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Experimental Analysis of the Performance of the Fault Diagnosis System Based on the Signed Directed Graph

by

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Abstract

Performance of fault diagnosis system based on signed directed graph (SDG) is experimentally analyzed. The performance of the system can be evaluated in terms of reliability, accuracy and speed, which are greatly influenced by the thresholds to be used for distinguishing abnormal from normal measurements. To search an optimal adjustment of thresholds is formulated as the maximization of a performance index which is the similarity to the ideal diagnostic result. Finally, we present a guideline on the determination of the thresholds in the application of fault diagnosis system based on SDG to practical chemical plants.

Keywords: Fault diagnosis, Graph theory, Signed directed graph, Threshold

1. Introduction

Although a variety of techniques for fault detection and diagnosis have been proposed in recent years, there are few application of fault diagnosis system to practical industrial plants. This reason is that research on fault diagnosis has mainly aimed at developing various types of diagnostic algorithms and constructing faulty models and databases, using (1) expert system[1)4)], (2) qualitative simulation[3)11)], (3) Neural Network [9)], (4) state estimator or extended kalman filter[10)2)], and (5) signed directed graph [5)6)7)8)].

It is, however, very important that fault diagnosis system can correctly recognize the state of a plant diagnosed to practical use of a fault diagnosis system based on any technique or concept as found in the above. In other words, good diagnostic result can not be obtained by the wrong state recognition even if the diagnostic algorithm is splendid and the used model or database is accurate.

The fault diagnosis system based on the signed directed graph (SDG), which has been developed as a qualitative model-based method, is useful to real-time diagnosis of failures

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that occur in large-scale, complex chemical plants. A variety of algorithms[5)6)7)8)] have been presented according to the way to use the information obtained from the plant diagnosed.

There are, however, two problems in the practical application of any algorithm. One is that the algorithm cannot deal with a multiple loop control encountered commonly in chemical processes, such as cascade, ratio control and so on, even if it can deal with a simple feedback control loops. The other is that determining thresholds to distinguish abnormal values from normal values of the measured variables is very difficult. These problems have influences on the accuracy and the reliability of the diagnostic results.

In this paper, we will discuss these two problems and analyze the performance of the fault diagnosis system based on SDG in the experimental investigation with the use of a mini-plant.

2. Fault Diagnosis System based on SDG

2.1 Basic Definitions

SDG is useful for representing the cause-effect relationship in a chemical plant. Nodes in the SDG represent state variables in the plant. Branches in the SDG represent the direct influence between the state variables. Positive and negative influences (or, reinforcement and suppression), respectively, are distinguished by signs "+" and "−" assigned to the branches.

A node in the SDG is assumed to take qualitative values "0", "+" and "−", representing the normal state, higher and lower than normal state, respectively. The combination of the signs given to all of the nodes is defined as a "pattern". A branch in the SDG is said to be consistent if its sign is equal to the product of the signs of its initial and terminal nodes. The nodes in the SDG are classified into two groups; one is a set of observed nodes which correspond to measured variables, the other is a set of unobserved nodes which correspond to unmeasured variables.

It is very difficult to determine the thresholds that distinguish the abnormal values from the normal values of the measured variables. In order to avoid this difficulty, Shiozaki et al. (1985) have proposed the concepts of the five-range signs and the five-range pattern. An observed node in the SDG is assumed to take five-range signs "+", "+?", "0", "−?", and "−", distinguished by using four thresholds b+, a+, a− and b−. The thresholds a+ and a− are called "first-kind thresholds", and the thresholds b+ and b− are called "second-kind thresholds". Signs "+", "0" and "−" are called "distinct signs", whereas the signs "+?" and "−?" are called "indistinct signs" and denote gray zones where it is not clear whether values of measured variables are normal or not. An observed node with the distinct sign is called "distinctly observed node", and an observed node with the indistinct sign is called "indistinctly observed node". Signs "+" and "−", respectively, are called valid signs corresponding to "+?" and "−?". An observed node with the valid sign is called "valid observed node", whereas an observed node with the sign "0" is called "invalid observed node". Furthermore, the combination of the five-range signs given to all of the observed nodes is defined as a "five-range pattern".

An elementary path is called "consistent path" if it is possible to make all the branches contained in it be consistent by assigning the sign "+" or "−" to all the unobserved nodes and the valid sign to all the indistinctly observed nodes on the path. When there exists at least one consistent path from a node n_c to each of the valid observed nodes, a tree composed of the consistent paths from n_c to all the valid observed nodes is called "consistent rooted tree" and the node n_c is called its "root".

The fault diagnosis can be performed under the presumption of the Single Cause, since the possibility of the simultaneous occurrence of more than one fault is considered to be extremely small. Under this presumption, a consistent rooted tree is considered to represent the possible way of propagation of failure and its root is considered to be a candidate for the cause of fault. Shiozaki et al. (1985) have proposed the efficient algorithm (basic algorithm) for enumerating the consistent rooted trees corresponding to a given five-range pattern.

2.2 SDG for Control loops

The basic algorithm had been improved so as to deal with simple feedback control loops[7]. The improved point is only to supplement the basic algorithm with pre-processing routine for checking the sign of the sensor output in the control loop, as summarized in **Table 1**. Nodes X, S and C represent controlled variable, sensor output, and controller output, respectively. Character "?" means that the corresponding nodes are treated as unobserved nodes. The other characters (+, +?, 0, −?, −) indicate the signs of the corresponding nodes. Case 2 and 3 are rules for permitting underdamped compensatory response for controlled variables. Furthermore, X and S are separately defined to diagnose a malfunction of sensor which causes the different sign of X from the sign of S.

In this paper, we propose a pre-processing routine for cascade control loops, which is very common in chemical plants. The cascade control consists of two loops; one is the primary or master control loop and uses a set point supplied by the operator, while the other is called the secondary or slave control loop and uses the output of the primary controller as its set point. Then, the pre-processing shown in **Table 1** is applied to primary and secondary loops independently, expect that the output of the secondary controller is compensated by the both outputs of the secondary sensor and the primary controller. This situation happens only in case of the malfunction of the secondary sensor, and is qualitatively recognized as the following conditions:

[Condition]
1) Sign[$C2$]="0", "+?" or "−?"
2) Sign[$C1$]*Sign[$S2$]="−(+)" or "−(+)?"
3) Sign[$b(C1, C2)$]*Sign[$b(S2, C2)$]="+(−)"
where,
$C1$=output of primary controller
$C2$=output of secondary controller
$S2$=output of secondary sensor
$b(i, j)$=branch from i to j
Sign[k]=sign of k

Table 1 Pre-processing for simple feedback control loops.

Case	Pre-Processing					
	Before			After		
	X	S	C	X	S	C
1	?	0	0	0	0	0
2	?	0/+?/−?	+/−	?	?	+/−
2'	?	0/+?/−?	+?/−?	?	?	+?/−?
3	?	0	?	?	?	?
4	the others			same as Before		

When the above condition is satisfied, the node $C2$ must be treated as unobserved node in order to obtain the consistent path from $S2$ to $C1$ via $C2$. Nevertheless, the primary control loop can be processed according to **Table 1**. If the condition is not satisfied, primary and secondary control loops are independently processed as simple feedback control loops. The diagnosis algorithm supplemented with the pre-processing routine for cascade control is called "SDG algorithm".

2.3 Structure of the System

Figure 1 shows the structure of fault diagnosis system based on SDG, which is decomposed in the three sub-systems; measurement system, signal processing system, and inference system.

[Measurement system]
A plant is normally equipped with sensors without redundancy. Signals from sensors are transferred to the signal processing system.
[Signal processing system]
Signal processing system decreases the noise influence and generates a five-range pattern with respect to observed nodes. A five-range pattern is called "abnormal pattern" if it contains at least one valid sign, and called "normal pattern" if it contains no valid sign. When the signal processing system generates an abnormal pattern, the plant is considered to fall in abnormal situation.
[Inference system]
Inference system deduces the cause of fault from the abnormal pattern given by the signal processing system, using the SDG as a qualitative model of the plant.

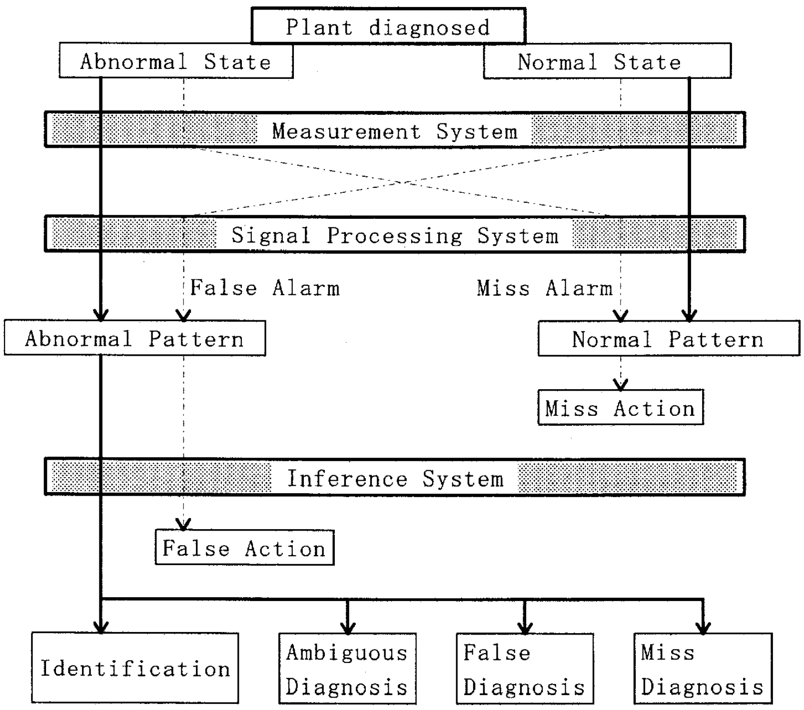

Fig. 1 Fault diagnosis system.

Table 2 Classification of diagnostic results obtained by fault diagnosis system based on SDG.

Plant	Monitoring	Inference	Total System
Normal State	Normal Pattern		Waiting
	Abnormal Pattern (False Alarm)		False Action
Abnormal State	Normal Pattern (Miss Alarm)		Miss Action
	Abnormal Pattern	Only Real Cause	Identification
		Candidates with Real Cause	Ambiguous Diagnosis
		Candidates without Real Cause	False Diagnosis
		Nothing	Miss Diagnosis

Table 3 Factors causing ambiguous, false, and miss diagnoses.

Diagnostic Results	Factors		
	Measurement	Signal processing	Inference
Ambiguous Diagnosis	Bad location of sensors Shortage of sensors	Incomplete Abnormal pattern	Redundancy in SDG Only use qualitative information
False or Miss Diagnosis		Inaccurate Abnormal pattern	Misconstruction in SDG Use erroneous information

Table 2 summarizes the diagnostic results obtained by the fault diagnosis system. "Waiting" and "Identification" are most desirable results. "False Action" and "Miss Action" take their rise in the monitoring system, that is, they result from "False Alarm" and "Miss Alarm" generated by bad adjustments of thresholds in the signal processing system. "Ambiguous Diagnosis" is better than "False Diagnosis" and "Miss Diagnosis" which are undesirable results. These results are caused by many factors as shown in **Table 3**. Ambiguous diagnosis caused by the factors in the measurement system is not avoidable, because a limited number of sensors are available under financial restriction and so on. However, the optimal location of sensors may be obtained in such a way to minimize the degree of the ambiguous diagnosis when the fault diagnosis system is designed. While the ambiguous diagnosis caused by the factors in the inference system is not avoidable as far as SDG algorithm is used, false and miss diagnoses caused by the factors in the inference system are avoidable by the careful design of the fault diagnosis system, provided that there is no shortcoming of SDG algorithm. The factors in the signal processing system result from not only a poor noise processing but also bad adjustments of thresholds as well as false and miss alarms.

Therefore, the adjustments of thresholds make a great influence on the diagnostic results of the fault diagnosis system based on SDG. The purpose of this paper is to discuss the optimal adjustments of thresholds.

3. Analysis of Performance

3.1 Performance Required

The following are required as the performance of fault diagnosis system:

(1) Reliability of diagnosis

The system can diagnose the real cause of fault. That is, identification and ambiguous diagnosis are desirable, whereas false action, miss action, false diagnosis, and miss diagnosis are undesirable.

Table 4 Relation between diagnostic results and thresholds.

Diagnostic Results	Threshold First-kind	Threshold Second-kind
Waiting	–	–
False Action	–	too small
Miss Action	–	too large
Identification	appropriate	appropriate
Ambiguous Diagnosis	too small	too large
False or Miss Diagnosis	too large	too small

(2) Accuracy of diagnosis
The system can identify the real cause of fault. That is, identification is the best and the smaller degree of ambiguous diagnosis is desirable.
(3) Speed of diagnosis
The fault is detected as soon as possible, and the diagnosis is completed before operators take appropriate actions for the fault.

The reliability and accuracy of diagnosis are discussed by the relation between the diagnostic results and the thresholds as shown in **Table 4**. If first-kind threshold is too small, ambiguous diagnosis may be performed, whereas if first-kind threshold is too large, false and miss diagnoses may be performed. If second-kind threshold is too small, false action or false and miss diagnoses may be performed, whereas if second-kind threshold is too large, miss action or ambiguous diagnosis may be performed.

The speed of diagnosis is discussed by the time margin allowed for taking actions for the failure. Form the standpoint of early detection, miss action is undesirable.

3.2 Performance Index

The following are useful definitions in order to clarify the criterions for the performance analysis:
(1) Fault Occurring Time (FOT_j)
FOT_j is the time when the j-th fault may occur in the plant, and is unknown in practical industrial plants, but known in the experiments.
(2) Diagnosis Completing Time (DCT_j)
DCT_j is the time when the diagnosis should be completed before operators take appropriate actions for the j-th fault, and is given by considering the characteristic of the plant and so on.
(3) Certainty Grade ($CG_j(i)$)
$CG_j(i)$ is the index of the accuracy of the i-th diagnosis for the j-th fault and is defined as follows:

$$CG_j(i) = \begin{cases} 1/C_j(i) & \text{(Identification or Ambiguous diagnosis)} \\ 0 & \text{(False or Miss action)} \\ -1 & \text{(False or Miss diagnosis)} \end{cases}$$

where, $C_j(i)$ is the number of candidates obtained in the i-th diagnosis for the j-th fault.

Assume that diagnoses are repeatedly executed in the range from FOT_j to DCT_j, the problem of analyzing the performance of the fault diagnosis system is formulated as follows:

[Problem]

$$\underset{TH1,\ TH2}{\text{Maximize}} \quad J=\sum_{j=1}^{N_f} w_j * (J_j/J_{jmax})$$

$$J_j=\sum_{i=1}^{N_j} CG_j(i)/N_j$$

where,

J_j=performance index for j-th fault

J_{jmax}=the maximum of J_j's for j-th fault

N_f=the number of faults considered

N_j=the number of diagnoses executed for j-th fault

$TH1$=first-kind threshold

$TH2$=second-kind threshold

w_j=weighting factor for j-th fault

Performance index J_j is defined as the similarity to the discrete step function as follows:

$$U(i)=\begin{cases}1 & (FOT \leqq i \leqq DCT)\\ 0 & (i < FOT)\end{cases}$$

$U(i)$ corresponds to the trajectory of $CG_j(i)$ in the case that the ideal diagnoses is repeatedly performed. That is, J_j is equal to 1 if the j-th fault is detected just in FOT_j and is always identified in the range of FOT_j to DCT_j. Inversely, J_j is equal to -1 if the j-th fault is detected just in FOT_j but is not diagnosed at all in the range of FOT_j to DCT_j.

It is obvious that the greater J_j is obtained in the case of the smaller ratio of miss actions (the faster detection), the smaller ratio of false or miss diagnosis (the higher reliability) and the greater $CG_j(i)$ (the higher accuracy).

J_{jmax} is used to normalize J_j and is the solution of the following maximization problem:

$$\underset{TH1,\ TH2}{\text{Maximize}} \quad J_j=\sum_{i=1}^{N_j} CG_j(i)/N_j$$

4. Experiments

4.1 Outline of the Mini-Plant

Figure 2 shows the flowsheet of the mini-plant used for the diagnostic experiments. Tank-A and tank-B are the feed tanks of hot water and cold water, respectively. The main equipment is the continuous stirred tank heat exchanger which consists of tank-C and tank-D. Tank-C is equipped with a heater in order to make an abnormal situation caused by the abnormal reaction, assuming that it is a continuous stirred tank reactor. There are four flow rate controllers (CF1, CF2, CF3, and CF4), one level controller (CL1), and one temperature controller (CT1) which are standard feedback controllers (i.e., PID). The level of tank-C is controlled by cascading CF1 with CL1, whereas the temperature of tank-C is controlled by cascading CF4 with CT1. On-off controllers are used to maintain the levels of tank A, B, D and E.

The SDG for the mini-plant is constructed as shown in **Fig. 3**, which consists of 56 nodes

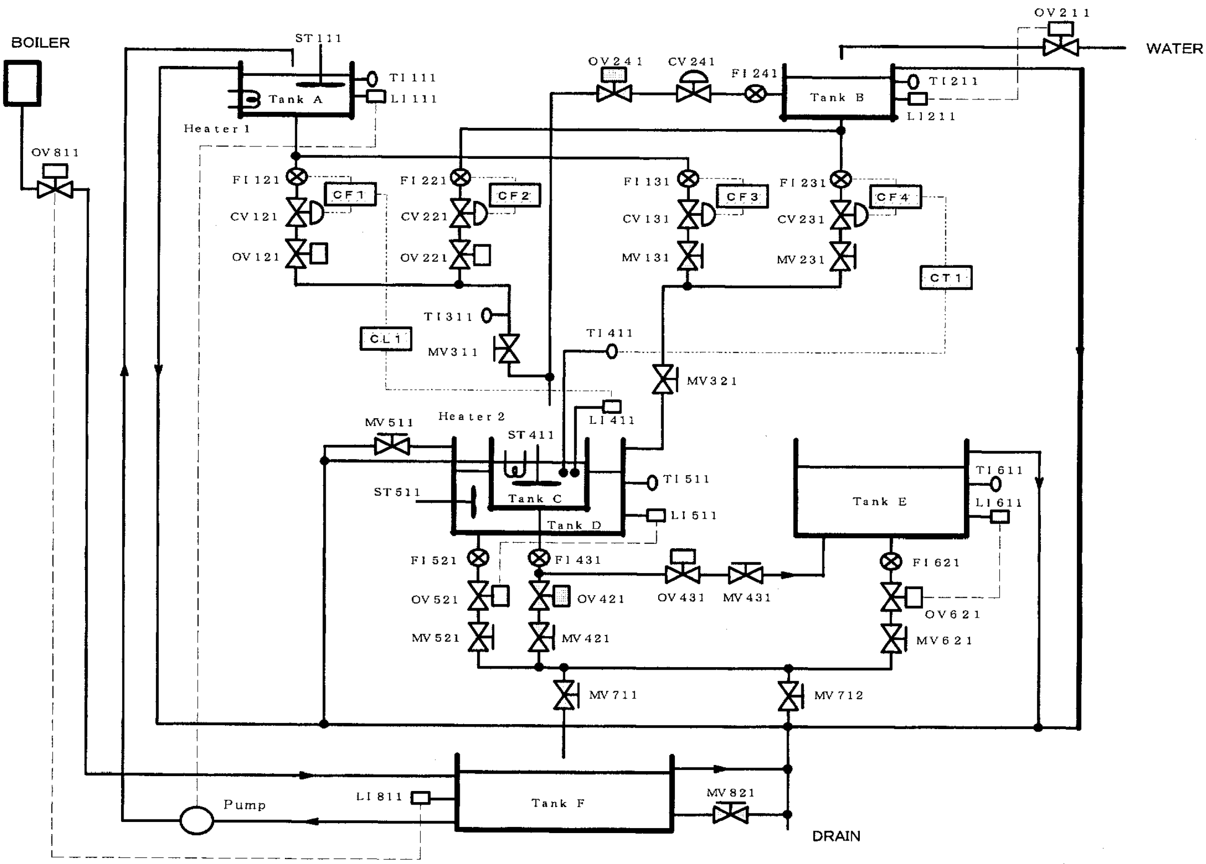

Fig. 2 Flowsheet of the Mini-Plant used in the experiments.

and 84 branches, leaving out the pipe from Tank-A to tank-D through the valve MV131, the pipe from tank-B to tank-C through the valve OV241, and Tank-F, because MV131 and OV241 are always closed in the experiments, and tank-F is a recovery tank for experiments. As a result, 24 observed nodes in the SDG represent measurements and control signals as shown in **Table 5**. Such signals are sampled every 5 seconds and processed by the moving-average method with 24 points, which correspond to the maximum period of changes in the outputs of on-off controllers at the steady state, so that on-off controllers are treated as PID controllers. **Table 5** summarizes the normal values and the standard deviations of the moving-averaged signals during one hour under the steady state experiment.

Representative causes of faults for this plant are assigned to signed nodes in the SDG, which are called "causal nodes", as shown in **Table 6**. There are 63 causal nodes to 80 causes of faults, since it is permitted that several causes are assigned to the same causal node.

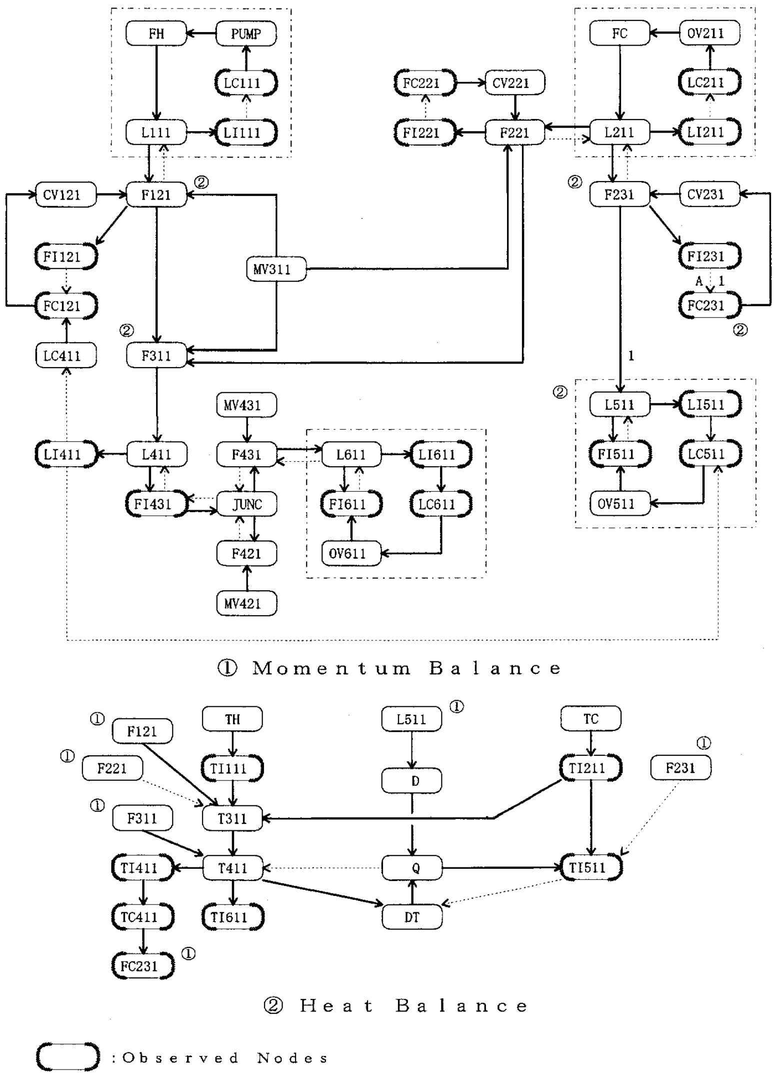

Fig. 3 SDG for the Mini-Plant.

Table 5 Measurements and their normal values and standard deviations.

Observed nodes	Measurements or Control signals	Normal Values	Standard Deviations	Units
LI111	Output of tank-A level sensor	0.9275	0.085371	high/low
LC111	Output of tank-A level controller	0.0725	0.085371	on/off
LI211	Output of tank-B level sensor	0.7774	0.223524	high/low
LC211	Output of tank-B level controller	0.2240	0.224562	on/off
LI411	Output of tank-C level sensor	25.3345	0.046711	cm
LI511	Output of tank-D level sensor	34.9213	0.103380	cm
LC511	Output of tank-D level controller	0.6058	0.031054	on/off
LI611	Output of tank-E level sensor	25.4273	0.119042	cm
LC611	Output of tank-E level controller	0.5308	0.065043	on/off
FI121	Output of flow rate sensor for CF1	1.1690	0.018979	liter/min
FC121	Output of flow rate controller(CF1)	42.6036	0.780484	%
FI221	Output of flow rate sensor for CF	20.4986	0.013327	liter/min
FC221	Output of flow rate controller(CF2)	27.8963	0.668710	%
FI231	Output of flow rate sensor for CF4	2.0081	0.064732	liter/min
FC231	Output of flow rate controller(CF4)	46.7340	0.840544	%
TI411	Output of temperature sensor for CT1	40.4296	0.114615	℃
TC411	Output of temperature controller(CT1)	1.9019	0.065251	liter/min
FI431	Outlet flow rate from tank-C	1.4418	0.018411	liter/min
FI511	Outlet flow rate from tank-D	1.8377	0.072671	liter/min
FI611	Outlet flow rate from tank-E	1.4713	0.124938	liter/min
TI111	Temperature in tank-A	56.2115	0.069557	℃
TI211	Temperature in tank-B	18.4352	0.097261	℃
TI511	Temperature in tank-D	28.7035	0.083109	℃
TI611	Temperature in tank-E	39.8376	0.072280	℃

Table 6 Causes of faults for the Mini-Plant.

Causal nodes	Causes of Faults
FH(+,-)	Hot water feed flow rate (increase, decrease)
FC(+,-)	Cold water feed flow rate (increase, decrease)
TH(+,-)	Hot water feed temperature (high , low)
TC(+,-)	Cold water feed temperature (high , low)
SENSOR(+,-)	Malfunction of sensor in control loop (output high, output low) SENSOR = FI121, FI221, FI231, TI411, LI111, LI211, LI411, LI511, LI611
CRTL(+,-)	Malfunction of controller (output high, output low) CTRL = FC121, FC221, FC231, TC411, LC111, LC211, LC411, LC511, LC611
CV(+)	Control valve stuck high CV = CV121, CV221, CV231
CV(-)	Control valve stuck low CV = CV121, CV221, CV231 or Pipe blocked or Valve closed OV121 closed when CV = CV121 OV221 closed when CV = CV221 MV231 or MV321 closed when CV = CV231
OV(+)	On-off valve stuck high OV = PUMP, OV211, OV521, OV621
OV(-)	On-off valve stuck low OV = PUMP, OV211, OV521, OV621 or Pipe blocked or Valve closed MV521 closed when OV = OV521 MV621 closed when OV = OV621
MV311(-)	Pipe blocked or Valve MV311 closed
MV431(-)	Pipe blocked or MV431 closed or OV431 closed
MV421(+)	Pipe leak or Valve MV421 open
TI421(+)	Abnormal reaction (running away)
D(-)	Fouled heat exchanger

4.2 Experimental Results

Twenty-five experiments were performed by generating the faults shown in **Table 7**. Assume that w_i is a unity, the performance index J was evaluated in the range of first-kind thresholds which is one to five times the standard deviation σ of the corresponding moved-averaged signals and in the range of second-kind thresholds which is four to nine times σ.

Table 8 shows the values of J_{jmax}, J_j/J_{jmax} and J for the combinations of $TH1$ and $TH2$. As to J_{jmax}, there are three groups as follows:

Table 7 Faults generated in the experiments.

No.	Fault Descriptions
1	TI411 output high (5℃)
2	FI221 output high
3	LI411 output low
4	FI121 output low
5	FI231 output low
6	LC411 output high
7	TC411 output high
8	FC221 output low
9	LC411 output high
10	LC411 output high
11	TC411 output low
12	CV121 stuck low
13	CV221 stuck low
14	CV121 stuck low
15	CV231 stuck low
16	OV621 stuck high
17	OV521 stuck high
18	OV121 closed
19	MV231 closed
20	MV311 closed
21	MV521 closed
22	MV621 closed
23	MV431 closed
24	MV421 open
25	Abnormal reaction in tank-C

Table 8 J_{jmax}, J_j/J_{jmax} and J obtained in the experiments.

		Jj/Jjmax														
		TH2 = 4σ TH1					TH2 = 5σ TH1					TH2 = 6σ TH1				
No.	Jjmax	1σ	2σ	3σ	4σ	5σ	1σ	2σ	3σ	4σ	5σ	1σ	2σ	3σ	4σ	5σ
1	0.5932	0.9336	0.9717	1.0000	1.0000	------	0.8614	0.9073	0.9400	0.9400	0.9420	0.7996	0.8533	0.8840	0.8840	0.8862
2	0.8430	1.0000	1.0000	1.0000	1.0000	------	0.9950	0.9950	0.9950	0.9950	0.9950	0.9853	0.9853	0.9853	0.9853	0.9853
3	0.4063	0.8545	0.9188	0.9722	1.0000	------	0.8506	0.9109	0.9628	0.9906	1.0000	0.8189	0.8725	0.9244	0.9523	0.9619
4	0.6379	0.5288	0.8334	1.0000	0.7838	------	0.4206	0.6788	0.7975	0.8062	0.4342	0.3792	0.5233	0.6393	0.6782	0.5441
5	0.3843	-0.4314	-0.3094	-0.8113	-0.4593	------	0.1324	0.2545	0.3737	0.7832	0.9032	0.1262	0.2410	0.3919	0.7653	1.0000
6	0.4132	0.1513	0.0699	0.0699	0.2500	------	0.2113	0.1300	0.1300	0.3100	0.2299	0.3613	0.2200	0.1600	0.1600	0.1600
7	0.1169	-2.8349	-2.8306	-2.8973	-3.4106	------	-0.5261	-0.4833	-0.9324	-2.2036	-2.1069	0.4269	0.5158	0.5013	-0.8452	-0.6903
8	0.8557	1.0000	1.0000	1.0000	1.0000	------	0.9919	0.9919	0.9919	0.9919	0.8955	0.9880	0.9880	0.9880	0.9880	0.9880
9	0.3970	0.9977	1.0000	1.0000	0.1791	------	0.9836	0.9866	0.9866	0.9866	0.9866	0.9212	0.9239	0.9239	0.9239	0.9239
10	0.4037	1.0000	1.0000	1.0000	0.9316	------	0.9866	0.9866	0.9866	0.9527	0.5095	0.9792	0.9792	0.9792	0.9792	0.9792
11	0.5804	0.9369	0.9962	1.0000	1.0000	------	0.8604	0.9213	0.9252	0.9252	0.9290	0.7445	0.8127	0.8165	0.8165	0.8205
12	0.3367	-0.1048	-0.1571	-0.3145	-0.9433	------	0.9964	0.9970	1.0000	0.9492	0.1631	0.9920	0.9926	0.9961	0.9454	0.6317
13	0.4149	1.0000	1.0000	1.0000	1.0000	------	0.9973	0.9973	0.9973	0.9973	0.9226	0.9889	0.9889	0.9889	0.9889	0.9889
14	0.4047	0.9956	0.7433	0.6570	0.3519	------	1.0000	0.8179	0.7919	0.7047	-0.5058	0.9773	0.9773	0.9807	0.9807	0.8063
15	0.8294	0.6505	0.6600	0.6600	0.7234	------	0.9401	0.9419	0.9431	0.9490	1.0000	0.9394	0.9404	0.9416	0.9416	0.9858
16	0.7629	0.9119	0.9324	0.9324	0.8919	------	0.9907	1.0000	1.0000	0.9797	0.9595	0.5698	0.5743	0.5743	0.5743	0.5541
17	0.7216	0.9084	0.9306	1.0000	0.9144	------	0.9084	0.9306	1.0000	1.0000	1.0000	0.9070	0.9282	0.9857	0.9857	0.9857
18	0.4141	0.9986	1.0000	1.0000	0.9626	------	0.9858	0.9874	0.9874	0.9874	-0.3941	0.9734	0.9751	0.9751	0.9751	0.8256
19	0.7529	1.0000	1.0000	1.0000	1.0000	------	0.9923	0.9923	0.9923	0.9923	0.9923	0.9766	0.9766	0.9766	0.9766	0.9766
20	0.7740	1.0000	1.0000	1.0000	0.7964	------	0.9911	0.9911	0.9911	0.9646	0.9380	0.9734	0.9734	0.9734	0.9734	0.9823
21	0.8235	1.0000	1.0000	1.0000	1.0000	------	0.9571	0.9571	0.9571	0.9571	0.9571	0.8023	0.8200	0.8200	0.8200	0.8200
22	0.7491	0.4927	0.5184	0.5298	0.5505	------	0.9849	0.9975	1.0000	1.0000	0.9083	0.9826	0.9928	0.9955	0.9955	0.9220
23	0.3321	0.5613	0.6465	0.5739	-0.7435	------	0.5309	0.6028	0.6594	0.8997	0.3848	0.5218	0.5884	0.6411	0.9852	0.9584
24	0.5083	0.5121	0.5284	0.5365	0.5365	------	0.5284	0.5528	0.5609	0.5609	-0.3089	0.5692	0.5935	0.6016	0.6016	-0.2357
25	0.1854	0.3592	0.5286	0.8652	1.0000	------	0.3511	0.5151	0.8468	0.9676	0.9784	0.3463	0.5081	0.8387	0.9520	0.9595
	J	0.5547	0.5762	0.5682	0.4352	------	0.7278	0.7523	0.7648	0.7457	0.5274	0.7327	0.7594	0.7878	0.7686	0.7200

Table 8 Jjmax, Jj/Jjmax and J obtained in the experiments (continued)

		Jj/Jjmax														
		TH2 = 7σ TH1					TH2 = 8σ TH1					TH2 = 9σ TH1				
No.	Jjmax	1σ	2σ	3σ	4σ	5σ	1σ	2σ	3σ	4σ	5σ	1σ	2σ	3σ	4σ	5σ
1	0.5932	0.7362	0.7918	0.8316	0.8316	0.8336	0.6816	0.7372	0.7834	0.7834	0.7854	0.6094	0.6743	0.7234	0.7234	0.7254
2	0.8430	0.9706	0.9706	0.9706	0.9706	0.9706	0.9657	0.9657	0.9657	0.9657	0.9657	0.9607	0.9607	0.9607	0.9607	0.9607
3	0.4063	0.7950	0.8388	0.8905	0.9183	0.9279	0.7686	0.8102	0.8622	0.8900	0.8993	0.7640	0.8056	0.8558	0.8836	0.8929
4	0.6379	0.3353	0.4753	0.5846	0.6235	0.6235	0.3149	0.4476	0.5031	0.5175	0.5175	0.2892	0.4002	0.4441	0.4498	0.4498
5	0.3843	0.1223	0.2355	0.3817	0.7348	0.9693	0.1187	0.2300	0.3713	0.7041	0.9388	0.1166	0.2279	0.3664	0.6888	0.9235
6	0.4132	0.9971	1.0000	1.0000	1.0000	1.0000	0.9903	0.9935	0.9935	0.9935	0.9935	0.9756	0.9797	0.9802	0.9802	0.9802
7	0.1169	0.4149	0.5013	0.5364	0.3721	0.5509	0.3969	0.4782	0.5646	0.8349	1.0000	0.3653	0.4320	0.5081	0.8323	0.9786
8	0.8557	0.9759	0.9759	0.9759	0.9759	0.9759	0.9679	0.9679	0.9679	0.9679	0.9679	0.9638	0.9638	0.9638	0.9638	0.9638
9	0.3970	0.8458	0.8476	0.8476	0.8476	0.8476	0.7574	0.7589	0.7594	0.7594	0.7594	0.7388	0.7401	0.7408	0.7408	0.7408
10	0.4037	0.9653	0.9658	0.9658	0.9658	0.9658	0.9576	0.9581	0.9581	0.9581	0.9581	0.9420	0.9425	0.9430	0.9430	0.9430
11	0.5804	0.6652	0.7379	0.7417	0.7417	0.7457	0.5880	0.6670	0.6709	0.6709	0.6747	0.4900	0.5753	0.5791	0.5791	0.5830
12	0.3367	0.9783	0.9789	0.9816	0.9834	0.8794	0.9653	0.9658	0.9691	0.9709	0.9727	0.9566	0.9572	0.9605	0.9620	0.9638
13	0.4149	0.9778	0.9778	0.9778	0.9778	0.9778	0.9752	0.9752	0.9752	0.9752	0.9752	0.9641	0.9641	0.9641	0.9641	0.9641
14	0.4047	0.9550	0.9560	0.9587	0.9592	0.9157	0.9449	0.9459	0.9484	0.9489	0.9489	0.9449	0.9459	0.9484	0.9489	0.9489
15	0.8294	0.9252	0.9260	0.9277	0.9277	0.9674	0.9111	0.9111	0.9134	0.9134	0.9532	0.8969	0.8969	0.8993	0.8993	0.9390
16	0.7629	0.5338	0.5338	0.5338	0.5338	0.5338	0.5102	0.5102	0.5102	0.5102	0.5102	0.4898	0.4898	0.4898	0.4898	0.4898
17	0.7216	0.9070	0.9282	0.9857	0.9857	0.9857	0.9059	0.9257	0.9715	0.9715	0.9715	0.9059	0.9257	0.9715	0.9715	0.9715
18	0.4141	0.9676	0.9710	0.9710	0.9710	0.9710	0.9609	0.9626	0.9626	0.9626	0.9626	0.9488	0.9503	0.9503	0.9503	0.9503
19	0.7529	0.9610	0.9610	0.9610	0.9610	0.9610	0.9454	0.9454	0.9454	0.9454	0.9454	0.9376	0.9376	0.9376	0.9376	0.9376
20	0.7740	0.9575	0.9576	0.9576	0.9576	0.9587	0.9469	0.9469	0.9469	0.9469	0.9469	0.9398	0.9399	0.9399	0.9399	0.9399
21	0.8235	0.7872	0.8057	0.8057	0.8057	0.8057	0.7855	0.8029	0.8029	0.8029	0.8029	0.7707	0.7886	0.7886	0.7886	0.7886
22	0.7491	0.9826	0.9928	0.9955	0.9955	0.9220	0.9826	0.9928	0.9955	0.9955	0.9220	0.9826	0.9928	0.9955	0.9955	0.9220
23	0.3321	0.5050	0.5658	0.6149	0.9341	1.0000	0.4839	0.5447	0.5938	0.8991	0.9868	0.4703	0.5312	0.5802	0.8817	0.9545
24	0.5083	0.7181	0.7480	0.7560	0.6260	-0.1788	0.8808	0.9105	0.9186	0.5935	-0.0813	0.9565	0.9917	1.0000	0.5772	-0.0976
25	0.1854	0.3398	0.4973	0.8269	0.9293	0.9353	0.3360	0.4914	0.8188	0.9137	0.9218	0.3323	0.4871	0.8107	0.9002	0.9067
	J	0.7431	0.7746	0.8069	0.8281	0.8094	0.7324	0.7633	0.7951	0.8229	0.8153	0.7197	0.7500	0.7808	0.8058	0.7970

Group 1 : $0.5 < J_{jmax}$ (Experiments 1, 2, 4, 8, 11, 15, 16, 17, 19, 20, 21, 22, 24)
Group 2 : $0.3 < J_{jmax} < 0.5$ (Experiments 3, 5, 6, 9, 10, 12, 13, 14, 18, 23)
Group 3 : $J_{jmax} < 0.3$ (Experiments 7, 25)

Experiments in the group 1 were successful in isolating the real cause, that is, not a few diagnoses executed gave the best results such as $CG_j(i) = 1$. Experiments in the group 2 were successful in diagnosing the real cause but getting two candidates ($CG_j(i) = 0.5$). This was not concerned to the adjustments of thresholds, but caused by the limitation of SDG algorithm. For example, the causal node LC411(+,−) becomes a candidate every time FC121(+,−) becomes a candidate, because there is only one branch from LC411 which is unobserved node to FC121 which is observed node (see **Fig. 3**). In other words, the consistent rooted tree whose root is LC411(+,−) is obtained by supplementing the consistent branch form LC411(+,−) to FC121(+,−) to the consistent rooted tree whose root is FC121(+,−). Experiments in the group 3 were successful in diagnosing the real cause but getting many candidates. This result is also caused by the redundancy of SDG and the only using qualitative information in the SDG algorithm.

As to J_j/J_{jmax}, the best values were obtained when $TH2 = 4\sigma$ or 5σ in many experiments,

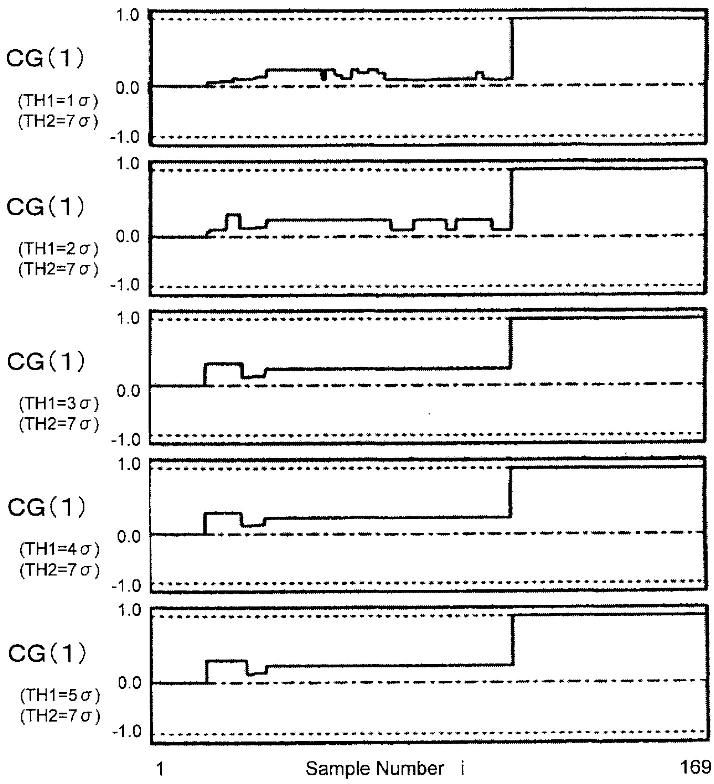

Fig. 4 Trajectory of $CG_j(i)$ in the Experiment 1 using $TH1=\sigma-5\sigma$, $TH2=7\sigma$.

but the smaller or negative values were obtained in some experiments. Such bad results were caused by false or miss diagnoses using inaccurate abnormal patterns. Then, two cases were examined. One case is that $TH1$ is changed in the extent of one to five times σ and $TH2$ is fixed to any value. The other case is that $TH1$ is fixed to any value and $TH2$ is changed in the extent of four to nine times σ. In the former case, J_j/J_{jmax} have the tendency to be greater for greater $TH1$ in many experiments, but smaller in a few experiments. **Figure 4** shows $CG_j(i)$ obtained in the experiment 1 using $TH1$ one to five times σ and $TH2$ seven times σ. The greater values of $CG_j(i)$ is obtained for the greater $TH1$, so that the degree of ambiguous diagnoses becomes smaller and J_j/J_{jmax} becomes greater for greater $TH1$. In the latter case, J_j/J_{jmax} have the tendency to be greater for greater $TH2$ in some experiments, but smaller in the other experiments. **Figure 5** shows $CG_j(i)$ obtained in the experiment 1 using $TH1$ four times σ and $TH2$ four to nine times σ. J_j/J_{jmax} is smaller for larger $TH2$, because the ratio of identification decreases (the ratio of ambiguous diagnoses increases) as $TH2$ becomes greater. **Figure 6** shows $CG_j(i)$ obtained in the experiment 6 using $TH1$ four times σ and $TH2$ four to nine times σ. While J_j/J_{jmax} is small up to six times σ because false and miss diagnoses are performed during some time after the fault is generated, J_j/J_{jmax} is large for $TH2$ more than six times σ because false and miss diagnoses are not performed.

Finally, the optimal J is obtained in the case that $TH1 = 4\sigma$ and $TH2 = 7\sigma$. Quasi-optimal solutions are, however, obtained for the combinations of $TH1$ and $TH2$, such as ($TH1 = 3\sigma$, $TH2 = 7\sigma$), ($TH1 = 5\sigma$, $TH2 = 7\sigma$), ($TH1 = 4\sigma$, $TH2 = 8\sigma$), ($TH1 = 5\sigma$, $TH2 = 8\sigma$) and ($TH1 = 4\sigma$, $TH2 = 9\sigma$).

From the above results, we conclude that the recommended $TH1$ is approximately four times of σ and the recommended $TH2$ is nearly two times $TH1$.

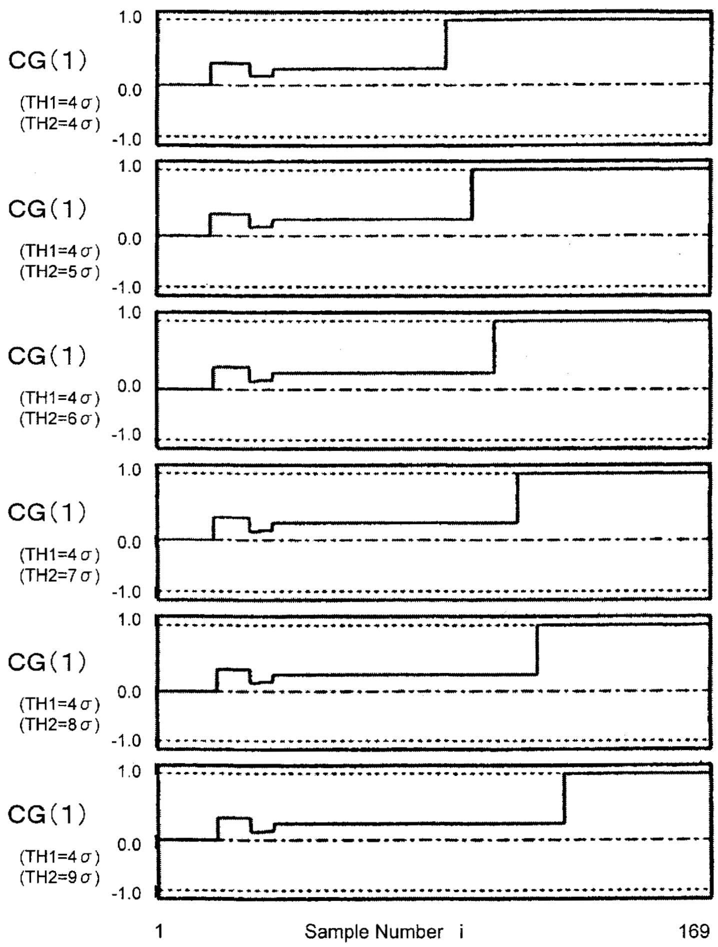

Fig. 5 Trajectory of $CG_j(i)$ in the Experiment 1 using $TH1=4\sigma$, $TH2=4\sigma-9\sigma$.

Conclusions

The new SDG algorithm which is supplemented by the pre-processing routine for cascade control loops has been proposed. As far as experimental results were investigated in detail, false and miss diagnoses didn't arise from the shortcoming of the new SDG algorithm, but the inaccurate abnormal patterns generated by the bad adjustments of thresholds.

In this paper, the performance of the fault diagnosis system based on SDG was mainly discussed. Considering that such performance is greatly influenced by adjustments of thresholds, the problem to search optimal adjustments of thresholds was formulated as the maximization of a performance index which is the similarity to the ideal diagnostic result. Furthermore, with the experiments using a practical mini-plant, where 25 faults were generated, optimal adjustments of thresholds were searched. As a result, the proposed method gave the reasonable thresholds.

References

1) Finch F.E. and M.A.Kramer; Narrowing diagnostic focus using functional decomposition. AIChE J., Vol.34, pp.25-36 (1987)

2) Gangiah V.K. and M.B.Rao; Two-level methods for incipient fault diagnosis in nonlinear chemical processes. Computers chem. Engng., Vol.16, pp.463-476 (1992)

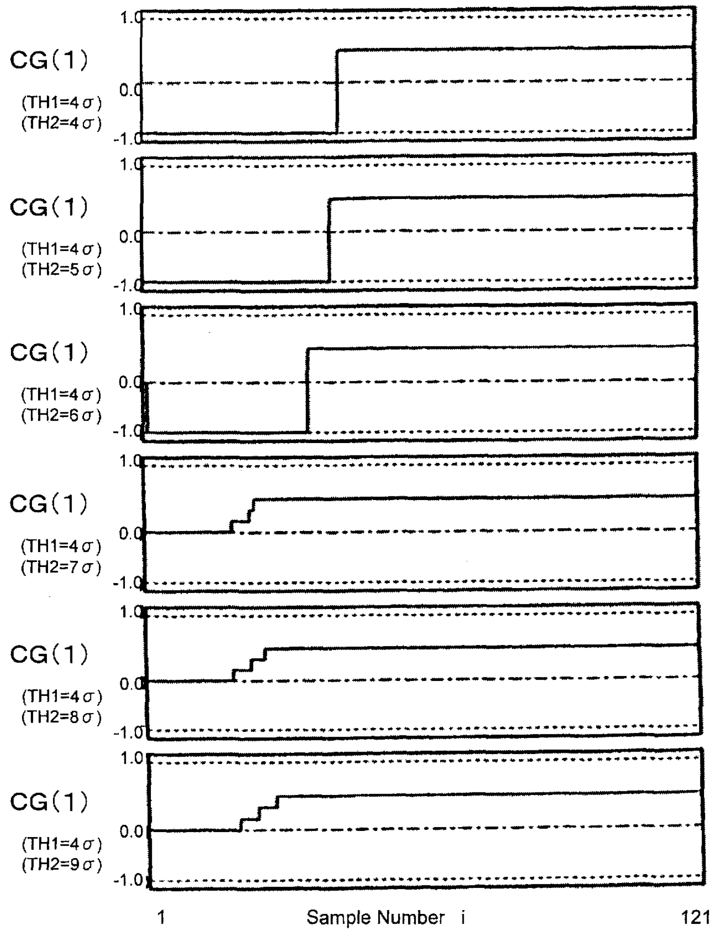

Fig. 6 Trajectory of $CG_j(i)$ in the Experiment 6 using $TH1=4\sigma$, $TH2=4\sigma-9\sigma$.

3) Oyeleye O.O. and M.A.Kramer; Qualitative simulation of chemical process system: Steady-state analysis. AIChE J., Vol.34, pp.1441-1454 (1988)

4) Ramesh T.S., J.F.Davis and G.M Schwenzer; Knowledge-based diagnostic systems for continuous process operations based upon the task framework. Computers chem. Engng., Vol.16, pp.109-127 (1992)

5) Shiozaki, J., H.Matsuyama, K.Tano and E.O'Shima; Fault diagnosis of chemical processes by use of signed directed graphs: Extension to five-range patterns of abnormality. Int. Chem. Eng., Vol.25, pp.651-659 (1985)

6) Shiozaki, J., B.Shibata, H.Matsuyama, and E.O'Shima; Fault diagnosis of chemical processes utilizing signed directed graphs-Improvement by using temporal information. IEEE Trans. Ind. Elec., Vol.36, pp.469-474 (1989)

7) Tsuge, Y., J.Shiozaki, H.Matsuyama and E.O'Shima; Fault Diagnosis Algorithms Based on the Signed Directed Graph and its Modifications. Int. Chem. Eng. Symp. Ser.92 , PSE'85, Cambridge, England, pp.133-144 (1985)

8) Tsuge, Y., B.Shibata and H.Matsuyama; Improvement of the accuracy of a fault diagnosis system utilizing the signed directed graph and its Modifications. Proceeding of 4-th International Symp. PSE'91, Montebello, Canada, II.20.1 (1991)

9) Watanabe K., I.Matsuura, M.Abe, M.Kubota and D.M.Himmelblau; Incipient Fault diagnosis chemical processes via artificial neural networks. AIChE J., Vol.35, pp.1803-1812 (1989)

10) Watanabe K. and D.M.Himmelblau; Fault Diagnosis in nonlinear chemical processes. AIChE J., Vol.29, pp.243-260 (1983)

11) Waters A. and J.W.Ponton; Qualitative simulation and fault propagation in process plants. Chem. Eng. Res. Des., Vol.67, pp.407-422 (1989)