MULTI-LOOP CONTROLLERS USING WAVELET PACKET DECOMPOSITION FOR FILM PROCESSES

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Abstract: In film processes, many actuators and scanning sensors are utilized to control film properties. Multi-loop controllers are applied to the pairs of actuators and scanned data, because they can be tuned without the precise process models. The selection of the measurement location corresponding to an actuator is not easy because the film is stretched and its edges are cut off. It is illustrated that inadequate pairing causes deterioration of the multi-loop controller performance. A method based on wavelet analysis is proposed to detect inadequate pairing and to prevent the deterioration of the controller performance. Copyright © 2002 IFAC

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1. INTRODUCTION

Many kinds of sheet and film are utilized in high added value products, such as liquid crystal display, magnetic and optical memory, flexible base sheets for electronics, and so on. The specification of the product qualities continues to be stricter and the number of the product varieties is increasing. Improving the control performance of film processes is substantial industrial interest.

The flat profile of the film product must be maintained in both machine-direction and cross-direction. A film process has many (more than 100) actuators in cross-direction. Film properties are most commonly measured by a scanning sensor, which travels across the film. Although the actuators are uniformly spaced across the machine, the portions of the measured points, which are affected by each actuator, greatly overlap due to fluid or solid mechanics. Because the distance between the actuators and the sensor is very long, there is a significant time delay between actuator manipulations and sensing the result of these manipulations. In this paper, the scanning interval is assumed to be much shorter than the time delay from manipulation to sensing its result. The scanning sensor can be considered many parallel sensors. The number of measurement points is usually more than the number of actuators.

Fig.1 Schematic diagram for a film process

Converting raw materials into film products involves complex processing operations, such as drying and stretching. The processes are too complex to be accurately modelled using first-principles. The quantity of experimental input-output data necessary to identify the reliable model becomes huge, because of the very high process dimensionality. The
improvement of the film products for high added value products is rapid and frequent. Therefore, multi-variable control schemes based on the precise process model are difficult to be applied to the film process.

In this paper, a controller design scheme based on a multi-loop controller is proposed. In a multi-loop controller, single loop controllers are applied for each pair of an actuator and a measurement point. Single loop controllers, such as PID controllers, can be tuned by trial and error on the site. Even though interactions between control loops exist, the controlled system can be stable because the film process without controllers is stable.

How to select the measurement point corresponding to each actuator is very important problem for the multi-loop controller. The film is stretched and its edges are cut as shown in Fig. 1. Even though the actuators are located at evenly spaced points in the cross-direction, the actuation of each actuator does not evenly affect the measured profile. The measurement position should be paired to the actuator so as to have the highest gain. If the pairing is inadequate, the actuation affects other measurement positions stronger than the paired measurement position. Therefore, the controller action causes strong disturbances to other controllers. In this paper, the effects of the inadequate position selection are illustrated. The multi-loop controller with inadequate pairing of the measurement positions and actuators amplifies the oscillation in cross-direction.

For the precise selection of the measured position corresponding to each actuator, experiments on the site are necessary. However, a number of the experiments are necessary to identify the adequate measurement position. The adequate measurement positions for each product specification might be different from each other. They might be changed in operation. It is very difficult to keep adequate pairing and to avoid the deterioration of the control performance by the inadequate pairing. In this paper, an on-line method to detect the inadequate measurement points and to suppress the amplification of the oscillation in cross-direction is proposed.

The inadequate measurement positions are detected by observing the amplification of the controller actuation in cross-direction. If the position is not adequate, characteristic amplification of manipulated values in cross-direction occurs. By applying wavelet packet decomposition to process values (PV) of the multi-loop controller in cross-direction, the difference between the neighbouring controllers can easily be analysed. In order to focus on the difference between the neighbouring variables, Haar function is utilized as the scaling function for wavelet packet decomposition. Because Haar function is not symmetric, the decomposed wavelet packets are not symmetric even if the original profile is symmetric. Therefore, a new wavelet packet decomposition method is proposed. By changing the initial data point, the wavelet packet decomposition is applied to the same profile many times. The averages of the decomposed wavelet packets are utilized the wavelet packets. The averages are symmetric if the original profile is symmetric.

In order to suppress the amplification of the ill pairing effects, the wavelet packet decomposition is utilized. The manipulated variable (MV) profile in cross-direction of the multi-loop controller is decomposed to wavelet packets. When the pairing is not adequate, the high frequency oscillation in cross-direction occurs. Therefore, saturation functions are applied to high frequency wavelet packets of MV. If the width of the saturation is narrow, the manipulated variable cannot be changed very much. In this case, the control performance of the disturbance rejection becomes poor, although the amplification of the inadequate pairing effect can be prevented. When the pairing is adequate, the width of the saturation should be wide. In this paper, on-line adjustment method of the saturation gaps is proposed. By recomposing the saturated wavelets, the filtered manipulated variable profile in cross-direction is obtained. Because the saturation is applied only to the high frequency wavelets, the low frequency profile can be control even where the measured position is not adequate. At the measured positions, which are adequately paired with actuators, saturation does not work and good control performance can be obtained.

In Section 2, the effect of the inadequate selection of the measured position is illustrated. In Section 3, the wavelet packet decomposition method for this control method is illustrated. In Section 4, the suppression method of amplification in cross-direction is illustrated. In Section 5, the effectiveness of this proposed control scheme is shown in simulation study.

2. EFFECTS OF MEASURED POINTS FOR A MULTI-LOOP CONTROLLER

The number of the measured points is usually more than the number of the actuators. For the application of a multi-loop controller, the same number of measurement points as the actuators’ must be picked up. As shown in Fig.1, the raw material from the point of the actuator is dried and stretched before the measurement. If the raw material film at the die is thick, the area of the product film becomes wide. The edges of the film are cut off before winding. It is difficult to know the precise correspondence of actuators and measurement positions. The correspondence might be changed in operation.

There is possibility that the selected measurement position is affected by another actuator stronger than the paired actuator. Fig.2 shows the behaviour when the measurement points are inadequately paired with actuators. The gaps of the die are roughly off-line adjusted with screws for each product specification.
The flow rates of the material through the die are precisely adjusted with heat bolts.

If the film at the measurement point 4 (Sensor 4) in Fig. 2 is thinner than the set-point value, the controller increases the heat of the actuator (Heater 4). The flow rate at Heater 4 is increased because the viscosity becomes low. In the case shown in Fig. 2, the result of the manipulations appears more significantly at Sensor 3 than at other sensors. The film at Sensor 3 becomes too thick. The controller decreases the heat of Heater 3. Its effect appears at Sensor 2. Therefore, oscillation occurs in cross-direction. Even if the controllers can make the measured profile flat, the manipulated variables to reject the effect of the disturbance are amplified in cross-direction and the thickness of the edge cut off is changed very much in the case shown in Fig. 2.

3. WAVELET PACKET DECOMPOSITION

In this section the analysis method of oscillation in cross-direction is illustrated. As shown in Fig. 2, the frequency of the oscillation in cross-direction is high. In order to suppress the amplification of the manipulated values in cross-direction, the magnitude of the high frequent oscillation is tried to be limited. If the oscillation of MVs in cross-direction is decomposed according to the frequencies and the high frequency element is decreased, the high frequent oscillation can be suppressed. However, the oscillation occurs only at the inadequate measurement positions. Wavelet packet decomposition is applied to the analysis of the cross-direction oscillation, because it can analyse the magnitude of high frequency element at each position. While the magnitude of high frequency element at the inadequate measurement location diverges according to time, the one at the adequate measurement location converges.

As the scaling function of wavelet analysis, Harr function is utilized, because the difference between the neighbouring values is focussed on. If the ordinary wavelet packet decomposition procedure is applied to symmetric profiles, the decomposed profiles do not become symmetric because Harr function is not symmetric. An algorithm of wavelet packet decomposition method, which can keep symmetric profiles, is proposed as shown in Fig. 3.

In the first stage of the wavelet packet decomposition, the ordinary procedure is executed twice by changing the initial data point and the average of the two results is calculated. If the number of the data is short, the same value as the edge’s value is supplemented to the edge for the wavelet packet decomposition. The decomposed wavelet packet on the k-th stage becomes the average of the k-th power of 2 results.

In order to consider the mismatch of the measurement positions and actuators, a large number of the wavelet decomposition stages are not necessary. Therefore, the increase of the calculation time from the ordinary wavelet packet decomposition is not significant.

![Wavelet packet decomposition diagram](https://example.com/wavelet_packet_decomposition.png)
Fig. 4 shows an example of the wavelet packet decomposition. The magnitudes of the residue are decreased according to the resolution. The smooth profile from Position 2 to Position 12 is extracted as the residue of the first resolution. The difference between neighbouring data is extracted as the signal in the first resolution. By applying saturation to this profile and recomposing the signal and the residue, the differences between neighbouring data are decreased.

The difference might be larger than the width of the saturation due to the residue profile. If the data are monotonically increased, the residue of the wavelet packet decomposition is also monotonic increased. In this case, the saturation on the signal in the first resolution cannot limit the difference between the neighbouring data. However, it is not important to limit the magnitude of the differences precisely. The oscillation in cross-direction, which is caused by the inadequate paring of measurement positions and actuators, has high frequency. Therefore, the saturation on the signal of the 1st resolution can suppress the divergence of the manipulated variables caused by inadequate pairing. Even if the saturation is applied, the disturbances in smooth profile can be rejected because the low frequency profiles are not removed. Only the disturbance, which has high frequency in cross-direction, cannot be rejected if the saturation is tight.

4. ADJUSTMENT ALGORITHM OF SATURATIONS FOR WAVELET PACKETS

The main disturbances for the thickness profile of the film are the gaps of the die. They are roughly offline adjusted with screws when the thickness of the product films is changed largely. The main disturbances are constant. Because the film process is stable, the divergences of the manipulated variables according to time are caused by the controllers with inadequate pairs. By applying the saturation to the manipulated values calculated from the single loop controllers, the controller can be stabilized even if the pairings of the actuators and measurement points are inadequate. However, the controller performance to reject the effects of the disturbances becomes poor. Therefore, the saturation should be applied only to position corresponding to the controllers with inadequate pairs.

An algorithm to tune the width of the saturation in each position is proposed as shown in Fig. 5.

Fig. 4 Example of multi-resolution plot generated using the proposed method

Fig. 5 Algorithm of tuning the saturation for MV.

The standard value of the width of the saturation is set small. To judge the adequacy of the pair, the decomposed signals of the controlled variable data are observed after the width of the saturation is expanded. If the magnitudes of the signal in the
wavelet first resolution are converged, the measurement position can be judged adequate. In this case, the width of the saturation is expanded again. In the other case, the width of the saturation is set back to the standard value. This algorithm is continuously applied on-line. The observation term to judge the convergence of PV (\(T_{obs}\) in Fig. 5) and the increment of the width of the saturation for manipulated variables (\(\Delta MV\)) are tuning parameters. They can be tuned on the site.

5. SIMULATION STUDY

In this section, the simple simulation model, which has 13 actuators in cross-direction, is utilized to show the effectiveness of the proposed algorithm. Fig. 6 shows the schematic diagram of the model. The numbers printed at the location of the sensors in Fig. 6 show the location of the actuators, from which the materials of the film come. The material from Heater 6 is expanded to the width for two sensors.

![Fig. 6 Schematic diagram of the model film process](image)

In the model, 15 sensors are located at the end. It is assumed that the 6th and 7th sensors get the same values. The film from the 1st heater is cut off. The three controllers at the centre have adequate pairs. The rests have inadequate pairs.

In this simulation, the increase of a MV causes the increase of PVs. Even if the pairing of the actuated heater and the measured point is inadequate, the gain keeps positive. This simulation shows the effect of propagation in cross-direction shown in Fig. 2.

The constant disturbance shown in Fig. 7 is added at the measurement positions in the simulations.

![Fig. 7 Constant disturbance](image)

Fig. 7 Constant disturbance

Fig. 8 shows the responses to the set-point changes in using a multi-loop controller without the saturation algorithm. Because of the inadequate pairing, the oscillation in cross-direction occurs. The magnitudes of controlled variables and the manipulations are amplified in the direction from the centre to the edges.

![Fig. 8 Responses of PV and MV to the set-point changes](image)

Fig. 8 Responses of PV and MV to the set-point changes

Fig. 9 shows the signal of the manipulated variables in the 1st resolution of the wavelet packet decomposition. Because the high-frequent oscillation in cross-direction is extracted from the signal in Fig. 9, its amplification can be detected much earlier from Fig. 9 than from Fig. 8.

![Fig. 9 Signal of MV in the 1st resolution of the wavelet packet decomposition](image)

Fig. 9 Signal of MV in the 1st resolution of the wavelet packet decomposition

![Fig. 10 Responses with fixed tight saturation](image)

Fig. 10 Responses with fixed tight saturation
Fig. 10 shows the responses with the fixed tight saturation on the wavelet 1st resolution signal of MV. By comparing Fig. 10 with Fig. 8, it can be understood that the saturation can suppress the amplification of the oscillation. However, the effects of the disturbance remain on the converged profile of controlled variables.

Figs. 11 and 12 show the effectiveness to adjust the width of the saturation. In this simulation, the setpoints are not changed. At the beginning, the tight saturations were set. At Time 300, the widths of the saturations were expanded. The length of the term to judge the convergence of PV was 150. At Time 450, the saturation functions except ones for the 6th, 7th and 8th positions were set back to the initial ones. The measured variables, whose pairings are adequate, are controlled without any offsets.

Fig. 11 PV with modification of the saturation

Fig. 12 MV with modification of the saturation

Fig. 13 shows the responses in the case that the pairings were changed into adequate ones at Time 500. It is shown that the multi-loop controller can achieve the offset free control if the pairings of the measurement positions and actuators are adequate.

Fig. 13. Responses with the correction of the pairing

6. CONCLUSION

It was shown that an oscillation in cross-direction occurred by the inadequate pairing of the actuators and measurement positions in a multi-loop controller. An algorithm to suppress the oscillation was proposed. The oscillation could be detected and could be suppressed by using wavelet packet decomposition. In order to deal with symmetric decomposition, a new wavelet packet decomposition algorithm was proposed. The amplification of the oscillation was prevented by applying saturation functions to the 1st resolution wavelet signal of the manipulated variables. In order to maintain the disturbance rejection performance, the width of the saturation for manipulated variables was automatically expanded by judging the convergence of the controlled variables.

Because the proposed controller was based on the single loop controllers, the controller tuning could be executed by trial and errors on the site. Neither controller tuning nor the adjustment of the saturation functions need precise process models. This control scheme was very easily applied to real plants. It has worked since April 2001 in some industrial film plants. The film product qualities were improved and high qualities have been maintained. The patent for this control scheme was applied in August 2001.

REFERENCES

