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Cascade Generalized Predictive Control Applied to Biaxial Film Production Process*

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Abstract: Biaxial film production is a complex industrial process with large time-delay, it includes two stretch processes: longitudinally and laterally, the disturbances often occur in the film-forming part. We propose in this paper a cascade generalized predictive control (CGPC) real-time algorithm developed for this control system. The use of CGPC algorithm instead of classical PI cascade controller is now very well applied to industrial practice due to the quick rejection of the effect of disturbances in the inner loop, the master loop takes into account more information about the future using GPC algorithm to give the setpoint of the inner loop.

Key words: generalized predictive control (GPC); cascade control system; computer control
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串级预测控制及其在涤纶片基生产线中的应用

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摘要: 涤纶片基拉膜生产线是一个大滞后的复杂工业生产过程,包含纵拉伸区和横拉伸区.生产中的扰动经常发生在铸片过程中.本文为此提出一种针对该类生产过程的预测控制算法.与典型的 PI 控制器相比,可以有效地克服内环的扰动,外环的预测控制器可以充分利用系统信息给出内环的设计值.

关键词: 预测控制; 串级控制系统; 计算机控制

1 Introduction

Like many film-forming process control systems, one stage in particular of the Biaxial film production process control system determines the film's final properties, that is, thickness and planeness. The film-forming processes come from different industries, yet are structurally similar and benefit from advanced control. Similar control problems arise also in the production of paper, metal slabs and foils[1]. It is worthwhile to point out other recent work in the area of sheet- and film-control. Featherstone et al[2] assume a model for a typical circular blownfilm process and then focus on identifying the model for the purpose of control. They propose that poor performance in industrial sheet- and film-control efforts are due to model mismatch and in particular incorrect identification of the signs of the model gains. Dave et al[3] use LP method to solve large-scale sheet- and film-control problems.

In contrast to previous work, we develop a cascade generalized predictive control system for the Biaxial film production process. Cascade control is one of the most successful methods for enhancing single-loop control performance particularly when the disturbances are associated with the manipulated variable or when the final control element exhibits nonlinear behavior. This important benefit has led to the extensive use of cascade control in chemical industrial process. Biaxial film production process control system is a complex industrial processing with large-lag and many disturbances, it is impossible to work well with a traditional single feedback

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loop. Industrial running results show that the CGPC algorithm is effective for this film thickness control process.

Today, model predictive control (MPC)[4~6] is not a specific control strategy but more of a very ample range of control methods developed around certain common ideas. The ideas appearing in all the predictive control family are the explicit use of a model to predict the process output at future time horizon, the calculation of a control sequence minimizing a certain objective function and the use of a receding strategy, so that at each instant the horizon is displaced toward the future, which involves the application of the first control signal of the sequence calculated at each step. So, MPC is regarded as one of model-based and optimization-based control method. Unlike the traditional optimal control, the success of predictive control stems from its basic principles that can be summarized in [7] as model prediction, rolling horizon optimization and error feedback correction. The control action at each is solved through parameter optimization with finite horizon while the real time information is used to reinitialize the optimization in a moving style. Such a mechanism makes the control law optimization-based combined with feedback and particularly suitable to industrial environment with disturbances and time-delay, etc. In our cascade control scheme, GPC algorithm is used in the slave loop and master loop to reject disturbances effectually and avoid time-delay.

2 Description of the process

Fig.1 shows the main features of the generic film production process. The productive process involves four parts. ① Flux process. Polymers are added to the hopper and heated into melt, then the melt flows into the die lip through the extruder and filter under certain pressure. The temperature and pressure are controlled by additional loops. ② Film-forming process. The sheet of flowing liquid is extruded through the die lip, which is like "man's lip with smile" shape, and pinned to the cast drum which is filled with cool water, so the high-temperature liquid is cooled immediately and formed the film, which is named "thick sheet". The cross shape of the film is also shaped like the lip. ③ Longitudinal stretch process. In this zone, there are two rollers, one is slow roller, the other is fast roller, and there is a heatbox between two rollers, the film is reheated and stretched longitudinally when it is pulled forward. ④ Lateral stretch process. In this zone, the film is reheated and stretched laterally, forming the "thin sheet" relatively, then it is rolled up on a drum as the final production. Compared with the paper, metal slabs and foils productive processes, there are two stretch processes in the Biaxial film production.

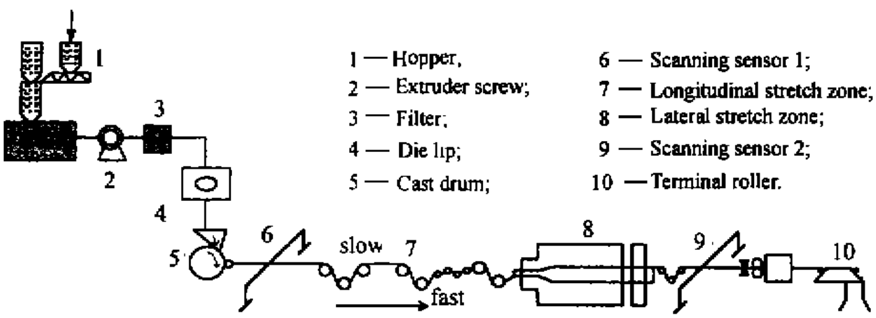

Fig. 1 Biaxial film production process

Besides the control of temperature, pressure and speed, which are all direct digital control (DDC), the position control of die-lip actuators and the rate control of cast drum are two important process control problems that determine final productive properties in large degree. In the film-forming process, the die is a large piece of metal that can be slightly deformed by the actuators. The control of cross-film shape variation, rather than the control of thickness itself, is not the main objective of this paper, and so the control of the die-lip position is neglected here.

In this paper, assume that the temperature, pressure and speed are controlled well according to productive condition, and the cross-film shape controlled by the die-lip actuators satisfies the need of film-forming, in fact, the actuators often hold unvarying because limited movement of the die-lip allows fine-tuning of the film thickness, it is difficult in real-time control.

The two scanning sensors (in Fig.1) consist of a radiation-emitting source and a detector. The sensor is mounted on a frame, scans back and forth over the film, and provides measurements in a zig-zag pattern along the sheet length. The sensor measurement divides the film into lanes, and only one of the lanes is measured at each time step. The sensed measurements can be used to estimate the film thickness across the sheet, and the estimate can be used in a predictive controller to remove disturbances.

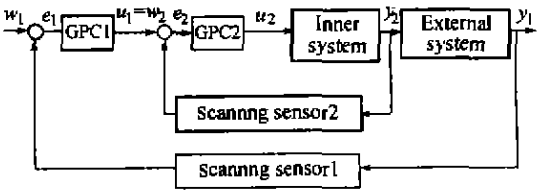

Fig. 2 Cascade control structure

The key control objective is to keep final production's deviation tolerance of the lengthways thickness within 1%, this thickness is mainly effected by the rate of the cast. The faster the cast rotates, the thinner the film's thickness is. Because the stretch speed including the longitudinal and lateral are proportioned to this rate, we choose the rate of the cast as the manipulated variable in the control system. The productive line's length is about 200 meters from the hopper to the terminal roller, the length from the cast drum to scanning sensor 1 is about 15 meters, whereas the distance between the two sensors is about 150 meters, so this is a large time-delay control system. In the meantime, the disturbances often occur in the film-forming part, it is essential to reject the effect of disturbances quickly. Based on the above views, we developed a cascade control scheme as Fig.2 for the Biaxial film productive process. In the master loop, the error between the set-point of the thin sheet's thickness w_1 and the measured value y_1 is the input of GPC1, the output u_1 is the thickness of the thick sheet, and this value is as the set-point of the slave loop, i.e. $u_1 = w_2$, the error between w_2 and the measured value y_2 is the input of GPC2, the output of GPC2 is the rate of the cast as the manipulated variable u_2. The inner loop is the longitudinal stretch process, and the external loop is the lateral stretch process. The cascade GPC algorithm will be described in the following section.

3 Cascade GPC algorithm

3.1 Basic GPC algorithm

GPC is an infinite horizon optimal control strategy with a quadratic performance criterion. We use the following CARIMA model of the plant:

$$A(q^{-1})y(t) = q^{-d}B(q^{-1})u(t) + C(q^{-1})\xi(t)/\Delta(q^{-1}), \quad (1)$$

where A, B, C are polynomials in the backward shift operator q^{-1} and $\Delta(q^{-1}) = 1 - q^{-1}$. In most cases, $C(q^{-1}) = 1$.

The j-step prediction of the system is given by the equation

$$\hat{y}(t+j \mid t) = \sum_{i=d}^{j} g_i \Delta u(t+j-i) + \rho_j, \quad (2)$$

with $\rho_j = \sum_{i=j+1}^{\infty} g_i \Delta u(t+j-i)$, as a matter of fact, ρ_j is simply the response of the plant assuming the future control values equal to the previous control $u(t-1)$. Hence it could be computed efficiently using the difference equation:

$$A(q^{-1})\Delta y^*(t+j) = B(q^{-1})\Delta u^*(t+j-d), \quad (3)$$

where $\Delta u^*(t+j-d) = 0$, for $j \geqslant d$.

The criterion we want to minimize here, in order to obtain the optimal control law, is given by the weighted sum of squares of predictive future system error $w(t+j) - \hat{y}(t+j)$ and increments of control values:

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} [\hat{y}(t+j) - w(t+j)]^2 + \lambda \sum_{j=1}^{N_u} \Delta u^2(t+j-1), \quad (4)$$

with the assumption: $\Delta u(t+j) = 0$ for $j \geqslant N_u$, where N_1 is the minimum costing horizon, N_2 is the maximum costing horizon, N_u is the control horizon, λ is the control weighting factor, $w(t+j)$ is the future setpoint or future value of the reference trajectory.

The j-predictive equation can be put into a vector form as follows:

$$\hat{Y} = G\tilde{U} + P, \quad (5)$$

with

$$\hat{Y} = [\hat{y}(t+N_1), \cdots, \hat{y}(t+N_1+N_2-1)]^{\mathrm{T}},$$

$$\tilde{U} = [\Delta u(t), \Delta u(t+1), \cdots, \Delta u(t+N_u-1)]^{\mathrm{T}},$$

$$P = [\rho N_1, \rho N_2, \cdots, \rho_{N_2-N_1-1}]^{\mathrm{T}},$$

$$G = \begin{bmatrix} g_{N_1} & g_{N_1-1} & \cdots & 0 \\ g_{N_1+1} & g_{N_1} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_{N_2} & g_{N_2-1} & \cdots & g_{N_2-N_u+1} \end{bmatrix}.$$

Substituting equation (5) into equation (4) gives the vector form of cost function:

$$J = (G\tilde{U} + P - W)^{\mathrm{T}}(G\tilde{U} + P - W) + \lambda \tilde{U}^{\mathrm{T}}\tilde{U}, \tag{6}$$

where W is the setpoint vector:

$$W = [w(t+N_1), w(t+N_1+1), \cdots, w(t+N_1+N_2-1)]^{\mathrm{T}}.$$

The solution which produces the optimal control sequence is obtained by considering the relation: $\partial J/\partial u = 0$, we have:

$$\tilde{U}_{\mathrm{opt}} = [G^{\mathrm{T}}G + \lambda I_{N_u}]^{-1}G^{\mathrm{T}}[W - P]. \tag{7}$$

3.2 Cascade GPC algorithm

It seems now interesting to develop a cascade structure, using the basic idea of GPC. This structure gives the possibility to control two different variables together, in order to satisfy constraints or to follow specified trajectories.

For this method, the plant is assumed to be divided into two parts: the output of the first part, which can be called the inner system, is the first variable to be controlled, and represents the input of the second part, or external system.

The output of the second part is the second variable that must be controlled. To do that, two GPC algorithms must be computed, as shown on the following general diagram as Fig.2.

The previous scheme has shown that the two loops of the cascade structure imply the definition of two GPC algorithms and consequently the minimization of two quadratic cost functions.

They will be globally defined in the same way as for one GPC algorithm:

$$J_1(N_{11}, N_{21}, N_{u1}) = \sum_{j=N_{11}}^{N_{21}} (\hat{y}_1(t+j) - w_1(t+j))^2 + \lambda_1 \sum_{j=1}^{N_{u1}} \Delta u_1^2(t+j-1), \tag{8}$$

$$J_2(N_{12}, N_{22}, N_{u2}) = \sum_{j=N_{12}}^{N_{22}} (\hat{y}_2(t+j) - w_2(t+j))^2 + \lambda_2 \sum_{j=1}^{N_{u2}} \Delta u_2^2(t+j-1), \tag{9}$$

with the assumption: $\Delta u_1(t+j) = 0$ for $j \geqslant N_{u1}$ and $\Delta u_2(t+j) = 0$ for $j \geqslant N_{u2}$.

The resolution must then be done as follows:

· First the minimization of J_1 will provide the optimal sequence $\{u_1\}$ defined between the horizons N_{11} to N_{21};

· It will represent the setpoint that must be followed by u_1 between N_{12} to N_{22};

· Then J_2 will be minimized, giving the optimal sequence $\{u_2\}$, the first value of this sequence will be applied to the system.

It is easy to admit that the cascade structure is possible if the relation $N_{22} \leqslant N_{21}$ is verified.

Equations (8) and (9) can now be written in a matrix form. Consider first the two predictive equations (which are similar to (5)):

$$\begin{cases} \hat{Y}_1 = G_1 \delta U_1 + P_1, \\ \hat{Y}_2 = G_2 \delta U_2 + P_2, \end{cases} \tag{10}$$

with

$$\hat{Y}_1 = [\hat{y}_1(t+N_{11}), \cdots, \hat{y}_1(t+N_{11}+N_{21}-1)]^{\mathrm{T}},$$

$$\hat{Y}_2 = [\hat{y}_2(t+N_{12}), \cdots, \hat{y}_2(t+N_{12}+N_{22}-1)]^{\mathrm{T}},$$

$$\delta U_1 = [\Delta u_1(t), \cdots, \Delta u_1(t+N_{u1}-1)]^{\mathrm{T}},$$

$$\delta U_2 = [\Delta u_2(t), \cdots, \Delta u_2(t+N_{u2}-1)]^{\mathrm{T}},$$

$$W_2 = [w_2(t+N_{12}), \cdots, w_2(t+N_{12}+N_{22}-1)]^{\mathrm{T}},$$

$$W_1 = [w_1(t+N_{11}), \cdots, w_1(t+N_{11}+N_{21}-1)]^{\mathrm{T}},$$

$$P_1 = [\rho_{11}, \rho_{12}, \cdots, \rho_{1N_{21}}]^{\mathrm{T}},$$

$$P_2 = [\rho_{21}, \rho_{22}, \cdots, \rho_{2N_{22}}]^{\mathrm{T}},$$

and where G_1 is the step-response matrix of the external system (assuming that the GPC2 algorithm correctly works so that $y_2 = w_2$, and G_2 is the step response matrix of the inner system.

Substituting equation (10) into equations (8) and (9), we obtain:

$$J_1 = [G_1\delta U_1 + P_1 W_1]^{\mathrm{T}}[G_1\delta U_1 + P_1 W_1] + \lambda_1 \delta U_1^{\mathrm{T}}\delta U_1, \tag{11}$$

and

$$J_2 = [G_2 U_2 + P_2 W_2]^{\mathrm{T}}[G_2 U_2 + P_2 W_2] + \lambda_2 U_2^{\mathrm{T}} U_2. \tag{12}$$

The optimal solution is finally given by considering $\partial J_1/\partial U_1 = 0$ and then with this result $\partial J_2/\partial U_2 = 0$:

$$\begin{cases} \delta U_{1opt} = (G_1^T G_1 + \lambda_1 I_{N_{11}})^{-1} G_1^T (W_1 - P_1), \\ \delta U_{2opt} = (G_2^T G_2 + \lambda_2 I_{N_{22}})^{-1} G_2^T (W_2 - P_2). \end{cases} \tag{13}$$

3.3 GPC parameter tuning

There is in fact no particular rule that enables an optimal choice of N_1, N_2, N_u and λ. Moreover it is possible to note the four following points:

· It is better to choose N_1 so that at least one element of the first row of G is nonzero; that implies that N_1 should be greater than the maximum expected dead-time of the process;

· N_2 should be chosen in order to satisfy $N_2 T$ equal to the time response of the process (T sampling period);

· Very often N_u is chosen so that $N_u \ll N_2$ and we previously stressed the fact that $N_u = 1$ is intersting;

· It is often hard to determine λ a priori. If the matrix $G^T G$ is invertible itself, even $\lambda = 0$ gives a solution. But in most cases, it seems better to choose λ very small but nonzero, so that the matrix $G^T G + \lambda I$ becomes invertible.

4 Industrial application results

This is a technical reconstruction project, and the control of temperature, pressure, speed, and the die-lip actuators are controlled by additional loops. In this section, we show the thickness control results by the cascade GPC in particular.

We adopted two-step method to enable the system running. In the first step, the master loop is opened and the inner loop controller is tuned with the master unit in manual mode. In this procedure, the master loop is opened, the set point of the thick sheet is given by operator, the inner loop's model is identified by the adaptive RLS algorithm with a forgetting factor, the rate of the cast is calculated by the GPC1 modules, and the parameters of GPC1 is turned. In this loop, the sample and control period is 15 seconds, which is equal to the scanning period of the sensor 1 back-and forth. In the second step, after the inner controller is tuned, the master controller is set in control mode and adjusted. In this procedure, the master loop treat the embedded inner loop as part of the process model and the master loop model can be identified using the input-output data. The calculated result of GPC2 is the thickness of the thin sheet, and as the set point of the inner control loop. In the master loop, the sample period is also 15 seconds, which is equal to the scanning period, so that the sample signal can be kept synchronization, the control period is 2 minutes, the average value of 8 set of data is as the thickness of the thin sheet.

Now, we give the real time thickness control results in Fig.3,4.

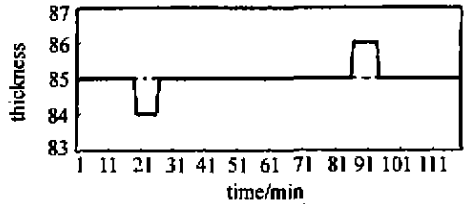

Fig. 3 Real-time control result of thin film setpoint: 85 μ

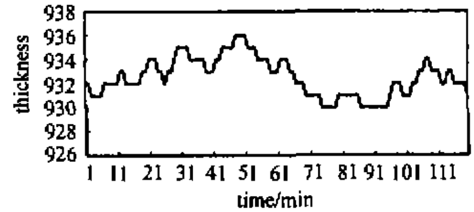

Fig. 4 Real-time control result of thick film when thin film is 85 μ

The parameters of GPC2 are: $N_1 = 1, N_2 = 4, \lambda = 0.5$, $N_u = 2$, the parameters of the inner loop are: $n_a = 2, n_b = 3$, and $\beta_{min} = 0.8$, the parameters of GPC2 are: $N_1 = 3, N_2 = 8, \lambda = 0.3, N_u = 2$, the parameters of the external loop are: $n_a = 2, n_b = 4$, and $\beta_{min} = 0.8$. The film's final properties which have been tested in laboratory by instrument, have proved the control results are very good. Unfortunately, the results by GPC algorithm can not be compared with PID algorithm due to the economic condition. We have only limited time to tune the parameter of GPC algorithm, which is programmed using Visual C language in advance. But the important fact that this productive process is running well from July 1997 to present is true, however, the old controller using cascade PID can not ensure the control system well regulated. So, Tianjin Photo Material Co. Ltd, P. R. China trust us to develop this control system, and obtained the satisfactory results.

5 Conclusion

There are many control systems with large-lag and disturbances in industrial production, it is impossible to work well with traditional single feedback loop. The (CGPC) algorithm developed in this paper is useful for this control problem. The running results of Biaxial film production process control system show the CGPC is effective for complex industrial control processes.

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