MODELING AND SIMULATION OF COMBINED CONTINUOUS AND DISCRETE SYSTEMS : CASE STUDY OF SPINNING PROCESS

TAKEAKI AKATSUKA

Toray Engineering Co., Ltd., Osaka 530

NOBUO FURUMATSU AND HIROKAZU NISHITANI

Nara Institute of Science and Technology, Ikoma 630-01

Key Words: Design Support, Spinning Process, Combined Simulation, Discrete Event Model, Continuous Process Model

In the previous paper, we proposed fundamental techniques to model and simulate combined continuous processes and discrete event systems, including sequential control, and developed a simulation program package for general use. In this paper, we apply the combined simulation method to analyze a proposed design of spinning processes in the synthetic fiber production plant. Repeated simulation is effectively used to make an appropriate decision on the number of equipment items. This case study includes various concrete techniques for modeling and simulation, and will help the process designer to model large-scale and complicated systems, and to analyze system performances.

Introduction

Generally a production system includes various elements and its scale is very large. Today it is difficult to make a correct decision on production system design and operation based only on past experience or small-scale experiments. In this case, simulation is one of the most practical and powerful methods; it has been used to confirm that the proposed design is reasonable or the production plan is adequate.

In the previous paper, we discussed the differences between discrete events and continuous processes in simulation (Akatsuka, Yoshida and Katoh, 1973; Akatsuka, Furumatsu and Nishitani, 1996, 1997). As a result, we proposed fundamental methods to model and simulate combined continuous process and discrete event systems, including sequential control. We also developed a simulation program for general use. It can be used to give a more accurate insight into complicated systems for decision making.

In this paper, we apply these techniques to process design of the spinning process in the synthetic fiber production system. There are many spinning machines in the plant but each machine does not have an exclusive doffing machine. A set of spinning machines shares a doffing machine. The number of doffing machines is an important design factor. It is important from the viewpoint of productivity and product quality to investigate how the doffing machines are operated. For this purpose, simulation of the spinning process requires modeling of both the discrete event and the continuous process.

In the following sections some combined

simulation techniques are reviewed at first with some supplements. Then the spinning process in the synthetic fiber production system is described in detail. The advancement of combined simulation by using the schedule table and the connection table is explained to show the interaction between different kinds of process models and the system program. Finally the design-by-analysis method using repeated simulation is discussed using numerical examples.

1. Fundamentals of Combined Simulation

1.1 System program and models

The combined simulation program developed by Akatsuka *et al.* (1973, 1996, 1997) is composed of two subsystems; the set of process models and the organizing system program. **Figure 1** illustrates the interaction between process models to be developed by the user and the system program prepared in the simulation package. Users build their own process

Fig. 1 Interaction between process models and system program

* Received on November 8, 1996. Correspondence concerning this article should be addressed to H.Nishitani.

Fig. 2 Management of resources and queue

models using prepared elements of the discrete event, continuous process, sequential control, and connection between the discrete event and the continuous process. The process model program provides data of these models to the system program. The data include information such as when each future event is to be executed, which event follows the current event, and how many resources are necessary to execute the event.

On the other hand, the system program gives information such as the current time, the next event, and necessary resources for the event, to the process model. The system program handles advancement of time by integration of the continuous system and manages the timing of each event by searching the schedule table with monitoring queues and resources. The system program takes out an event from the queue when the resources seized by another event are released. Such queue management is carried out by a system program incorporating "Catch" and "Release" functions. Queues for event occurrence are controlled by "QueueIn" and "QueueOut" function in the process model. Discrete events in simulation models are written in the form of the function of C language. Figure 2 illustrates queue management and resource accounting.

The system program also calculates the statistical data of the current simulation run such as the production rate, the maximum queue length, the average queue length, the frequency of event, and the use of resources. Plant design engineers can evaluate design alternatives with statistical data resulting from repeated simulation runs. The production simulation including checking of the due date of products and finding of bottlenecks provides important information for redesign of processes.

1.2 Implementation of simulation

Whenever future events are determined in the course of simulation, necessary data such as the time when the event happens, the following event, and other attribute parameters related to the event, are registered into the schedule table. Each set of entries in a row of

Fig. 3 Schedule table and discrete events

the schedule table is called an entity.

When the simulation time reaches the earliest event in the schedule table, the corresponding entity is taken out from the table. The event function, which is designated by the event number in the entity, is executed with the attribute data. Future events will be determined during execution of the current event. Simulation repeats this cycle of event registration and execution.

An example of the relation between the schedule table and discrete events is shown in Fig. 3. In this case, the first entity in the schedule table is taken out at time 0.9. The entity means that the function of event No. 3 in the production line No. 3 is executed in this example.

Continuous processes are usually described by the state equations derived from the material and energy balance equations with various rate equations. The set of differential equations of the state equations are integrated to advance time. Algebraic and logic equations can be handled in the continuous process model. The time interval for numerical integration is so small that this time axis can be regarded as the basic simulation clock. The discrete event is executed one by one sequentially, while a set of continuous processes are integrated simultaneously.

Sometimes a process must be represented by a few distinct groups of dynamic state equations. To control individually each group, we introduced a "Block" function in front of each group of state equations. Using a "BlockControl" function, the simulation system program can start, stop, hold or keep integrating each block of state equations. Execution of the continuous process is shown in Fig. 4, where "starting integration" is to start integration from the initial values, "integration" means to keep integrating, "stopping integration" means that integration is to stop and the state variables are to be set to their initial values, and "holding" is to stop integration and keep the state variables at the current values.

Fig. 4 Execution of continuous process

Fig. 5 Filament yarn winder (one package for one spindle)

2. Synthetic Fiber Production Process

Melted polymer is extruded from the fine nozzles at the upper end of the spinning machines. This melted polymer is transformed into a thin yarn as it is cooled by the cold air while running down, and is wound up by a winding machine into a yarn package. The yarn is heat treated on a heating roller just before winding. The heating roller has both a section for heating and a sensor on each yarn path. But these heating sections on the heating roller are controlled by only one temperature controller with the sensor at the center of the heating roller. If the temperature on the yarn path goes over the limit, the quality of the yarn at that point on the yarn path drops to a lower grade. This filament yarn winding machine is shown in Fig. 5.

A doffing machine is needed when the yarn is fully wound on the core tube or the bobbin. It takes several hours to wind a bobbin fully. The doffing machine removes the package of yarn from the winding machine and supplies a new core tube on the spindle of the winding machine. Sometimes yarn breaks during winding. When this happens the yarn break sensor gives an alarm signal to the process computer. This computer commands a doffing machine to move to the position of yarn break and to doff the yarn as a small package. The ratio of small package number to full package number is an important index of spinning technology. Winding is restarted after doffing of a full

Fig. 6 Yarn winding sequence

package or a small package.

We investigate how many doffing machines are necessary to achieving a specified production rate economically. For this purpose the working rate of doffing machines must be evaluated under the estimated conditions of yarn break. It is also required to examine the waiting time for doffing and the temperature profile on the heating roller from the viewpoint of yarn quality. Therefore, we must calculate the temperature profile on the heating roller under discrete events such as yarn break and waiting for doffing.

3. Modeling of Spinning Process

3.1 Discrete event models

The yarn winding process can be classified into winding, doffing and yarn break. The automatic doffing machine is called for when the computer gives a signal that the yarn is fully wound at each winder position. If a doffing machine is available at this time, then the machine is sent to the position. The machine doffs the full package of yarn and sets a new core tube on the spindle of the winding machine. The doffing machine carries the yarn package to the yarn carrier station and gets a new core tube from the storage. If every doffing machine is in use at another position when called, the new doffing operation is postponed until the machine is released at any position. The doffing machine is also called for when the yarn breaks during winding; the doffing operation begins though the yarn is not fully wound.

The sequence of these operations can be generally described by a typical discrete event model shown in Fig. 6. In the discrete event model, a resource is caught at first if the resource is available, then the event starts. If the resource is not available at the time, the event is postponed, *i.e.*, the event is put into its corresponding queue. It starts when another event releases the resource and the required resource is available for the current event. In this example the resource is the automatic doffing machine and activities represented by discrete event models are doffing and yarn winding operations.

3.2 Continuous process models

Although each yarn is wound at a constant speed, a package does not always reach a full package at the time forecasted at the beginning of winding since it breaks randomly. The timing of yarn break is very difficult to determine. In this study we have applied statistical data to the random number generation to forecasting when a yarn break happens. The exponential distribution is used to generate the yarn break timing.

$$time = A \exp(\text{random number}) \quad (1)$$

where *time* is the duration until the yarn breaks after the beginning of winding and *A* is a constant.

The yarn winding equations are represented as follows:

$$dW_i / dt = wt, \quad W_i(0) = 0 \quad (i = 1, \dots, n) \quad (2)$$

where *w* is constant and *n* is the number of winders.

The heat balance equations on the heating roller are represented as follows:

$$\begin{aligned} CdT_j / dt &= hQ - gQ_f - (aT_j + b)(T_j - T_r) + K(T_{j-1} - T_j) - K(T_j - T_{j+1}) \\ T_j(0) &= T_o \quad (j = 1, \dots, n) \end{aligned} \quad (3)$$

where T_j ($j=1, \dots, n$) is the heating roller temperature at the place where the yarn of *j*th winder is touching to the roller and $T_o=T_1$, $T_{n+1}=T_n$. T_r is the room temperature. Q and Q_f are heat energy supplied from the heater and heat energy removed with yarn, respectively. C , a , b , and K are constant parameters.

The 0-1 variables of *h* and *g* represent the state of on-off control of heater and whether the yarn is broken or not on the heating roller, respectively.

$$h = 1 \text{ for } T_m - T_s < 0, \text{ and } h = 0 \text{ for } T_m - T_s > 0 \quad (4)$$

$$g = 1 \text{ for during winding, and } g = 0 \text{ for stopped winding} \quad (5)$$

where T_m is the controlled temperature and T_s is its set-point value. When the temperature at the middle of the heating roller is selected as the controlled variable, $m = [(n+1)/2]$. Where $[x]$ denotes the maximum integer which is not greater than *x*.

Each yarn winding equation starts and stops individually, because each winding machine is independent. On the other hand, the heat balance equations must be handled simultaneously because these equations are physically related. The logic equation to describe temperature control of heating roller is also

Fig. 7 Yarn winding program

handled with the continuous system model. As a consequence, there are $n+1$ groups of the state equations which must be handled separately. Figure 7 illustrates these model programs with "BlockControl" function to manage each group of state equations. The continuous process is simulated by integrating each group of differential equations.

4. Execution of Combined Simulation

The simulation program of the yarn winding process is summarized in Fig. 7. The execution of combined simulation using the schedule table and the connection table is explained in detail for the winding process, with one package for one spindle shown in Fig. 5.

(1) Starting of simulation

The initial winding amount of each package in Eq. (2) is set as shown in Table 1. For each winder, doffing (event No. 1) after full winding is registered into the connection table with the key number and winder number as shown in Table 2. Then the yarn break time is forecasted using an exponential distribution, and the yarn break is registered into the schedule table with the occurrence time (0.9), event No. 3 and winder No. 3 as shown in Table 3. Integration of the yarn winding equation for each winder ($i=1, \dots, 5$) and integration of the temperature profile equations ($i=6$) is started by setting the value in the function "BlockControl (*i, k*)" as shown in Fig. 7.

(2) 0.5 hrs after starting

The winding amount of each winder at 0.5 hr.

Table 1 Initial amount of winding

Winder No.	1	2	3	4	5
Winding amount	1.0	2.0	0.5	1.5	2.5

Table 2 Connection table at start time

Key	Event No.	Attribute (Winder No.)
1	1	1
2	1	2
3	1	3
4	1	4
5	1	5

Table 3 Schedule table at start time

Current activity	Time	Event No.	Attribute (Winder No.)
Winding	0.9	3	3

Table 4 Amount of winding at 0.5 hr.

Winder No.	1	2	3	4	5
Winding amount	1.5	2.5	1.0	2.0	3.0

after starting is summarized in **Table 4**. Since the package of winder No. 5 is full at this time, doffing should be started. The winder catches a doffer, and event No. 1 (start doffing) begins by reference to the connection table in Table 2. Then at 0.9 hr. (occurrence time), event No. 2 (start winding), and winder No. 5 are added to the schedule table as the end time of doffing, *i.e.*, the starting time of winding, next event number and winder number, respectively. The schedule table at this time is shown in **Table 5**.

(3) 0.9 hr. after starting

The winding amount of each winder at 0.9 hr. after starting is summarized in **Table 6**. The yarn breaks for winder No. 3 as registered in the first entity in Table 5. The system program stops integration of wider No. 3 and starts doffing for a small package. At the same time, according to the second entity in Table 5, winder No. 5 finishes doffing (event No. 2) and the winding equation of winder No. 5 starts integration. These two entities are taken out from the schedule table here. A future yarn break timing is calculated as 1.3 hr. and registered into the schedule table as shown in **Table 7**. Simulation keeps running by repeating to write and search both the schedule table and the connection table at appropriate time.

Table 5 Schedule table at 0.5 hr.

Current activity	Time	Event	Attribute (Winder No.)
Winding	0.9	3	3
Doffing	0.9	2	5

Table 6 Amount of winding at 0.9 hr.

Winder No.	1	2	3	4	5
Winding amount	1.9	2.9	1.4	2.4	3→0

Table 7 Schedule table at 0.9 hr.

Current activity	Time	Event No.	Attribute (Winder No.)
Doffing with yarn break	1.3	3	5

Table 8 Data for simulation in case of one package for one spindle

Spinning machine:	1
Winding position/one machine:	5
Winding amount:	3 kg
Doffing time:	0.4 hour
Heat transfer coefficient:	$K=2 \text{ W / } ^\circ\text{C}$
Heat flow taken by yarn:	$Q_r=40 \text{ W}$
Heater capacity:	$Q=400 \text{ W}$
Heat radiation coefficient:	$a=0.00012 \text{ W/(} ^\circ\text{C)}^2$
Heat radiation coefficient:	$b=0.3 \text{ W/} ^\circ\text{C}$
Heat capacity of heating roller:	$C=1.08 \times 10^4 \text{ J/} ^\circ\text{C}$
Set point temperature:	$T_s=250. ^\circ\text{C}$
Ambient Temperature:	$20 ^\circ\text{C}$
Initial data of winding equation:	
Winder No.1:	1
No.2:	2,
No.3:	0.5
No.4:	1.5
No.5:	2.5

5. Simulation Results

Simulation was run for old and new spinning processes. The old process is where a winding machine has a spindle with one package. The new process is where a winding machine has a long spindle with many packages. Regardless of winding machine structure, modeling is the same for both processes.

5.1 Winding process with one package for one spindle

Simulation was done for two cases for 5 winding machines as shown in Fig. 5. The first case is when there is only one doffing machine and the second case is when there are two doffing machines. Simulation data are summarized in **Table 8**. Simulation is achieved as described in the previous section using the schedule table and the connection table. Simulation results for 20 hour cperation show that queues happened 10 times in

Table 9 Simulation results in case of one package for one spindle

unit (times)

	Need for resource	Doffing	Yarn break	Queue for doffing	Queue for yarn break		
For 5 winders & 1 doffer	33	24	9	4	6		
For 5 winders & 2 doffer	34	25	9	0	1		
	Maximum length queue for doffing	Maximum length queue for yarn break	Maximum time queue for doffing (hr.)	Maximum time queue for yarn break (hr.)			
For 5 winders & 1 doffer	1	2	0.3	0.7			
For 5 winders & 2 doffer	0	1	0	0.2			
Queue time	less than 0.1 (hr.)	0.1	0.2	0.3	0.4	0.5	total
For 5 winders & 1 doffer	1	3	2	2	1	1	10
For 5 winders & 2 doffer	0	0	1	0	0	0	1

Fig. 8 Simulation results under one auto-doffer **Fig. 9** Filament yarn winder (many packages for one spindle)

total; 4 times for full package doffing and 6 times for yarn break doffing. **Figure 8** illustrates the doffing record for each winder, the state of the doffing machine, and the temperature profile on the heating roller. The doffing machine is called for 33 times and its operating hours are 13.3. The result is summarized in **Table 9**. The maximum waiting time is 0.7 hr.. In case there are two doffing machines, a queue occurs only once for yarn break doffing, and the maximum waiting time can be decreased to 0.2 hr.. Therefore, two doffing machines are recommended to keep yarn quality.

Table 11 Simulation results in the case of many packages for one spindle

unit (times)

	Need for resource	Doffing	Yarn break	Queue for doffing	Queue for yarn break
For 24 winders	155	150	5	24	3
For 30 winders	189	183	6	51	6

	Maximum length queue for doffing	Maximum length queue for yarn break	Maximum time queue for doffing (hr.)	Maximum time queue for yarn break (hr.)
For 24 winders	3	1	0.3	0.1
For 30 winders	2	1	0.4	0.5

Queue time	less than 0.1 (hr.)	0.1	0.2	0.3	0.4	0.5	total
For 24 winders	6	17	3	1	0	0	27
For 30 winders	6	33	6	7	3	2	57

Table 10 Data for simulation in the case of many packages for one spindle

Spinning machine: 1
 Winding position/one machine: 24,30
 Winding amount: 3 kg
 Doffing time: 0.1 hour
 Heat transfer coefficient: $K=2 \text{ W / } ^\circ\text{C}$
 Heat flow taken by yarn: $Q_f=40 \text{ W}$
 Heater capacity: $Q=400 \text{ W}$
 Heat radiation coefficient: $a=0.00012 \text{ W/(} ^\circ\text{C)}^2$
 Heat radiation coefficient: $b=0.3 \text{ W}^\circ\text{C}$
 Heat capacity of heating roller: $C=1.08 \times 10^4 \text{ J}^\circ\text{C}$
 Set point temperature: $T_s=250. ^\circ\text{C}$
 Ambient Temperature: $20 ^\circ\text{C}$

Fig. 10 Simulation results in case of 24 winders for one doffer

However, since the total operating time is 13.6 hr., the use rate of two doffing machines falls by half.

5.2 Winding process with many packages for one spindle

Figure 9 shows a winding machine with a long spindle with many packages. All packages on the spindle are doffed at once when all packages are wound fully or there is at least one yarn break. Recent winding machines have many packages long spindles. Usually 24 winders are handled by one doffing machine. We examined the feasibility to increasing the number of winders to 30 for one doffing machine. The simulation data for 30 winders are summarized in **Table 10**. **Figure 10** illustrates the record of each winder, the state of the doffing machine, and the temperature profile on the heating roller. In the case of 24 winders for one doffer, full package doffing happens 150 times and yarn break happens 5 times in 20 hr. as shown in **Table 11**. Queue happens 24 times for full package doffing and 3 times for yarn break doffing. The maximum waiting time is 0.3 hr.. When the number of winders for one doffer is increased to 30, full package doffing happens 183 times and yarn break happens 6 times in 20 hours. Queue happens 51 times for full package doffing and 6 times for yarn break doffing. The number of queues increases twice and the maximum waiting time becomes 0.5 hr.. The simulation results are summarized in **Table 11**.

The maximum waiting time must be kept within the limits for yarn quality. The distribution of waiting time for doffing in **Table 11** shows that 30 winders are too many to be handled by one doffer under the specified conditions. It may be concluded that some innovation is required to increase the number of winders.

Conclusion

The maximum waiting time for doffing is critical for quality control of the fiber winding process in a synthetic fiber production plant, so we want to examine the performances under uncertainty by simulation as precisely as possible. Both discrete event models and continuous process models are built for the combined simulation. For this purpose the combined simulation method is used effectively. The uncertainty in yarn break in the spinning process is represented by an exponential distribution derived from experience. Production systems are generally very large scale and complicated systems. It is now difficult to make decisions on design and production scheduling based only on past experience, or small scale experiments.

Simulation is one of the most powerful methods of these cases used to confirm that the proposed plant design is correct and the production plan is adequate. More convenient modeling elements are desired to be added to the simulation program to describe easily the behavior of automatic machines for factory automation.

Literature Cited

- Akatsuka, T., N. Yoshida and A. Katoh; "Integrated Continuous and Discrete System Simulation Program," *Information Processing in Japan*, **13**, 23 - 28 (1973)
- Akatsuka, T., N. Furumatsu and H. Nishitani; "Combined Discrete and Continuous Simulation for Plant-wide Decision Making," AIChE Annual Meeting, Paper 193f, Chicago-U.S.A. (1996)
- Akatsuka, T., N. Furumatsu and H. Nishitani; "Modeling and Simulation of Combined Continuous and Discrete Systems," *J. Chem. Eng., Japan*, **30**, 285 - 292 (1997)