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Study on a Self Diagnostic Monitoring System for an Air-Operated Valve: Development of a Fault Library

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Abstract

In the interest of nuclear power plant safety, a self-diagnostic monitoring system (SDMS) is needed to monitor defects in safety-related components. An air-operated valve (AOV) is one of the components to be monitored since the failure of its operation could potentially have catastrophic consequences. In this paper, a model of the AOV is developed with the parameters that affect the operational characteristics. The model is useful for both understanding the operation and correlating parameters and defects. Various defects are introduced in the experiments to construct a fault library, which will be used in a pattern recognition approach. Finally, the validity of the fault library is examined.

Key Words : diagnosis, air-operated valve, SDMS, fault library, pattern recognition

1. Introduction

Safety is the primary issue in a nuclear power plant. Thus, many efforts have been made to improve plant safety. Surveys of past accidents indicate that the degradation of components comprising safety-related systems has been the major cause. Therefore, it is essential to monitor the condition of such components continuously.

An air-operated valve (AOV), which is used to control the fluid in flow systems such as a feedwater system, is one of the critical components that must be monitored since its operational behavior is directly related to plant safety. However, most studies and reports to date have focused on switch setting and periodic maintenance, while neglecting to investigate the monitoring of degradation and the identification of defects in AOVs [1,2]. Therefore, in this paper, a new approach is introduced to monitor and diagnose AOVs effectively.

An AOV consists of several components that are interconnected with air hoses, wires, springs, etc. To maintain the condition of AOVs, it is important to identify the location where defects take place and the original cause and severity of the defects. However, it is difficult to identify defects since all the components of an AOV are closely connected and related. As such, a defect in one component affects the characteristics of other components, leading to misdiagnoses or the incapacity to make a diagnosis without possessing significant experience. Therefore, a self-diagnostic system is needed to help the plant operators, who may have not sufficient experience in diagnosing AOVs, to estimate the performance and to maintain the safe-operating condition of the AOVs. For self-diagnostic systems, several approaches have been introducing, including pattern recognition, neural networks, and model-based approaches. In this paper, a fault library is constructed for a pattern recognition approach, which is effectively used in PNNL (Pacific Northwest National Laboratory) [3,4]. Many defects are intentionally introduced in order to obtain the pattern of the various defects, and the pattern of each defect is examined in terms of whether it is independent of other patterns. Force-balance equations are also derived so as to obtain a better understanding of the relations between the parameters of the AOVs and to enhance the robustness of the diagnosis.

2. Operational Principle of an AOV

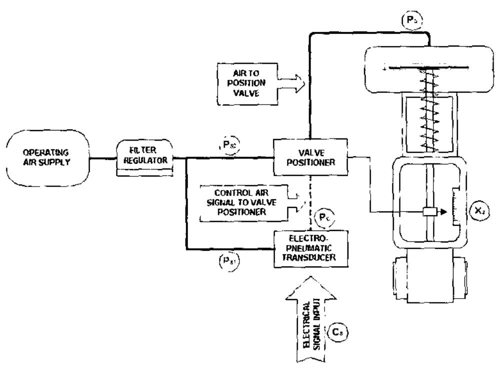
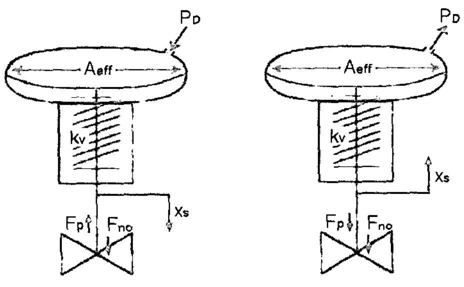


Fig. 1. Schematic Diagram of a Diaphragm Air-Operated Valve

An air-operated valve consists of an air actuator, a valve, and other accessories that control air pressure. In this paper, a direct acting diaphragm actuator with spring return and an unbalanced disc globe valve, which is the widely used AOV in nuclear power plants, are studied [2].

Figure 1 shows a schematic diagram of an AOV. Compressed air is supplied to a filter/regulator to eliminate moisture and oil in the supplied air and to decompress to the operating pressure of the actuator. The filtered and regulated air (P_{S1}, P_{S2}) is then fed to an electro-pneumatic transducer and a positioner. The electro-pneumatic transducer provides the positioner with control air pressure (P_C) in proportion to the electrical signal(C_S) and the positioner controls the diaphragm pressure (P_D) according to the control air pressure. This diaphragm pressure causes the valve stem to stroke. At this time, the information of the stem position (x_s) is fed back to the positioner through a lever and the positioner adjusts the diaphragm pressure.

To understand the principle of operation and to identify the important parameters to be monitored, a simple relation is developed. These include characteristic parameters that vary with time and are closely related to performance and design parameters, which do not vary with time. Therefore, to diagnose defects of an AOV, it is necessary to monitor the characteristic parameters.



(a) Downward stroke (b) Upward stroke

Fig. 2. Schematic Diagram of Operating Forces on an AOV While the Stem Moves Downwards and Upwards

A schematic diagram of operating forces on an AOV is shown in Figure 2. The force produced by the diaphragm pressure (P_D) is balanced with the spring force, packing force, disc weight, and so on. The following is the force balance equation for the downward stroke.

$$P_D = \frac{k_v(x_s + x_{pre}) + F_P - F_{no}}{A_{eff}} \quad (1)$$

where

P_D : diaphragm pressure; measurable variable

A_{eff}: effective area of the diaphragm; design parameter

k_v : spring constant of a valve; characteristic parameter

x_s : stem position; measurable variable

x_{pre} : precompressed length of the spring; design parameter

F_p : packing force; characteristic parameter

F_{no} : force that does not change its direction regardless of the direction of the stroke, such as disc weight; design parameter

Similarly, a force balance equation can be derived for the upward stroke.

$$P_D = \frac{k_v(x_s + x_{pre}) - F_P - F_{no}}{A_{eff}} \quad (2)$$

From these relations, it is recognizable that some characteristic parameters such as the packing force can be estimated from the measurable variables (the diaphragm pressure and the stem displacement) and design parameters (A_{eff}).

$$F_P = \frac{A_{eff}(P_{D(down)} - P_{D(up)})}{2} \quad (3)$$

However, there are other characteristic parameters that merit monitoring that cannot be derived from the relation with measuring variables and design parameters. Therefore, a pattern recognition method is suggested as a diagnostic tool. The following section describes the procedure to construct a fault library providing patterns of the measuring variables for each defect.

3. Experimental Set-up and Procedures

A photograph of the experimental set-up is shown in Figure 3. Control signal (C_S), supply air pressure (P_{S1}, P_{S2}), control air pressure (P_C), diaphragm pressure (P_D), and stem position (x_s) were measured as specified in Figure 1. The pressure supplied from the filter/regulator was measured at two positions in front of the E/P transducer (P_{S1}) and the positioner (P_{S2}), respectively, in order to characterize each component accurately, even though the two points are connected directly through the air pipe.

The control signal is designed as shown in Figure 4 to provide the full cycle of the opening

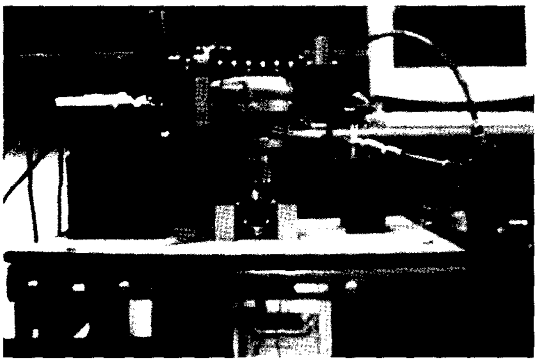


Fig. 3. Photograph of the Experimental Set-up

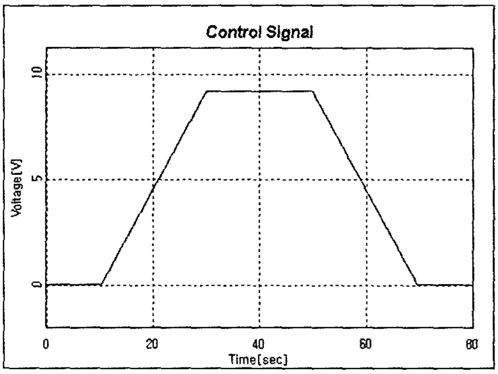
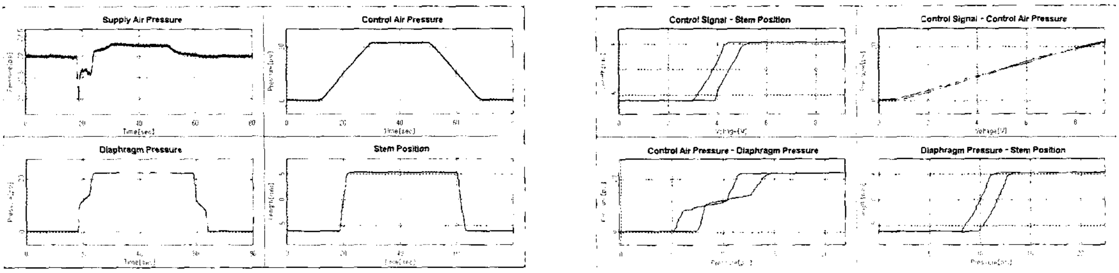


Fig. 4. Control Signal Provided to the E/P Transducer



(a) In the time domain (b) In the characteristic domain

Fig. 5. Measured Signals

and closing stroke. As the voltage of the control signal increases, the stem moves downwards, and vice versa. All the signals were measured at the same time during the stroke. Figure 5 shows the measured signals under normal conditions, which will be utilized as the baseline in constructing the fault library for the pattern recognition approach. The time-based graph represented in Figure 5 (a) is useful for judging the quality of each measured signal but not effective for identifying defective components. Therefore, two signals are paired to separate the characteristics of each component, as shown Figure 5 (b). For example, the graph of the control signal vs. the control air pressure shows the characteristics of the E/P transducer since they are the input and the output of the E/P transducer. It is seen that the E/P transducer has fairly linear response characteristics. Similarly, the graph of the diaphragm pressure vs. the stem position provides information related to the valve.

4. Fault library

To apply the pattern recognition approach, a fault library was constructed through experiments on the AOV with various defects. Several frequently occurring defects were intentionally introduced to the major components of the AOV. The level of each defect was carefully controlled to determine the sensitivity and robustness of the fault library. 12 defects are considered in this paper, as listed in Table 1. Their locations are given in Figure 6. 4 event points in 4 measured signals are selected where each signal changes abruptly, as shown in Figure 7. The selected 16 event points do not coincide with each other and

Table 1. List of Defects in a Fault Library

No.		List
1		Restricted supplied air
2	2-1	Zero setting point of the E/P transducer ↑
	2-2	Zero setting point of the E/P transducer ↓
3	3-1	Span of the E/P transducer ↑
	3-2	Span of the E/P transducer ↓
4		Leakage at the position A
5		Clogging at the position A
6	6-1	Initial response point of the positioner ↑
	6-2	Initial response point of the positioner ↓
7		Stuck feedback linkage arm
8		Leakage at the position B
9		Clogging at the position B
10	10-1	Actuator spring preload ↑
	10-2	Actuator spring preload ↓
11	11-1	Packing load ↑
	11-2	Packing load ↓
12	12-1	Stiffness of the feedback spring ↑
	12-2	Stiffness of the feedback spring ↓

are related to the characteristics of the components. In addition, the values of each signal at 16 event points vary as the performance of each component varies. Therefore these values are recorded and compared with those of the baseline, which is found to be very effective in classifying the various defects. In the following section, the procedure to construct the fault library is discussed in greater detail with examples.

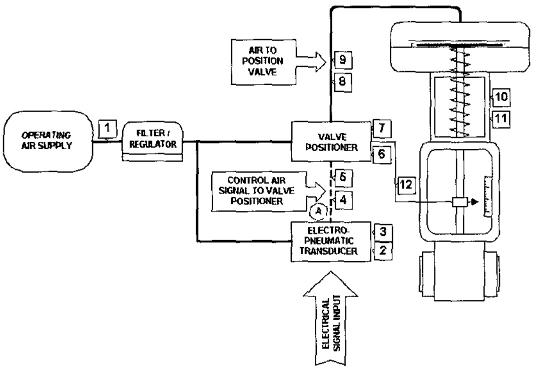


Fig. 6. Locations of Defects

4.1. Leakage at the Position A

First, consider the case when there is leakage between the E/P transducer and the positioner (position A). To make the air leak, a hole was drilled in each air pipe and several sizes of holes, as shown in Figure 8, were tested to evaluate the sensitivity to leakage level. Figure 9 shows the baseline (gray) and the measured data (black). From Figure 9 (a), we see that the times and the corresponding values at events of the measured signals are different from those of the baseline even though the control signal is the same. Due to leakage, the control air pressure does not increase at the same rate as the baseline and does not reach the designated pressure.

However, it cannot be definitely stated that the changes in both the diaphragm pressure and the stem position are solely caused by the control air pressure. To clarify the causes, the characteristic domain (Figure 9 (b)) is introduced. The control signal vs. control air pressure graph, which represents the characteristics of the E/P transducer, shows a distinct reduction in the slope

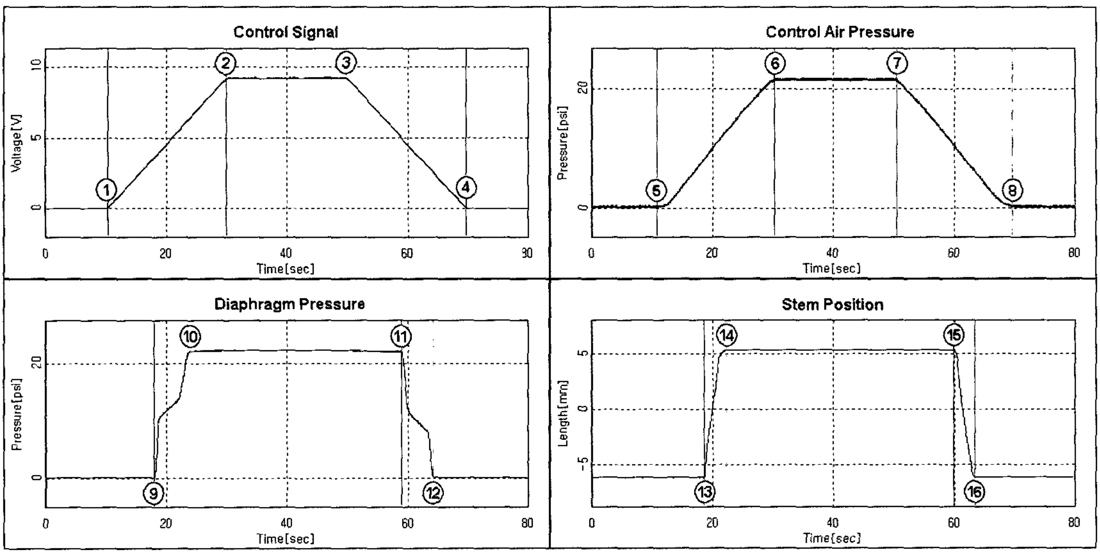


Fig. 7. Event Points Where the Values of Each Signal are Recorded

Table 2. Pattern of the Parameters when There is Leak at Position A

■ Control Air Pressure

Pc(⑤)	Pc(⑥)	Pc(⑦)	②~③ slope	②~③ slope′	Pc(⑧)
<	↘*	↘*	<	<	<

Pc(⑧)′	t(⑤) − t(①)	t(⑥)	t(⑦)	t(⑦)−t(⑥)	t(⑧)−t(③)	t(⑥)−t(②)	t(⑦)−t(③)
<	↗	↘*	↗*	↗*	↘	↗*	↗*

P(ⓝ) : Pressure at event ⓝ
t(ⓝ) : time at event ⓝ
ⓝ : event number(① ~ ⑯)
↗ : increased value of a parameter compared with the baseline
↘ : decreased value of a parameter compared with the baseline
< : irrelevant
* : importance of the parameter

and the maximum value. However, there is little change in both the control air pressure vs. diaphragm pressure graph and the diaphragm pressure vs. stem position graph, which represent the characteristics of the positioner and the valve, respectively. Therefore, it is easily recognizable that defects are not located in the positioner or the valve. These relations can be distinguished by comparing the values and the time at event points, as defined in Figure 7. Table 2 shows the patterns of the defined parameters when there is leakage at position A. The parameter can be the time, the value at an event point, or the slope between two event points. Arrows represent the direction of change and asterisks (*) represent the importance of the parameter for a specific defect.

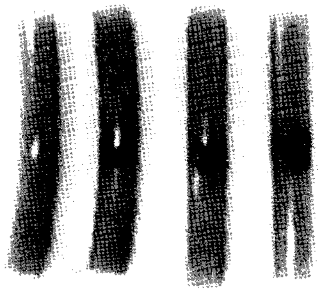
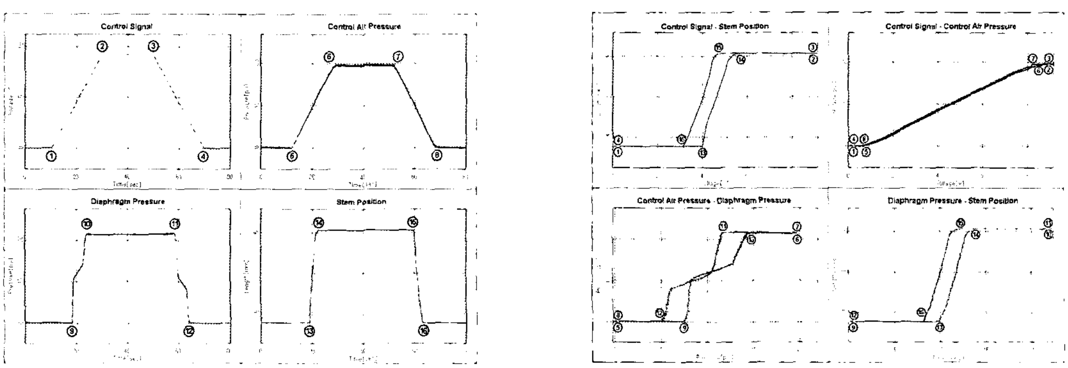


Fig. 8. Air Pipes with Several Sizes of Holes



(a) In the time domain

(b) In the characteristic domain

Fig. 9. Effect of Leakage at Position A

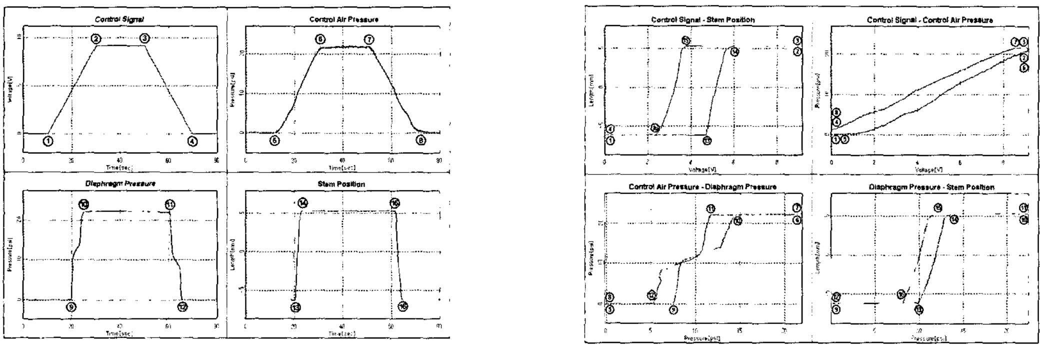
4.2. Clogging at Position A

The air pipe or the air path of the components sometimes clogs due to dust or rust. The clogging phenomenon can be simulated by reducing the air path of the air pipe, as shown in Figure 10. The amount of clogging was controlled by the screw. Unlike the case of leakage, clogging delays the responses in strokes, as shown in Figure 11(a), since clogging increases the resistance of the airflow in the pipe. However, clogging at position A does not affect the characteristics of the positioner and the valves, as shown in Figure 11 (b). The patterns are given in Table 3.

Fig. 10. Clogged Air Pipe

4.3 Stiffness of the Feedback Spring

The feedback spring, which connects the feedback linkage arm and the valve stem, as shown in Figure 12, can be degraded during operation. As the stiffness of the feedback spring decreases, the feedback force on the feedback linkage decreases, causing an increase in the diaphragm pressure even though the same control air pressure is supplied to the positioner as the baseline. This phenomenon causes the stem to move faster in the time domain (Figure 13 (a)) and makes the slope of the diaphragm pressure with respect to the control air pressure steeper in the



(a) In the time domain (b) In the characteristic domain

Fig. 11. Effect of a Clogged Air Pipe at Position A

Table 3. Pattern when the Air Pipe is Colgged at the Position A

■ Control Air Pressure

Pc(⑤)	Pc(⑥)	Pc(⑦)	②~③ slope	②~③ slope′	Pc(⑧)
<	<	<	<	<	<

Pc(⑧)′	t(⑤) - t(①)	t(⑥)	t(⑦)	t(⑦)-t(⑥)	t(⑧)-t(③)	t(⑥)-t(②)	t(⑦)-t(③)
<	↗	↗*	↗	↘*	↗*	↗*	<

characteristic domain (Figure 13 (b)). The patterns of the parameters are provided in Table 4.

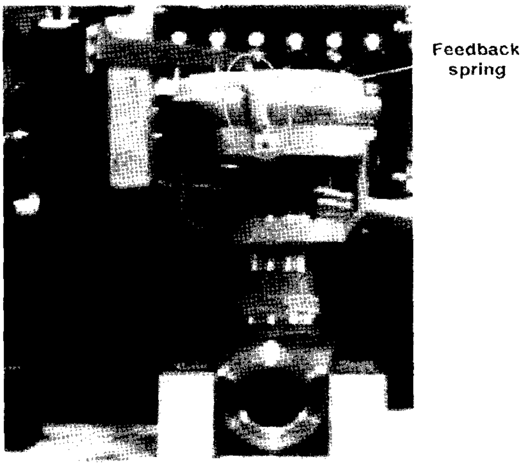
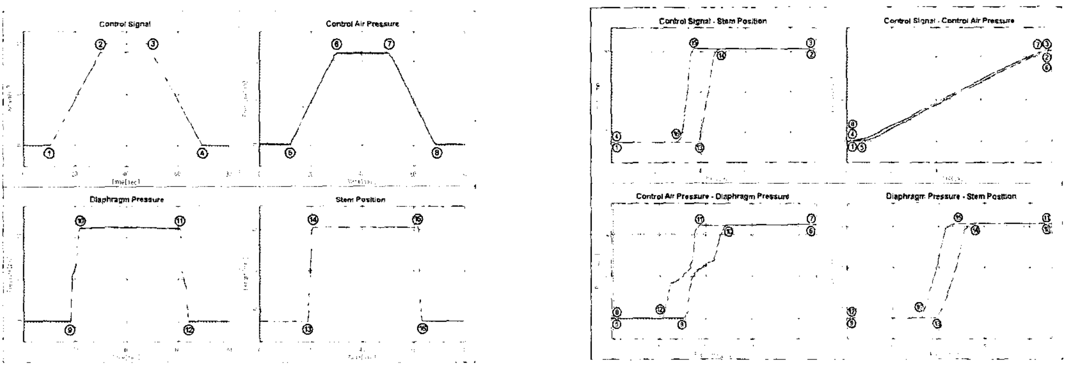


Fig. 12. Feedback Spring

Above are three cases from the twelve frequently occurring cases. Patterns of other cases can be obtained similarly. The presented pattern tables list only a portion of the entire data as the whole table is too long to present here. The patterns are verified based on the mechanical logic of operation.

5. Conclusions

In this paper, a fault library for the most frequently occurring defects was constructed for future utilization in a self-diagnostic system for AOVs in nuclear plants. The method to extract the patterns from the experimental data was discussed and the validity of the fault library was assessed with the principle of operation and



(a) In the time domain (b) In the characteristic domain

Fig. 13. Effect of Feedback Spring Stiffness

Table 4. Pattern of when the Feedback Spring Stiffness is Lowed

■ Diaphragm Air Pressure

P_D(⑨)	P_D(⑬)	P_D(⑭)	avg(P_S(⓪~①)) - P_D(⑩)	avg(P_S(⓪~①)) - P_D(⑪)	⑥~⑦ slope	⑥~⑦ slope′	P_D(⑮)	P_D(⑯)
<	<	<	<	<	<	<	<	<

P_D(⑫)	P_D(⑩)	P_D(⑪)	P_D(⑫)′	t(⑨)−t(①)	t(⑬)−t(①)	t(⑭)−t(①)	t(⑩)−t(①)
<	<	<	<	<	<	↘*	↘*

t(⑪)−t(⑩)	t(⑪)−t(③)	t(⑮)−t(③)	t(⑯)−t(③)	t(⑫)−t(③)	abs (tb(⑨)−t(⑨))	abs(tb(⑩)−t(⑩))
↗*	↗*	↗*	<	<	<	<

various experiments. The following conclusions can be drawn.

First, the time-domain is useful to check the quality of a measured signal and the characteristic-domain is essential to classify a defective component. Second, 16 event points are defined and found to be effective in identifying defects. The times and the values at the 16 event points provide a distinct pattern for each defect. Additionally, since the 16 event points are determined for easy selection, the proposed method can be automated and used in a self-diagnostic system. Therefore, the fault library is a very useful tool in identifying defects in AOVs. Finally, the self-diagnostic system will improve plant safety and reduce maintenance costs.

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Reference

1. Tom Walker, "AOV Setup Parameters", *Air Operated Valve User's Group 20th Annual Conference*, 1~26(01/11/01), Clearwater, Florida (2001).
2. DR. Harold L. Ornstein, "Air-Operated Valve Failure Data", *Air Operated Valve User's Group 20th Annual Conference*, 6~15 (01/12/01), Clearwater, Florida (2001).
3. L.J. Bond et al., "On-line Intelligent Self-Diagnositc Monitoring for Next Generation Nuclear Power Plants", *NPIC&HMIT 2000*, 1~10, Washington DC (2000).
4. Don B. Jarrell et al., "Prognostic and Condition Based Maintenance(CBM) - A Scientific Crystal Ball", Plant reliability for now and future Ⅱ, *ICAPP paper* 1194, 1~7 (2002).