FAULT DETECTION USING PARAMETER TRANSFER FUNCTIONS

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ABSTRACT

To reduce the number of alarms in NPP many techniques have been proposed for process monitoring and diagnosis. The object of our investigation is a dynamic process with digital signals. The general parametric model defines the transfer function form and it covers all dynamic characteristics between two monitoring parameters. To determine the proper model coefficients we are using recoursing least square methods. The transfer function coefficients define the correlation between two variables in desired time period. During process monitoring just the relation is observed because the number of coefficients and the structure is predefined with transfer function form. During plant operation the transfer functions for important parameters must be calculated and estimated. The estimated values are input parameters for an analytical algorithm. It determines which part of system causes the transient and recognises it. The proposed methodology allows a computer to monitor the system behaviour and to find out the most probable cause for abnormal condition.

1. INTRODUCTION

Computing techniques allow rapid data processing and permit development of real-time fault detection systems. They are executing during normal and abnormal conditions and help the operator to find out faults significant for safe reactor operation. Conventional systems use limited testing methods for abnormal conditions detection. An operator is notified when a measured parameter exceeds a predefined setpoint. However, it is not necessary that an exceeded parameter is directly linked with faults. Usually exceeded parameter triggers an alarm and then the operator has to diagnose the alarm cause. To reduce the number of alarms many techniques have been proposed for process monitoring and diagnosis.

In the paper [1] many approaches for fault detection and isolation are reviewed. They base on residual generation and their differences are in methods to generate it. In first few steps our approach for fault detection follows one of basic concepts, "parameter identification approach", mentioned in this paper. Both approaches use algorithm for parameter identification. Though our method uses calculated parameters as inputs for transient diagnosis instead for residual generation. The paper discusses the possibility how to apply the suggested methodology on simple mathematical model of the system controlled by one Proportional-Integral (PI) controller.

2. METHODOLOGY

The purpose of our investigation is to establish the methodology to distinguish causes from consequences when steady state conditions are degraded and a transient begins. The method described uses the fact that faults of a dynamic system are reflected in physical parameters. The idea is to detect the faults via estimation of the parameters of the transfer functions (mathematical models). To determine proper model coefficients recoursing least square method is used as technique for process identification. During process monitoring just the relation is observed because the number of coefficients and the structure is predefined with transfer function form. The method is based on time depended data of the system. Flow chart on figure 1 describes the suggested methodology.

In the first step identification algorithm on data is performed and transfer functions between selected parameters are calculated. In the second step we determine the meaning of transfer functions and assign them one value from a fuzzy set. In the next step a sequence of fuzzy values is analysed with the analytical algorithm. It determines the expected system responde on transient initiation or the cause for abnormal system behaviour.

2.1. System identification

Several techniques for process identification have been proposed [2]. They depend an on signals and process types. In our case the object of investigation is a dynamic process involving digital signals. We want to define relationships between various selected parameters in the observed dynamic system. The relation is determined by transfer function written as difference equation. The general parametric model defines the linear transfer function form (equation 1). This form must cover all dynamic characteristics of two monitored parameters.

$$G(z) = K_s \frac{b_0+b_1z^{-1}+b_2z^{-2}+\dots+b_nz^{-n}}{1+a_1z^{-1}+a_2z^{-2}+\dots+a_mz^{-m}} \qquad (1)$$

The system is observed on-line in real time. Recoursing methods are suitable for identification. Proper model coefficients are set by recoursing least square method [2]. The transfer function coefficients define the correlation between two variables in a desired time interval. Values of coefficients could be different but still describe the same behaviour.

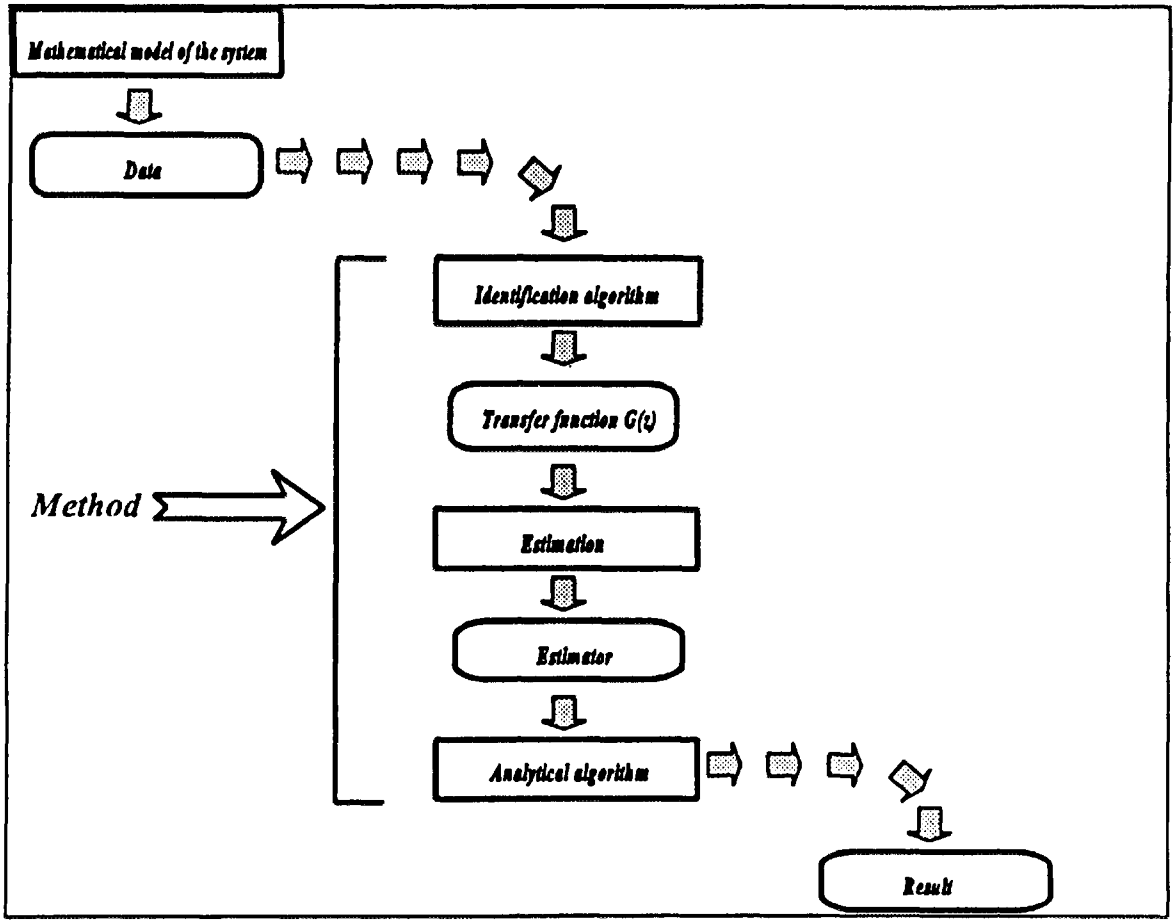

Figure 1: Flow chart of method

2.2. Estimator

Next step during system behaviour detection is to determine meaning of the transfer function. To understand the meaning of the relation between coefficients we declare the corresponding estimator. Meaning and type of estimator may be different, depending what kind of estimating they perform. The number of inputs and outputs may be different. Sometimes the estimator gives the final result such as "valve error", but usually the result is just one value from fuzzy set: increasing, decreasing, stable.

We assume that the observing system has recognized steady state when we start monitoring. When significant change in the system appears, the automatic monitoring system must detect and mark it as transient. Three different transfer functions were analysed. We have tried to define an additional parameter that converts coefficients into one single value. This procedure of estimation produces parameter known as the estimator that joins the major information of transient at desired time. In the paper [3] is described simple estimator for transient detection based on residual. The purpose of it is to determine the cause of the transient in the pressurizer. In our case we have done estimation direct from coefficients of transfer function without residual generation.

The estimator form is dependent on type of transfer function. First we define following predefined transfer function (equation 2) for identification:

$$G_{ident}(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 - z^{-1}} = \frac{Y(z)}{U(z)} \qquad (2)$$

At the beginning the observed system is in steady state and its parameters have constant values. Because we want to detect and recognise the transient, only the parameter variation from the steady state is measured. The difference form for equation (2) is for the input written as

$$\begin{aligned} \Delta y(k) - \Delta y(k-1) &= b_0 \cdot \Delta u(k) + b_1 \cdot \Delta u(k-1) + b_2 \cdot \Delta u(k-2) \\ u(k) &= u_{00}(k) + \Delta u(k) \\ y(k) &= y_{00}(k) + \Delta y(k) \end{aligned} \qquad (3)$$

Parameter u_{00} represents the steady state value and Δu the difference between the steady state and the present value for the k^{th} input parameter. The same form is used for the output parameter (y_{00} and Δy).

The correlation between two parameters is written as transfer function (b_0, b_1 and b_2). Equation (3) shows that only influence of an input parameter on an output parameter is measured. In the case that output parameter has changed ($\Delta y(k)$ is not equal zero) and the input parameter has not changed ($\Delta u(k)$, $\Delta u(k-1)$ and $\Delta u(k-2)$ are equal to zero) then the transfer function coefficients could have any value. We can conclude that input parameter does not cause the change of an output parameter and here we put the coefficients (b_0, b_1 and b_2) value to zero.

To determine the correct estimator one must find a suitable mathematical relation between coefficients of the transfer function. Equation (2) could be divided into three parts: proportional, integral and differential.

$$\begin{aligned} G_{ident} &= K_p + \frac{K_i}{1-z^{-1}} + (1-z^{-1}) \cdot K_d \\ K_p &= -b_1 - 2 \cdot b_2 \\ K_i &= b_0 + b_1 + b_2 \\ K_d &= b_2 \end{aligned} \qquad (4)$$

The integral part is very interesting because we are looking for mathematical term to identify influence of input parameter on output parameter. If we write the integral part of equation (4) in difference form we get the equation (5).

$$y(k) - y(k-1) = K_i \cdot u(k) \qquad (5)$$

The equation shows that change of the output further depends on the input and its gain coefficient K_i. We assume that if we calculate transfer function between two parameters and sum all its coefficients into one value (K_i), then this value may be used as a measure how input influences the output. The adequate estimator ($Estim_x$) is determined as

$$
\begin{gathered}
Estim_x = | \, b_{0_x} + b_{1_x} + b_{2_x} \, | \\
If\ (\ Estim_x > E_{treshold}\ )\ Then\ Estim_x = 1\ Else\ Estim_x = 0 \\
E_{treshold} \ldots\ldots \text{ estimation sensitivity} \\
x \ldots\ldots\ i^{th} \text{ transfer function}
\end{gathered}
\tag{6}
$$

Finally all estimators ($Estim_x$) for all transfer functions are joined into one value (Estim). To mark individual parameter activity during transient the binary coding has been used as follows

$$
Estim = \sum_{x=0}^{N-1} 2^x \cdot Estim_x \tag{7}
$$

During the system monitoring procedure every data sample is extended with an additional parameter Estim. It contains data about dynamic behaviour of system parameters. The faults or system unusual behaviour may be detected by an algorithm based on Estim parameter.

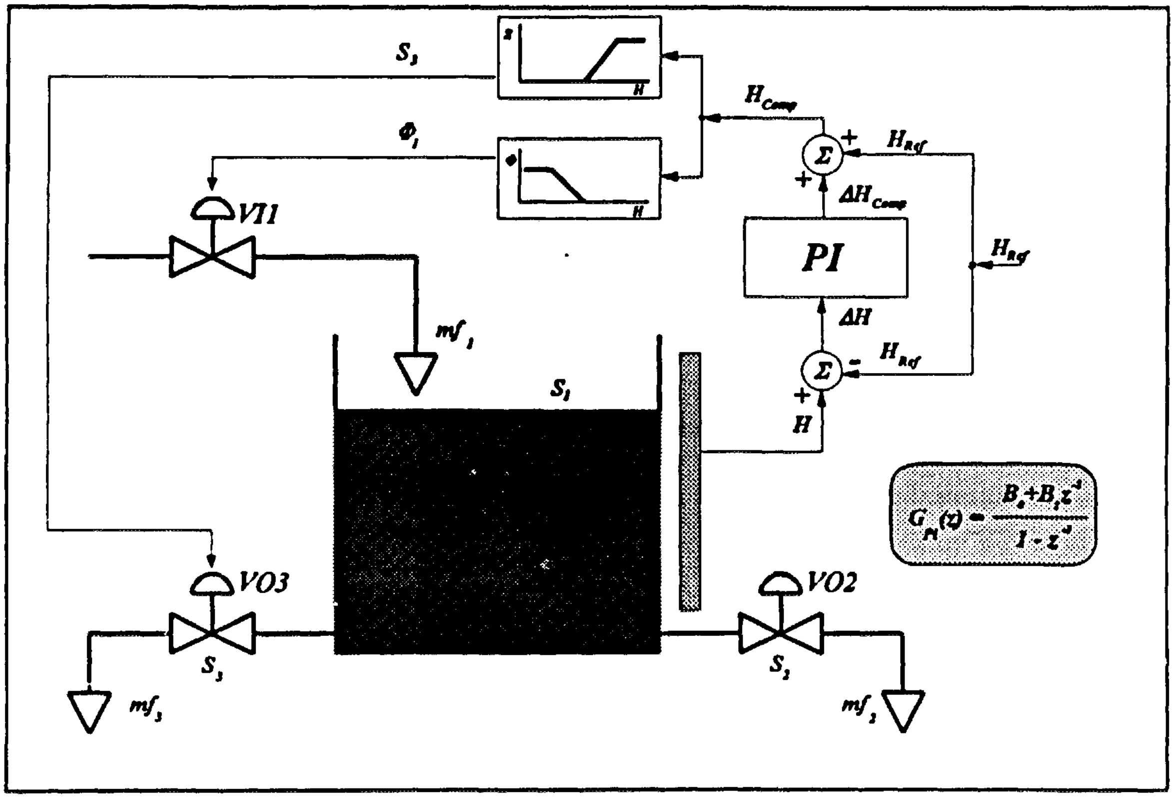

Figure 2: Observed system (water storage tank)

2.3. Analytical algorithm

Analytical algorithm for fault or system unusual behaviour detection strongly depends on the observed system. It is composed of different rules based on previous knowledge and experience gained about the system.

As a test the case a water storage tank was selected as the monitored object. The mathematical model of natural relation between parameters of this system is straight forward. PI (Proportional-Integral) controller has been added to reduce the steady state error after transient. The model serves just for data generation during transient initiation. Figure 2 shows its construction of the system selected for the case study.

It is assumed that the system requires constant mass flow through valve VO2. To assure constant mass flow through it the water level must be kept at some level. For this reason the control system with PI controller and two valves VI1(to add water) and VO3 (to remove water) have been added.

Four parameters have been observed:

- water level (h_w)
- mass flow through valve VI1 (mf_1)

- mass flow through valve VO2 (mf_2)
- mass flow through valve VO3 (mf_3)

Algorithm must recognise the steady state values for all four parameters (h_{w00}, mf_{100}, mf_{200}, mf_{300}). We assume that if a parameter does not change in ten seconds then its present value corresponds to its steady state condition.

The critical parameter in observed system is the water level. We assume that all faults will be reflected on the level behaviour. Three parameters influencing transfer functions have been calculated as show in table 1.

Table 1: Input and output parameters for transfer functions

input parameter	output parameter	transfer function name	estimator
mf_1	h_w	TF_1	$Estim_1$
mf_2	h_w	TF_2	$Estim_2$
mf_3	h_w	TF_3	$Estim_3$

Four different system states have to be detected:

- steady state; (DSS)
- system transient as demand for increasing or decreasing output flow mf_2; (DST)
- leak; (DLS)
- other transients; (DO)

The steady state is detected and confirmed when Estim value is equal to zero. This means that none of the observed parameter changed from its steady state value. Expected transients, such as a demand for increasing and decreasing output mass flow, are reflected in changes of mf_2 and mf_1 or/and mf_3. In case of a leak from the tank only the mass flow mf_1 will increase to compensate for the lost water. In table 2 roles for system behaviour diagnose are showed.

At the beginning and at the end of a transient the estimator does not give a clear picture of the basic transient, but more or less shows which parameter initiates the transient or mitigates the consequence of it. We have performed one simple rule to recognise the main transient. The basic diagnosis of DST and DLS have been made favourite. That mean if DST and DLS had been diagnosed from previous data, then diagnosis cannot be changed for next sample except, if the parameter Estim has been equal to zero in last ten data samples (system had returned to new or previous steady state). The last rule helps to detect the end of a transient.

Table 2: Roles and relations for system behaviour diagnose.

$Estim_1$	0	1	0	1	0	1	0	1
$Estim_2$	0	0	1	1	0	0	1	1
$Estim_3$	0	0	0	0	1	1	1	1
Estim	0	1	2	3	4	5	6	7
Diagnosis	DSS	DLS	DO	DST	DO	DO	DST	DO

With more sophisticated construction of an analytical algorithm also other conclusion could be made such as sensor fault, size of leakage, etc. The final diagnosis could be checked by testing conditions at the beginning and in the end of transient.

3. CASE STUDY

Three calculations were performed for three different transients to test the proposed methodology: demand for decreased and increased output mass flow and leakage. First data have been collected in steady state conditions from mathematical model (described in a previous chapter). After some time the transient has been initiated. Measured parameters have been estimated continuously during steady state and transient.

Parameters initiating the transient had been changed in three different ways:

- step
- linear
- exponential

3.1 Output mass flow decreasing

The cross section in out flow valve VO2 has been decreased from 0,01 m^2 to 0.0002 m^2 in fifty seconds. Change of valve cross section has caused a decrease of output mass flow mf_2 from 0.14 kg/s to 0.0025 kg/s.

In all three cases the water level has increased and the mass flow mf_1 has decreased. When the transient has been initiated as step change the water level had increased so high that valve VO3 had been opened for some time period to release additional water from the tank. In next few seconds water level had decreased too low and some correction had been done by opening the valve VI1. During linear change of output mass flow the same correction had been made.

For all three simulated cases algorithm has recognised the correct transient. Annunciator of a transient during step change has been displayed twice as long because control system needed more time to solve the problem. Time depended graphs for this example are on figure 3.

3.2 Output mass flow increasing

This case is the same as in the previous except that the cross section in valve VO2 has been increased from 0,01 m^2 to 0.0199 m^2 and that has leaded to increase output mass flow mf_2 from 0.14 kg/s to 0.28 kg/s. In all three cases the water level has decreased and the mass flow mf_1 has increased. The valve VO3 has stayed close during transient.

Algorithm has recognised the correct transient. Announcement for transient during linear change has been displayed a little longer because control system has followed demand for increasing mass flow from the system and in the end it has made some over shooting. Time depended graphs for this example are showing on figure 4.

3.3 Leak

In last example an orifice has been added into tank shell. Through this orifice the water has been leaked from a tank in three different ways as it has been described. The valve VO3 has stayed closed during the transient and no change on mass flow mf_2 has been detected. Only the change in water level and mass flow mf_1 have been detected.

In this case the algorithm has recognised the correct transient too. Announcement for transient during step and linear change has been displayed mostly the same time. During exponential change the algorithm has announced twice that transient has appeared. After few seconds when the transient had appeared the control system has caught dynamic nature of orifice increasing and the system status has been recognised as steady state very soon. Some time later the orifice had increased slower and the algorithm has detected leak again. Time depended graphs for this example are showing on figure 5.

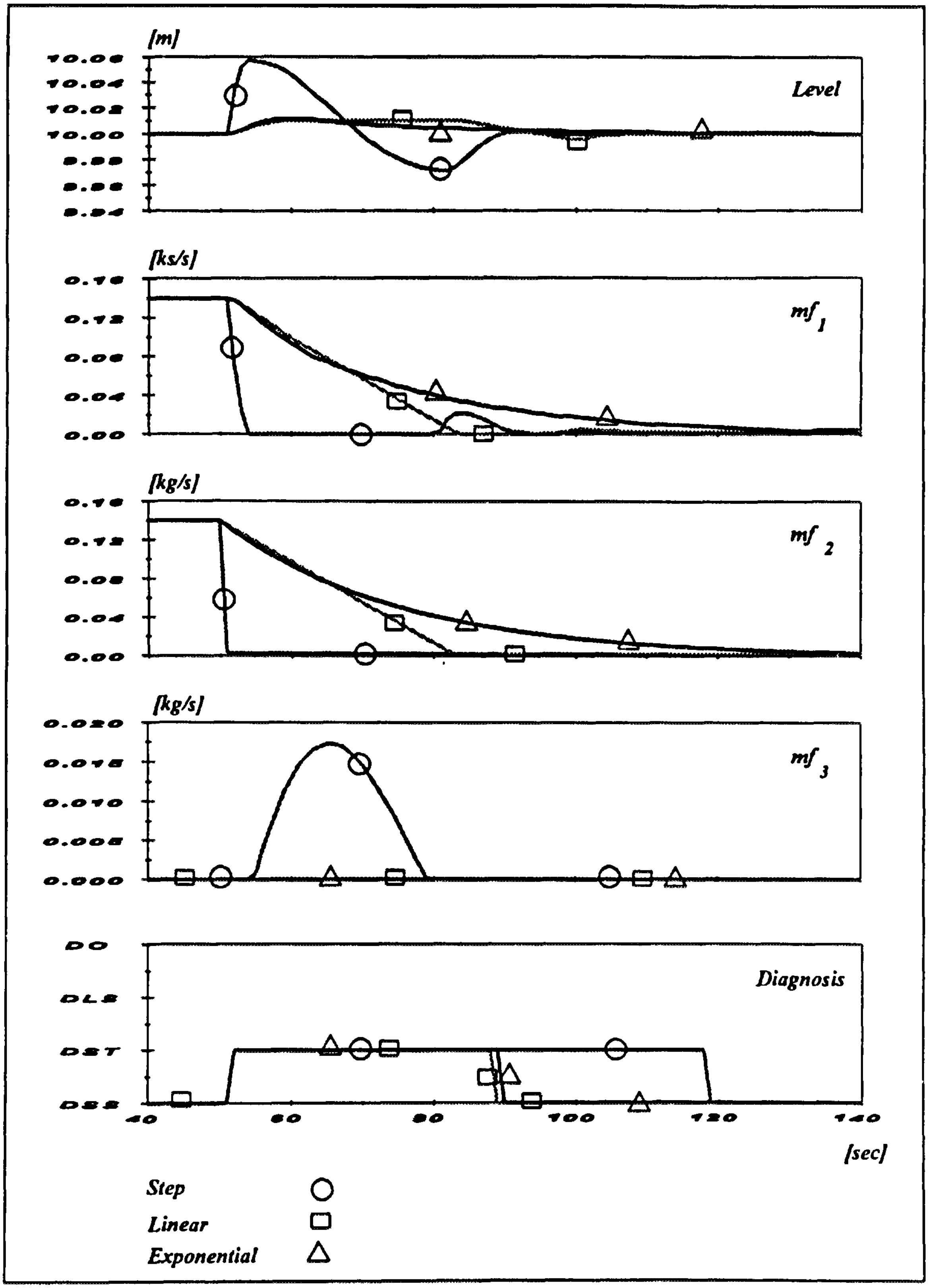

Figure 3: Output mass flow decreasing

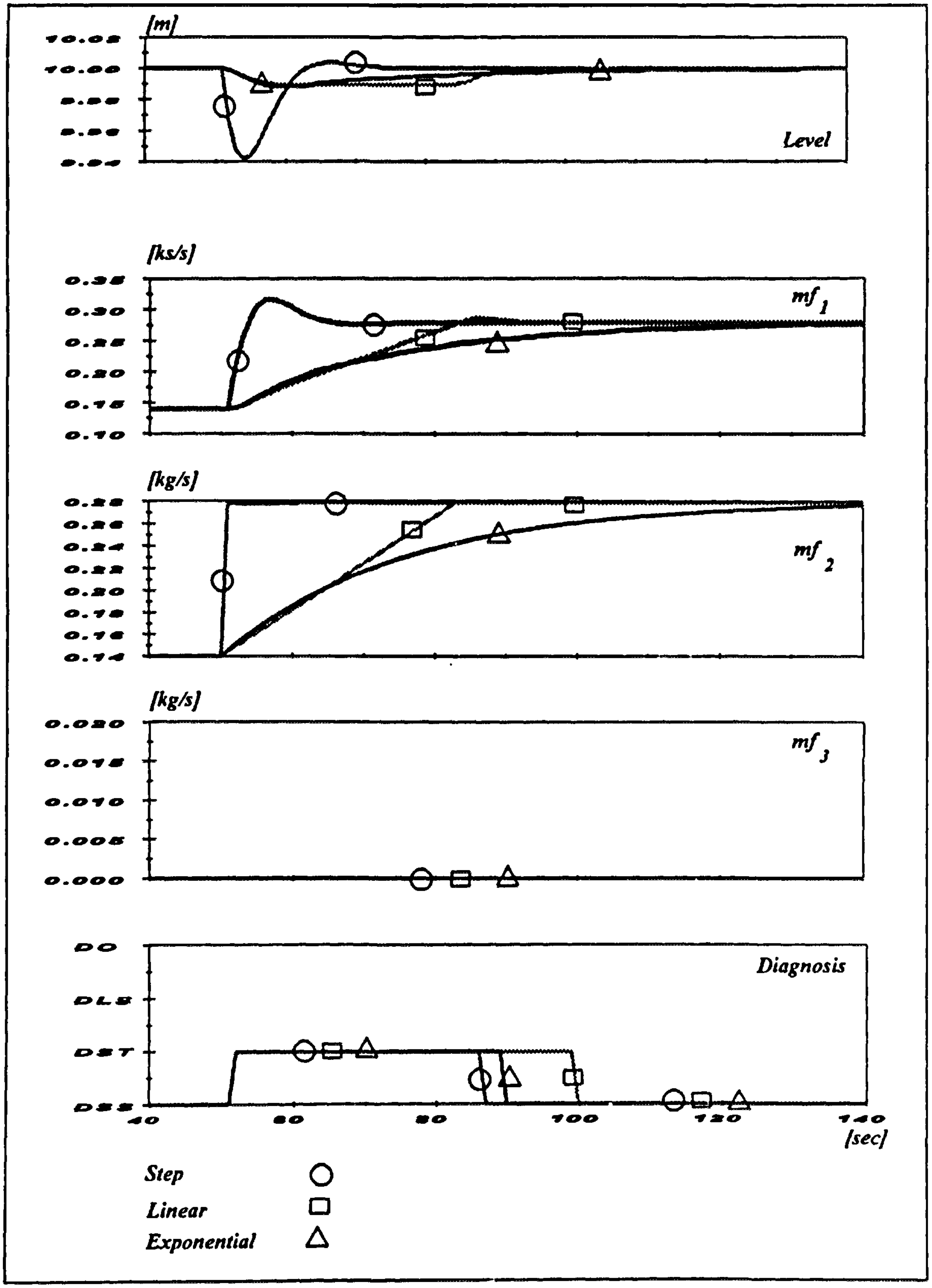

Figure 4: Output mass flow increasing

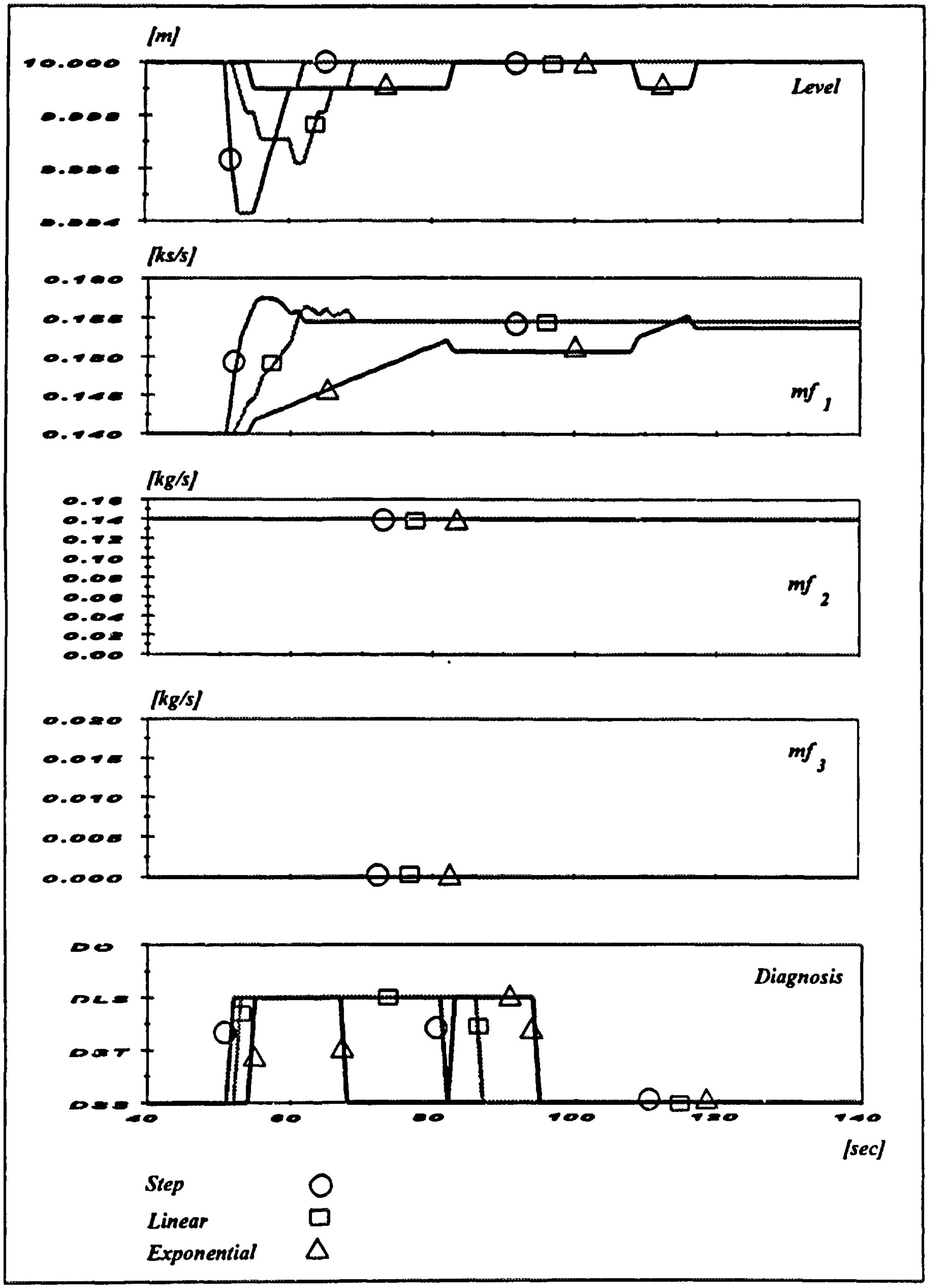

Figure 5: Leak

4. DISCUSSION

Data written as time depended graphs are very suitable for humans but its form has little value for computer processing. All computer codes for system diagnostic are written by human and they are using the human way of thinking which is based on data form suitable for them. A good example is Emergency Operating Procedures. During monitoring the operator must compare the terms like: increasing, decreasing, stable, stable in some limits, unstable, etc.. That approach gives expert more space to write more flexible diagnostic system but data acquisition system in the plant deals just with the real numbers. When the computer has to perform the diagnostics, it must convert that into fuzzy set chosen by the expert.

The purposed approach is based on transfer function between two parameters. Its coefficients describe dynamic relation of two parameters in a defined time period. When graph shape is changed, the values of coefficients change too. The set of values in time interval for input and output parameters are converted in few or more less constant values. They are very suitable for analysis with mathematical operators such as: equal, nonequal, higher, smaller, etc. It is suggested to use different estimators to determine the meaning of a transfer function. With proper estimators computer code can automatically determine the relation between two parameters, analyse all relations and announce to the operator that some change has occurred in the observed system. The goal of proposed method is to allow a computer to monitor the system behaviour and to find out the most probable cause for transient.

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