is not due to a specific deficiency in the model-based controller design method *(10)*, since poor performance would occur for any controller that attempted to control a model with misidentified modes *(6)*.

The effect of the misidentified modes is not so apparent in the responses for the modal-based controller design (Fig. 8). Since the modal-based controller does not perform actuator movements in any of the spatial directions associated with misidentified modes, these spatial directions are not excited. The performance achieved by the modal-based controller is specified by the number of accurately known modes. If the model were improved, then the control would improve.

DISCUSSION

The two main factors that affect the control response are the actual disturbance and the number of controlled directions. The modal-based controller only suppresses disturbances in the controlled directions, so the amount of offset is determined by the projection of the disturbance in the uncontrolled directions. Because of actuator constraints, it is difficult to provide effective control in directions corresponding to the modes of small magnitude, since their open-loop effect on the output is small *(6)*. In addition, fundamental modes of small magnitude tend to be associated with directions of higher spatial frequencies (Figs. 3 and 4). The control of these directions will be more sensitive to mapping errors. Thus there is a practical limit on the number of allowable gains that can be included in the model. Some fundamental modes are so small in magnitude that they have little effect on the output, as seen in Fig. 5. This makes it difficult to identify these modes, since the number of experiments required to accurately identify them would be impractically large. Controlling the modes of small magnitude also increases the wear on the actuators, since their control requires large input manipulations. The modal-based controller provides a straightforward means of handling such difficulties in a clear and explicit manner.

CONCLUSION

The modal-based controller overcomes the practical problem noted by Bialkowski *(1)*, who found that the performance of many control systems was worse than operation in manual mode. Poor performance will be the outcome for any controller that attempts to control all of the fundamental modes of the sheet/film. The modal-based controller design method avoids this problem by using the modal accuracy estimates to allow control of only the reliably known fundamental modes. **TJ**

Featherstone is a graduate student and Braatz is an assistant professor in the Dept. of Chemical Engineering, University of Illinois at Urbana–Champaign, 600 South Mathews Avenue, Urbana, IL 61801.

Support from the DuPont Young Faculty Award is gratefully acknowledged.

Received for review July 28, 1997.
Accepted Feb. 10, 1998.

	Standard deviation (σ)
Initial disturbance	0.3847
Modal based	0.0488
Model based	
at CS-1	0.3642
at CS-2	3.5069

I. Standard deviation (σ) of the initial disturbance profile and steady-state profiles using modal-based and model-based control algorithms

LITERATURE CITED

1. Bialkowski, W. L., *InTech* 33(2): 27(1986).
2. Hensen, F., *Plastics Extrusion Technology*, Oxford University Press, New York, 1988.
3. Braatz, R. D., Ogunnaike, B. A., and Featherstone, A. P., *Proceedings of the IFAC World Congress*, Elsevier Science, Tarrytown, NY, 1996, p. 319.
4. Featherstone, A. P. and Braatz, R. D., *1995 American Control Conference Proceedings*, American Automatic Control Council, Green Valley, AZ, p. 2692.
5. Hovd, M., Braatz, R. D., and Skogestad, S., *Automatica* 33: 433(1996).
6. Featherstone, A. P., "Control relevant identification of large scale sheet and film processes," Ph.D. thesis, University of Illinois, Urbana, 1997.
7. Braatz, R. D. and VanAntwerp, J. G., *Proceedings of the 1996 IEEE International Conference On Control Applications*, IEEE, Piscataway, NJ, p. 155.
8. Heaven, E. M., Kean, T. M., Jonsson, I. M., *et al.*, *Proceedings of Second IEEE Conference on Control Applications*, IEEE, Piscataway, NJ, 1993, p. 227.
9. Braatz, R. D. and VanAntwerp, J. G., *Control Systems '96 Preprints*, CPPA Montreal, 1996, p. 15.
10. Chen, S.-C. and Wilhelm, R. G., Jr., *1986 American Control Conference Proceedings*, American Automatic Control Council, Green Valley, AZ, p. 1409.