Approach to Diagnostics and Monitoring of Pneumatic Systems

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Introduction

Diagnostics and operation monitoring of pneumatic components and their systems is an important problem both for the producers and industrial customers of pneumatic installations. D&M (Diagnostics and Monitoring) system could introduce solutions for the following tasks:

- Performance monitoring of pneumatic components (cylinders),
- Compressed air consumption accounting,
- System tuning automation,
- Detection of changes in operation mode and conditions.

Constant observation of pneumatic components wear is a key assumption for predictive maintenance. Air consumption monitoring is a part of energy resources accounting. Stability of parameters and operation precision of pneumatic system in production lines could be directly related to the quality of released production.

Basic restrictions to the D&M system were defined by requirements for as few as possible new hardware and installations, minimum interference with a pneumatic system to be monitored, invariance to environment conditions such as working pressure and variations of operation rhythm.

The basic idea of the structure and operation principles of this D&M system was initially proposed in [1]. We have implemented the D&M system with some improvements. Later on we tested operation of it conducting initial experiments. In this paper we present description of the system, gained experience and suggestions about the ways to overcome discovered disadvantages.

Features of pneumatic systems operation and representative signal

The quality of pneumatic systems operation is defined by [2]:

- Level of components wear,
- Quality and pressure of compressed air,
- Changes of cylinders loads,
- Correct tuning.

During long lasting operation sealings of pneumatic cylinders are worn off. This causes an increase of air leakage between the volumes of a cylinder, decrease of cylinder's force and speed. Usually this process is very slow and involves thousands of cycles.

In a case of non-hermetic connections compressed air pressure decreases, its consumption grows up. Air leakage may progress slowly or appear suddenly.

Fast operation state changes may be invoked either by tuning cylinder's throttles or variation of loads. Fast changes could cause differences even in two consecutive cycles.

All mentioned factors influence dynamic air flow speed in the supply lines. Therefore, differential pressure signal measured between the terminals of Venturi tube is a representative signal, that indicates conditions of the system operation. Venturi tube is mounted in the central air supply line. Such method of air flow measurement does not influence operation of pneumatic units and enables monitoring of multicomponent system using only one sensor.

In Figure 1 dependence of differential pressure patterns on working pressure P_0, load and cylinder's sealing wear level is presented. It is obvious, that the mentioned factors define cycle duration, signal magnitude and phase. Patterns were acquired monitoring one cyclically moving cylinder. Sealing wear was simulated intentionally introducing air leakage channel between the volumes of the cylinder. Third column presents differential pressure patterns (Defect 2) measured using wider orifice for air penetration compared to the second column (Defect 1).

Majority of pneumatic systems operates in cyclic or repeatable manner. In such case air flow speed or proportional differential pressure could be described using the following expression

$$p(t) = \sum_i \left\{ k_{pi} \cdot P_i \left(t - \sum_{j=1}^{i-1} T_j \right) + a_{pi} \right\} + n(t) \quad (1)$$

where $P_i(t)$ - differential pressure pattern of the i-th cycle of a pneumatic system, T_i - duration of the i-th cycle, k_{pi} and a_{pi} - respectively multiply factor and shift at the i-th system's cycle, $n(t)$ - random item that describes disturbances in the measurement channel (compressed air pressure oscillations in the supply lines, instability of pneumatic components operation and etc. $P_i(t)$ is defined in time interval $t \in [0, T_i]$ and equal to 0 elsewhere. Period T_i may differ depending on operation conditions – working pressure, load, faults. Besides, edge jittering effect was observed during experiments with pneumatic test bench. It could be caused by instability of

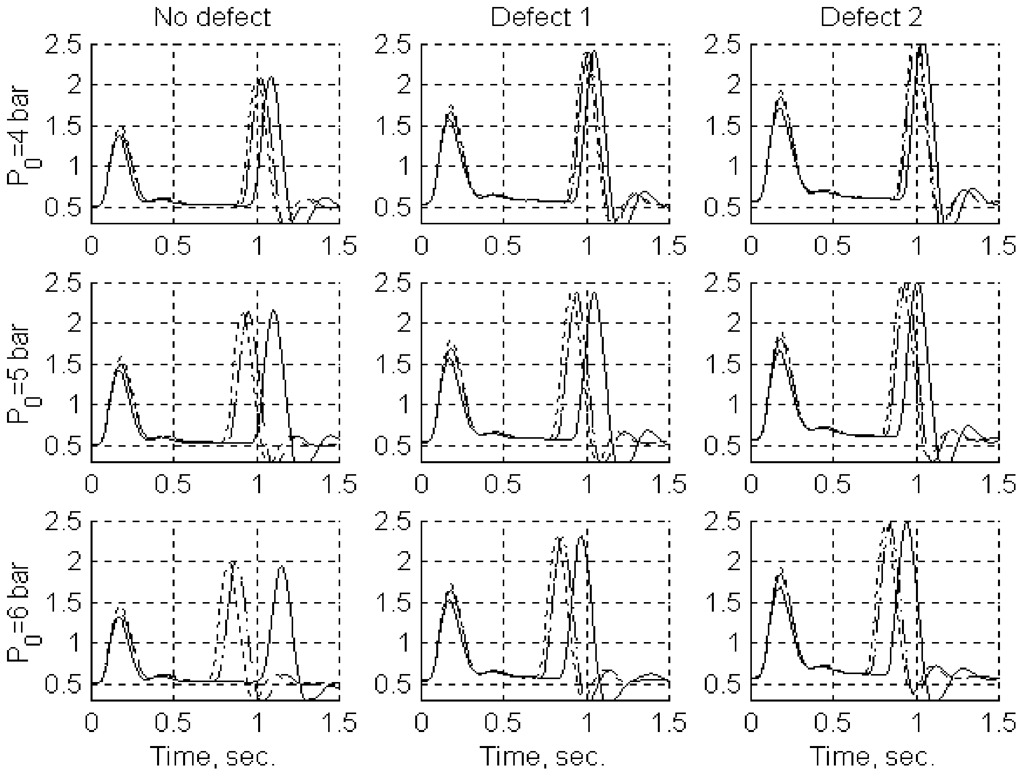

Fig 1. **Variations of differential pressure signal shape (patterns) in dependence to working pressure P_0, load and cylinder's sealing wear. Magnitude axis units are relative. Load is coded by line style: solid – 50 N, dashed – 15 N, dotted – 0N. Every pattern was calculated after synchronously averaging 10 measured differential pressure samples series.**

component (cylinders) internal friction contacts.

System implementation

Structure of the system is presented in Figure 2. It consists of:

- Collection of Venturi tubes with different diameters,
- High speed differential pressure transducer (nominal response time 0.1 msec., sensitivity 10 mV/psi),
- Differential amplifier with low-pass filter,
- Controller with ADC and discrete inputs for synchronization signals,
- Personal computer (PC).

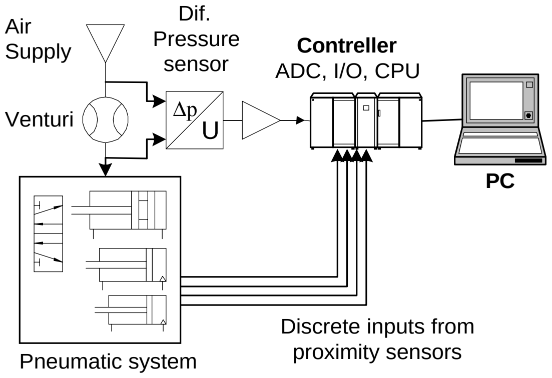

Fig 2. **Monitoring and diagnostics system structure.**

Unit selection of Venturi tubes with several different diameters is used for the optimization of system's sensitivity of air flow to differential pressure conversion in pneumatic installations with very different air flow limits.

Pressure difference Δp at the terminals of Venturi tube is measured with a differential pressure transducer. Δp is related to the speed of air flow [3]

$$V = K \cdot \sqrt{\frac{\Delta p}{\theta}} \qquad (2)$$

where K - Venturi tube factor, θ - air density.

Differential pressure signal is amplified and filtered using low-pass electrical filter in order to reject high frequency oscillations induced by high speed pneumatic valves. PC is dedicated for configuration and settings control, visualization and results storage.

Digital processing of sampled differential pressure is carried out by the controller. Because of the huge variety of pneumatic systems configurations it is difficult to define differential pressure signals space corresponding to acceptable and fault operation in advance. Therefore, classification algorithm based on the comparison of reference and detected during monitoring or testing features vectors is used (Figure 3). Reference features vector is acquired in learning stage.

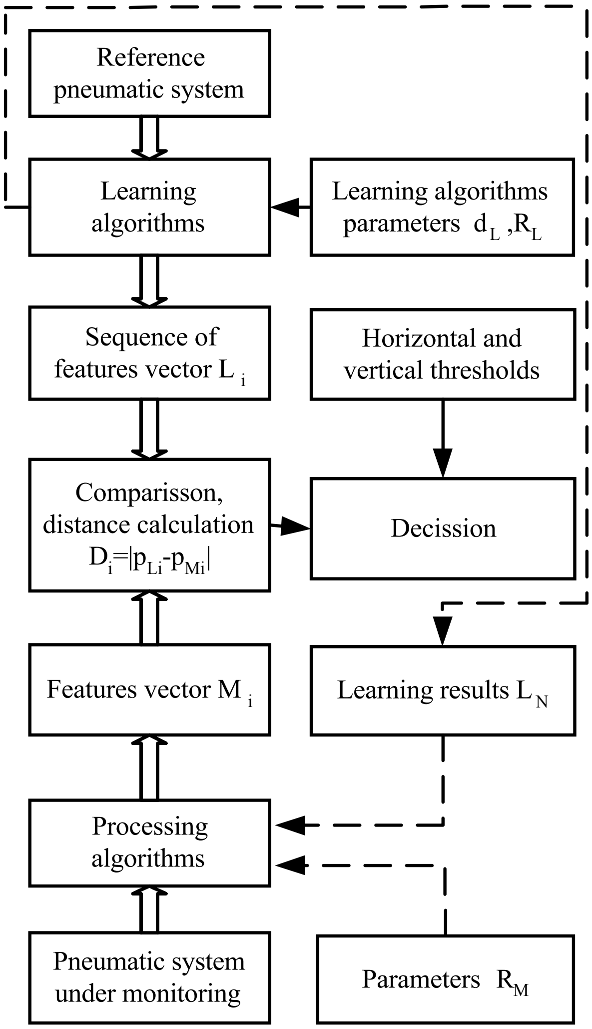

Fig 3. **System operation algorithm.**

The learning is carried out under the assumption that pneumatic system operates according to technical specification, i.e. in an acceptable way for the user. The result of the learning is the sequence of features vectors $\overrightarrow{L_i} = \{p_{Li}, t_{Li}, d_{Li}, \min_{Li}, \max_{Li}\}, i = 1, L_N$, which approximates function $P_L(t) = \langle P(t) \rangle$. p_{Li}, d_{Li}, $\min_{Li}$, $\max_{Li}$ -are average value of differential pressure, its deviation, minimum and maximum values in time segment t_{Li} respectively. $\langle\ \rangle$ denotes synchronous averaging operation. Length L_N of the sequence $\vec{L_i}$ depends on the complexity of the shape of differential pressure pattern, deviation of the item $n(t)$ in expression (1) and parameters of learning algorithms. L_N is determined in learning stage and later is passed to processing procedures of monitoring stage.

Learning procedure is shown in Figure 4. R_L sampled $P_i(t_k)$ series are accumulated in the RAM memory of the controller. Start of the pneumatic system cycle, as well as start of series $P_i(t_k)$ is indicated by the selected proximity sensor attached to the one of system's cylinder. Then every series $P_i(t_k)$ is divided in to two segments of equal duration $P_i\left(t_k^{(1)}\right), t_k^{(1)} = 0, \Delta t, 2\Delta t,..T_i/2$ and $P_i\left(t_k^{(2)}\right), t_k^{(2)} = T_i/2 + \Delta t..T_i$. Average of differential pressure value in the first segment

$$p_1 = \left\langle M\left[P\left(t_k^{(1)}\right)\right]\right\rangle = \frac{1}{R}\sum_{r=1}^{R_L}\left(\frac{1}{K}\sum_{k=1}^{K}P_r\left(t_k^{(1)}\right)\right), \tag{3}$$

deviation

$$d_1 = \left\langle D\left[P\left(t_k^{(1)}\right)\right]\right\rangle = \frac{1}{R}\sum_{r=1}^{R}\left(\frac{1}{K}\sum_{k=1}^{K}\left(P_r\left(t_k^{(1)}\right) - p_1\right)^2\right), \tag{4}$$

where K is number of sampled in the first segment, R_L - number of synchronously averaged cycles.

First segment is divided in half once more if $d_{L1} > d_L$. d_L is parameter to be set by the operator before the start of learning. Division of newly formed segments will proceed until condition $d_{Li} < d_L$ will be met. The same iterative process is carried out in the segment $t_k^{(2)}$ [1].

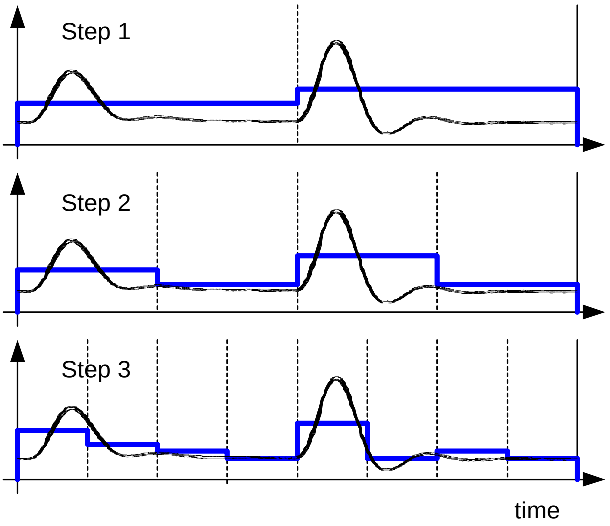

Fig 4. **Illustration of the sequence of features vectors extraction.**

During monitoring or testing sequence of features vectors $\overrightarrow{M}_j = \{p_{Mj}, t_{Lj}, d_{Mj}, \min_{Mj}, \max_{Mj}\}, j = 1, M_N$ is extracted assuming $L_N = M_N$. Synchronous averaging is made out of R_M cycles. Usually $R_M < R_L$. Comparison of learning and monitoring sequence features vectors is made segment-by-segment. This way sequence of distances $D_i = |p_{Li} - p_{Mi}|, i = 1, L_N$ is calculated.

In a pneumatic system composed from several or more components, different parts of function $P_i(t)$ represent the operation character of the appropriate component, e.g. cylinder. To trace the position of cylinder's piston usually proximity sensors are used. Synchronization marks from proximity sensors may be employed to separate entire pneumatic cycle into subcycles. In Figure 5 it is shown the possible selection of two subcycles in three cylinders system, when operation of cylinder C2 is out of our interest.

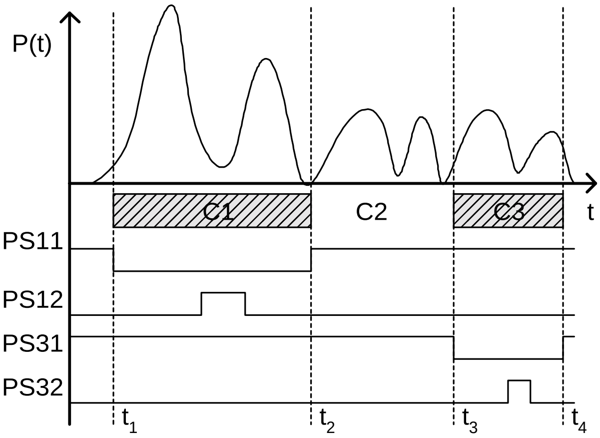

Fig 5. **Selection of subcycles of interest. PS – Proximity Sensor. PS11 – signal from PS attached at the one end of cylinder C1.**

Detection of operation state changes

Fault or defect in this work does not mean complete failure of pneumatic component, but indicates deterioration of performance and increased air consumption. The user himself should select particular level of component's wear which should be interpreted as fault. Only user of pneumatic installation should decide how many percent in increased energy consumption is not acceptable any more and when it is economically profitable to change the cylinder.

Acceptable limits may be defined in units of elements of features vectors extracted during learning:

- p_{Li},
- d_{Li},
- $\min_{Li}$, $\max_{Li}$
- number of adjacent segments.

Features of the fault situation are described both in horizontal and vertical directions, i.e. in time and magnitude axis. D&M system makes a positive decision about the possible fault only when processed differential pressure pattern differs from learning pattern more then defined limits in set number of time segments. For example, we may request the system to detect system operation change when approximated learning and monitoring differential pressure patterns, described by sequences $\vec{L}_i$ and $\vec{M}_i$, have differences more than 20% of magnitude value in at least three time segments. This way fault space is determined by the following conditions:

$|p_{Li} - p_{Mi}| > 0.2 \cdot p_{Li}$, for any three adjacent i values.

Because monitoring processing algorithms involve synchronous averaging operation, the speed of fault situation detection depends on the number of averaged cycles as well as duration of a cycle. If the chosen number of averaged cycles is small, operation changes will be detected relatively fast, but confidence levels Δp_{Mi} of monitoring pattern magnitudes will be larger. At this stage of the work Δp_{Mi} is not calculated and decision making procedures do not encounter its value.

In Figure 6 there are shown averaged differential pressure patterns and their variations measured in the test bench composed from 5 cylinders. Horizontal axis holds time within one cycle of pneumatic system. One pattern in 3D space of Figure 6 was achieved by processing $R_M = 3$ sampled patterns of pneumatic cycles.

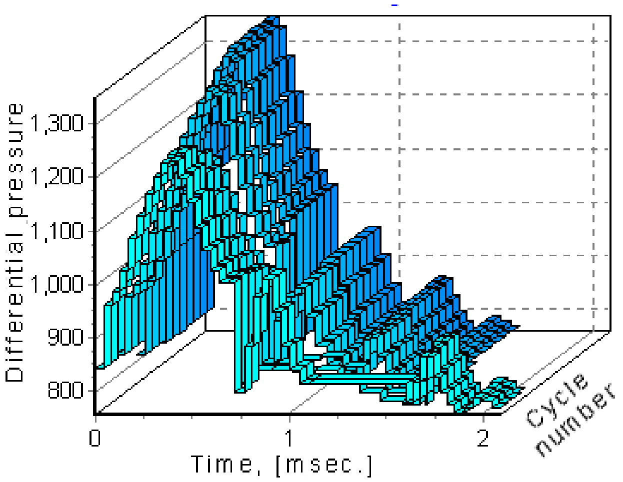

Fig 6. **History of differential pressure patterns. Differential pressure units are relative.**

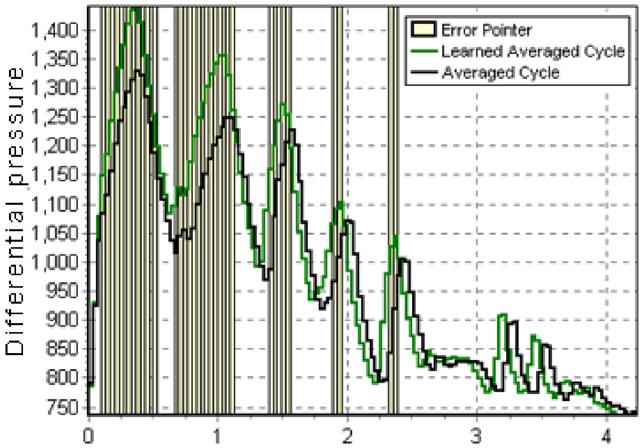

Fig 7. **Comparison of averaged learning and monitoring differential pressure patterns and detection of operation mode change. Differential pressure units are relative.**

Figure 7 presents detected change in pneumatic system operation invoked by readjusting one throttle.

Described D&M system has the following advantages:

- Universal algorithms invariant to the origin of the representative signal. Differential pressure signal may be substituted for example by vibroacoustic signal measured on the surface of cylinders.

- Diagnostics results are easy to interpret.
- Implemented flexible possibilities to change parameters of signal processing algorithms and decision making procedures.

Discussion

Initial experiments revealed some disadvantages of the method and system.

In a pneumatic system some rhythm changes that are not important to the operation correctness may take place. Such a changes should not be detected. Rhythm changes result in a distortion of time axis. In the present D&M system these changes are automatically compensated using Time Adjustment procedure [1,4]. It enables to equalize number of time segments in learning and monitoring patterns. However, cycle duration normalization does not take into account the fact, that different parts of the cycle could be distorted in a different manner. This way, suitability of the Time Adjustment procedure is under discussion. In multicomponent pneumatic system rhythm change of one component influences distribution of time fragments of differential pressure patterns of entire cycle. Figure 8 gives an example when speed of the cylinder C1 decreases, while speed of C2 and C3 does not. After the linear time axis normalization we can see differences in pattern fragments representing operation of C2 and C3. In fact, this is not a case.

A way to overcome the problem is to use earlier described division of the cycle to subcycles. Synchronization marks should be defined by proximity sensors of cylinders.

Applying of DTW (Dynamic Time Warping) algorithms [5] is another solution which does not require installation of additional hardware (proximity sensors and connecting cables). The problem of DTW is formulated as a path finding problem over a finite grid (Figure 9).

$$\begin{aligned} D(i,j) = \min[&D(i-1,j-1), \\ &D(i-1,j), D(i,j-1)] + d(i,j), \end{aligned} \qquad (5)$$

where $d(i,j) = (p_{Li} - p_{Mj})^2$ - local (Euclidean) distance. Grid nodes are filled with corresponding local distances between test and reference patterns sample pairs.

Global distance $D(L_N, M_N)$ is a sum of all local distances calculated on the optimal path (Figure 10). DTW algorithm is suitable to compensate local expansion and compression of test pattern of differential pressure.

DTW makes it possible to characterize difference between $\overrightarrow{L_i}$ and $\overrightarrow{M_i}$ with one number $D(L_N, M_N)$. This could be an advantage in a case of automatic decision making procedures. When decision is supposed to be done by an expert, $D(L_N, M_N)$ does not introduce any advantage. Even more, it disables possibility to locate particular component responsible for the operation change of the entire system.

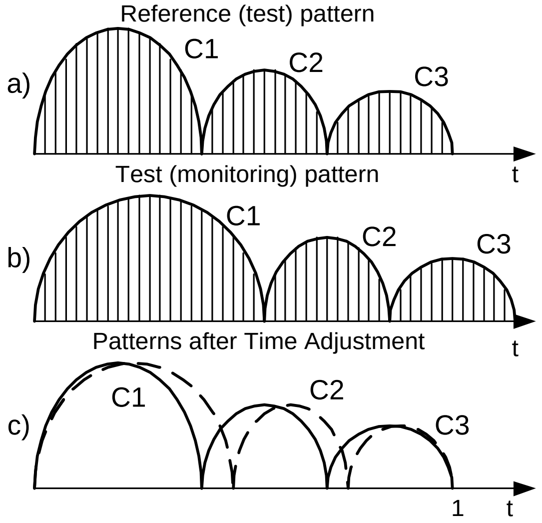

Fig 8. **Time axis distortion and normalization.**

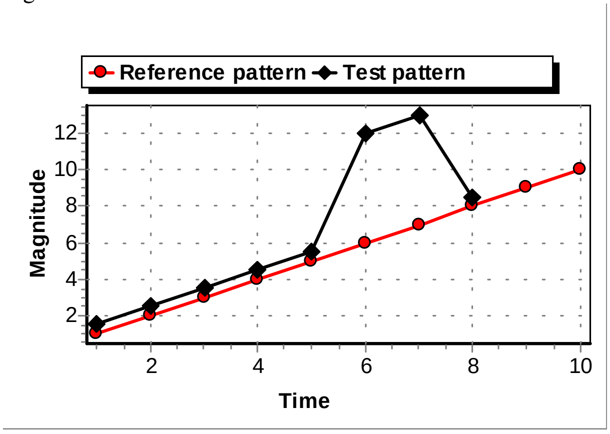

Fig 9. **Reference pattern length N=10 points, test pattern length M=8 points.**

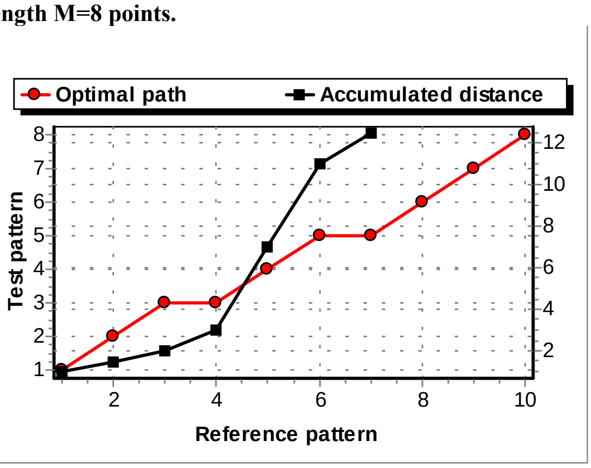

Fig 10. **Optimal path between reference and test patterns and accumulated distance (total 85 iterations were made).**

A disadvantage of DTW algorithm is requirements for large memory resources. It increases very significantly when length of the patterns exceed 10 points. Size of required memory depends on the number of possible ways in the search of optimal path, because dynamic programming problem is solved using recursive programming functions [6]. To reduce search area and necessary calculations local and global restrictions could be entered [5].

Concluding it should be mentioned that successful exploitation of DTW algorithm and its advantages requires to design new sequences of features vectors $\overrightarrow{L_i}$ and $\overrightarrow{M_i}$ with a smaller lengths L_N and M_N. It is no longer necessary to ensure equal length of the sequences.

Conclusions

Described diagnostics and monitoring system makes a minimal influence upon the operation of pneumatic installations. It could be used as portable testing equipment as well as constant monitoring system. Employed learning principle enables to characterize new or reference system's operation by the set of coefficients. Detection of operation changes is made by comparing coefficients measured during monitoring or testing to the respective ones acquired during learning stage. The approach is not suitable for old systems that have no available reference systems. Nevertheless, minimum built-in information about the model of an object and adaptation capabilities of the D&M system opens application possibilities for wide variety of pneumatic system.

Another very promising feature, though not covered in detail in this paper, is a possibility to evaluate air consumption and monitor its trends. Calibration of measurement channel "air flow – Venturi tube – differential pressure – signal conditioning – ADC" is necessary to be able to express air consumption in standard units, e.g. liters per second. Static pressure measurement channel must be introduced also.

At the current stage of development the system is capable to detect changes in pneumatic system operation but fault classification or defected component localization is up to expert. Visualized data records in detected fault situation are easy to interpret by a specialist in pneumatics field.

The further work should be done to investigate and solve problems and disadvantages mentioned in paper. It also could be a challenge to supplement system with the ability to monitor pneumatic systems operating in non-repeatable or cyclic manner.

Acknowledgements

This work has been supported by FESTO B.V., Holland. We are very thankful to Mr. Harry Smith for ideas he shared with us and to Mr. Alfons de Laat for all he did to initiate this project.

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Approach to Diagnostics and Monitoring of Pneumatic Systems

Abstract

Paper presents method ant its technical implementation for pneumatic systems diagnostics and monitoring. The purpose of the system is to detect changes in operation mode due to working pressure or load variations, component wear or incorrect tunning. The method is based on the comparison of dynamic air flow patterns in main supply line of the pneumatic installation. Special digital processing algorithms are used to extract sequences of feature vectors characterizing both reference and observed system. State of the pneumatic system under monitoring is evaluated according to the distance between these sequences.

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Pneumatinių sistemų diagnostikos ir monitoringo metodas

Reziumė

Straipsnyje aprašytas pneumatinių sistemų diagnostikos ir monitoringo metodas bei jo techninis realizavimas. Sistema yra skirta aptikti darbo pokyčiams dėl darbinio slėgio ar apkrovų pasikeitimo, komponentų susidėvėjimo ar išderinimo. Metodas yra pagrįstas oro srauto pneumatinės sistemos tiekimo kanale dinaminių greičio kreivių palyginimu, naudojant specialias skaitmeninio apdorojimo procedūras. Apsimokymo stadijoje iš skirtuminio slėgio kreivių suformuojama požymių vektorių seka, charakterizuojanti atraminės sitemos darbą. Monitoringo stadijoje detektuojama einamoji požymių vektorių seka. Pagal šių sekų skirtumą yra sprendžiama apie stebimos pneumatinės sistemos būseną.