

Multimodel Approach Applied For Failure Diagnosis

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Abstract. *This paper presents a method of diagnosis targeting the failure models used to represent the different behaviour able to affect complex systems. This method, based on the multimodel approach, is leans on two processes. The first one allows of determining the potential failure model set affecting the normal behaviour of the considered system. The second process, based on the validity calculation principle passing by a generation of residue, and allows to detect and to localize failures. We proposed new methods for Validity calculation.*

keywords. *Multimodel Approach, Failure Detection and Isolation (FDI), Residue, Validity of models.*

1. Introduction

In a need to improve the engineering technology competitiveness, diagnosis, by assuring the surveillance of physical systems arouses since around thirty years a growing interest in the industrial world and the scientific research. From the reason that industrial systems become more and more complexes and sophisticated, it suited to associate them an effective module of supervision to improve their reliability and their performance. Consequently, the security of the staffs and environment are improved. In this case, many methods of failure diagnosis, particularly methods of redundancy based on analytics model were developed [10, 24, 28], which have the capacity to detect the occurrence of the failures and to determine its locations.

Usually, in the area of FDI, failure in system results in changes of the dynamical behavior so that the failures may be detected by evaluating the residuals generated by comparing the model output and the system output [29]. According to [4, 7, 13, 25, 26, 27, 30] there are essentially two ways of generating residuals: state estimators and parameter estimators.

Among success approach to modeling dynamical system is the multimodel approach [1, 6, 18, 19, 21, 22, 23, 24, 25, 31, 32]. In this case, authors in [16, 17, 33], have provided the observer to generate the residue for failures detection.

However some failure may affect all such residues, so that if we generate residues with a single model, we can only detect but not isolate such failures [8].

In order to overcome this difficulty, in [2, 3, 8, 9, 14], authors have tried to combine techniques from multimodel theory with knowledge based method. It consists in using on-line dynamical models for the plant in normal situations, failing situations and their integration in library models.

This paper is organised as follows: in Section 2, the general scheme of diagnosis based on multimodel approach is presented. In Section 3, a solution for Failure Detection and Isolation based on the calculation of the validity is presented. In Section 4, an application to a hydraulic process, the "three-tank-system", is considered to illustrate the adopted method. Finally, Section 5 is devoted to conclusion.

2. Failure Detection And Isolation Scheme

The system is modelled mathematically by many models; each one described some particular state of the system. Model localization, or isolation, means determining which model represents at best the current system state. One of the models represents the properly working system, while the other models represent failure states. The use of different models to represent individual failures allows for very specific detection.

The structure of the failure scheme using multiple models and supervisor is shown in fig.1

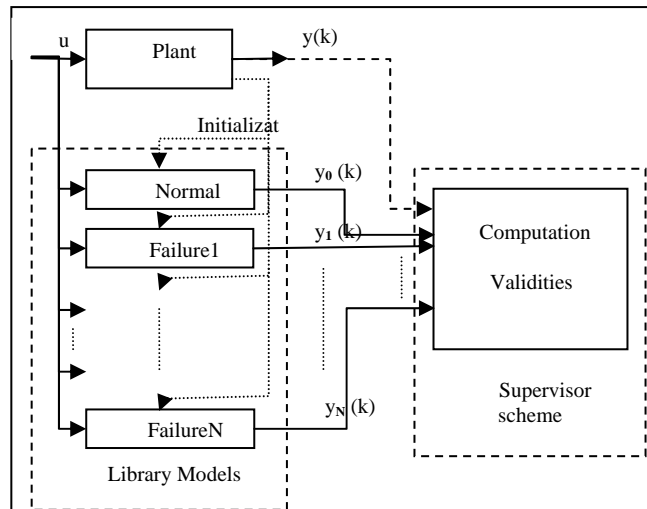


Fig. 1. Structure of the failure diagnosis scheme.

Assume that there are N possible failures situations and we have $N + 1$ models $\{M_i\}_{i=0}^N$, where the normal model M_0 corresponds to the no failure situation, and the failure models M_i , $i = 1, 2, \dots, N$ represent the i^{th} failures situations. Note that most

existing multimodel failure diagnosis methods are based on linear models; while nonlinear multiple models are rarely used. In the case, the dynamic of real process can be represent by $f(x, u, k)$, the nominal model by $f_0(x, u, k)$ and the other models corresponding to each failure by $f_i(x, u, k)$:

$$M_i \begin{cases} x_i(k+1) = f_i(x_i, u, k) \\ y_i = g_i(x_i, u, k) \end{cases} \quad i \in [0, N] \quad (1)$$

By running on-line library models, the residues $r_i(k)$ are generated by:

$$r_i(k) = |y(k) - y_i(k)| \quad (2)$$

where $y(k)$ is the system output and $y_i(k)$ is the output of the model M_i which corresponds to the i^{th} failure situation.

The accent is then setting on the techniques of exploitation of these residues. According to the basic concept of multimodel approach, this technique consists on the calculation of validity which will be employed here for FDI. So, we realize the importance that is necessary to accord to validity calculation which will be the subject of above the section.

3. Validity Calculation Methods

The validity $v_i(k)$ of model M_i is a measure of the result that model M_i is the correct dynamical of actual system. There are used for the detection and the localization of the failure(s) when it takes place.

In the literature, several authors were interested in the development of validities calculation methods [14, 19, 21, 22, 29, 34]. We limit ourselves here to the presentation of five validities calculation methods where three are proposed by ourselves.

Leaving of the principle that an ideal model in validity equal to 1, a fundamental property results from it naturally; it is about the convex sum validities given by:

$$\begin{cases} v_i \in [0,1] \\ \sum_{i=1}^N v_i = 1 \end{cases} \quad i = 1, \dots, N \quad (3)$$

3.1. Normalized Residue Based Method

This method was proposed by [14, 18, 19] defined by:

$$r_i'(k) = \frac{r_i(k)}{\sum_{j=0}^N r_j(k)} \quad (4)$$

$$v_i(k) = \frac{1 - r_i'(k)}{N} \quad (5)$$

This method does not provide the sensitivity needed to properly classify the failure model, especially when the number of models is large. For example for $N = 11$, and when the residue $r_i(k) = 0$, the validity of the model M_i is equal only to 0.1.

3.2. Reinforced Residue Based Method

To overcome the limitations of the precedent method, the idea of the reinforcement of the validities was introduced in [14, 18].

Let the validity of model M_i be given by :

$$v_i(k) = 1 - r_i'(k) \quad (6)$$

where $r_i'(k)$ is as given in (4). The reinforcement of the validity is accomplished via the following relation:

$$v_i^{renf}(k) = v_i(k) \prod_{\substack{j=0 \\ j \neq i}}^N (1 - v_j(k)) \quad (7)$$

To maintain the sum of the reinforced validities to 1, we establish:

$$\tilde{v}_i^{renf}(k) = \frac{v_i^{renf}(k)}{\sum_{j=0}^N v_j^{renf}(k)} \quad (8)$$

In this case the validity of model M_i depends particularly on how distinct the models are from each other and on the level of measurement noise.

3.3. Sequential Clustering Based Method

The competition principle is inspired by the sports tests of championship and it's presented by figure 2.

To clarify the report between two domains, we adopt an analogy presented as follows:

- The number of teams represents the number of models of the base which one notes N .

- Result and score of every challenge represent the validity of every model M_i .

All the teams play among them, so the number of contests is equal to $N(N - 1)/2$ matches.

Description:

In the first step, we have a generation of the residues according to relation (2) presented in section 2.

The score of every match, noted by $v(i, j)$ and $v(j, i)$ defined in steps 2 and 3, allows us to affect final result for every team (i) by following step (method) described in step 4. Indeed, for every match, the team (i) and the team (j) receives respectively one "1" and zero "0" if score (i) is superior to the score (j), and in the opposite case the opposite occur. But in case where two scores (i) and (j) are equal: a 'threshold' describes the degree, from which we consider this equivalence. Consequently, we introduce the notion of equality by maintaining scores obtained as final result for the team (i) and (j).

Finally, the collection of final results for every team (i), explained by step 5, allows calculating the validities of every team (i). Principle is to discriminate between the victorious team which has the biggest score and to allocate it value 1 for its validity whereas the others will have a zero as validity to assure the property of the convex sum. But on the other hand, there is more that a victorious team in the sense of the notion of equality defines in step 4, their associated validities are going to be equal 1 to distribute according to step 6 and the other teams will maintain 0.

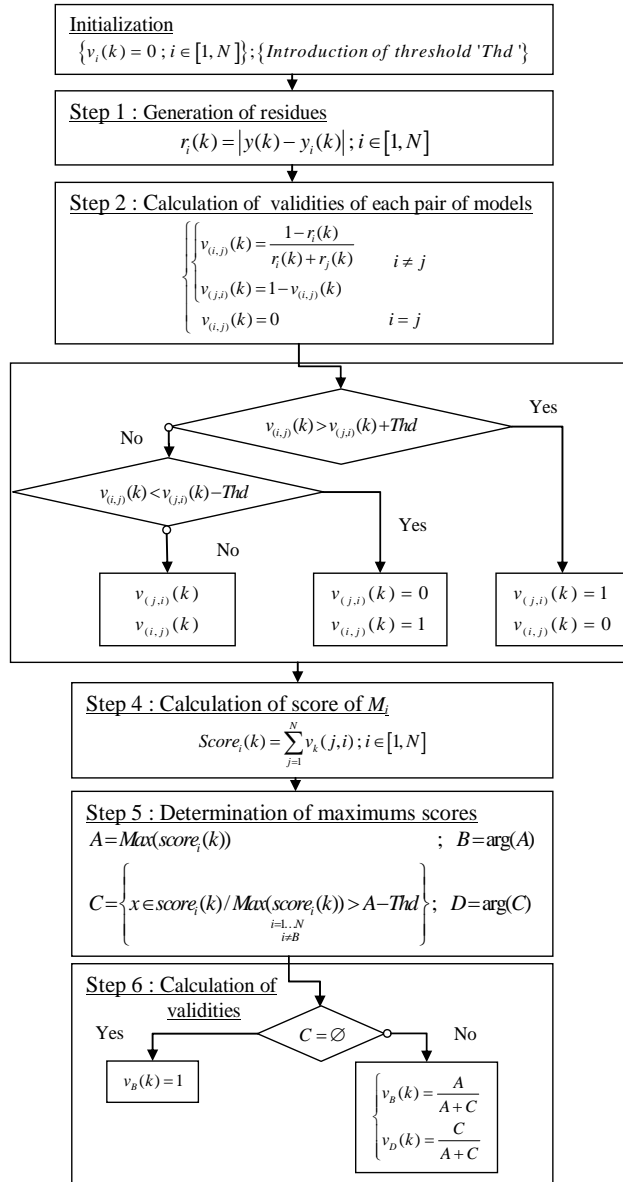


Fig. 2. Validities calculation using sequential clustering method.

3.4. Exponential Based Method

In this case, the proposed method of validity calculation for each models M_i is given by:

$$v_i(k) = \frac{e^{-\frac{1}{2}y_i^T(k)R^{-1}y_i(k)}}{\sum_{i=0}^N e^{-\frac{1}{2}y_i^T(k)R^{-1}y_i(k)}} \quad (9)$$

Where R is the covariance of the measurement noise, " T " means transpose, $y(k)$ is the measurement of the actual system output, and $y_i(k)$ is the output of model

3.5. Exponential based method with reinforcement

The expressions of reinforced and normalized validities are described, respectively by the following formulae:

$$v_i^{renf}(k) = v_i(k) \prod_{\substack{j=0 \\ j \neq i}}^N (1 - v_j(k)) \quad (10)$$

$$v_i^{\sum renf}(k) = \frac{v_i^{renf}(k)}{\sum_{j=0}^N v_j^{renf}(k)} \quad (11)$$

4. Application to a three-tank-system

4.1. Process description

The three-tank-system model shown in figure 3 is written using the well known "mass balance" equations. The system can be conveniently represented as in [10, 11, 12] by:

$$\begin{cases} S_1 \frac{dh_1(t)}{dt} = q_1(t) - q_{12}(t) \\ S_2 \frac{dh_2(t)}{dt} = q_{12}(t) - q_{23}(t) - q_{10}(t) \\ S_3 \frac{dh_3(t)}{dt} = q_2(t) + q_{23}(t) - q_{20}(t) \end{cases} \quad (12)$$

Where $h_i(t)$, $i \in [1, 3]$; is the liquid level in tank i . S_i , $i \in [1, 3]$; is the section of tank i . g ; is a constant of gravity. q_{ij} represents the flow rate from tank i to j , $i, j \in [1, 3]$, which, according to Torricelli's rule is given by :

$$q_{ij}(t) = \mu_i \cdot S_p \cdot \text{sign}(h_i(t) - h_j(t)) \cdot \sqrt{2g|h_i(t) - h_j(t)|} \quad (13)$$

$\mu_i, i \in [1, 4]$; is the output coefficients flows which are used here to describe the state of valve by affecting the value ‘1’ for the open ones and the value ‘0’ for the opposite case

Notice that $q_{10}(t)$ and $q_{20}(t)$ represents the outflow rate with:

$$q_{i0}(t) = \mu_i \cdot S_p \cdot \sqrt{2gh_i(t)} \quad i \in [1, 2] \tag{14}$$

The full system model is then obtained as follows

$$\begin{cases} \dot{x}_1(t) = -C_1 \cdot \text{sign}(x_1(t) - x_2(t)) \cdot \sqrt{|x_1(t) - x_2(t)|} + \frac{u_1(t)}{S_1} \\ \dot{x}_2(t) = C_1 \cdot \text{sign}(x_1(t) - x_2(t)) \cdot \sqrt{|x_1(t) - x_2(t)|} \\ \quad - C_2 \cdot \text{sign}(x_2(t) - x_3(t)) \cdot \sqrt{|x_2(t) - x_3(t)|} \\ \quad - C_2 \cdot \sqrt{x_2(t)} \\ \dot{x}_3(t) = C_2 \cdot \text{sign}(x_2(t) - x_3(t)) \cdot \sqrt{|x_2(t) - x_3(t)|} \\ \quad - C_3 \cdot \sqrt{x_3(t)} + \frac{u_2(t)}{S_3} \\ y(t) = x_3(t) + w(t) \end{cases} \tag{15}$$

Where $x_i(t)$ is the liquid level in tank i and $C_i = (1/S_i) \cdot \mu_i \cdot S_p \cdot \sqrt{2g}$. The control signal $u_i(t), i = 1, 2$ is the input flow $q_i(t)$. S_p is the section of all valves. $w(t)$ is the measurement noise.

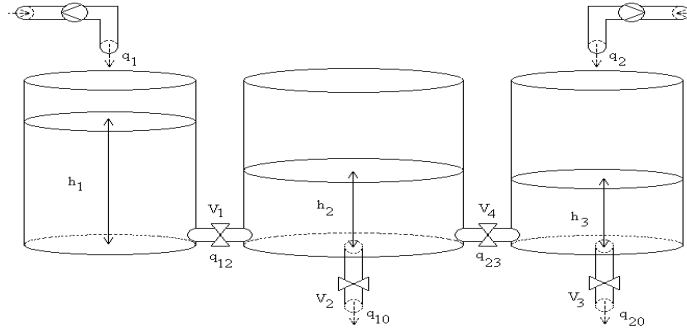


Fig. 3. Three-Tanks-System.

The subject of the normal mode of system is to keep constant quantities of water for two consumer’s mass. In this case, we have all valves opened ($\mu_i = 1$) and a constant debit sending by two pumps.

The considered models failures to know are six; two reproduces the failure of each pump and the four last ones models represent failures corresponding to the failure of

each valves (V_1, V_2, V_3, V_4). By adding the model of nominal functioning, the library models are determining. The residues are generated by comparing models library and the output of system. The actual state mode of system is detected by different techniques of validities calculation describing in section 3, where two are proposed in the literature and three are proposed by ourselves.

The diagnosis failure results for six failure situations are given as below. We also conducted many simulations to verify the effectiveness of our diagnosis failures scheme. However, in this work we will consider normal functioning and failure of valve (V2).

Parameters:

$$S_p = 0.00065 m^2 ;$$

$$S_1 = S_3 = 0.0491 m^2 ; S_2 = 0.0616 m^2$$

$$q_1 = 0.000154 m^3 .s^{-1}$$

$$q_2 = 0.00025 m^3 .s^{-1}$$

$$g = 9.81 N.m^2$$

$$X_0 = [0.40116 \ 0.10249 \ 0.05124] \text{ (initial state vector)}$$

We notice that we have discretized the system with a zero-order hold block and we have fixed the time of sampling at $T_e=5s$.

4.2. Normal mode

At first, we are going to study the case where system is in a mode without failing in which we are interested in the evolutions of validities by the various techniques in both cases to know; the case where system is noised and the case where system is without the correlation of this last one. These evolutions of validities (free noise case) are shown in figure 4, 5, 6, 7 and 8.

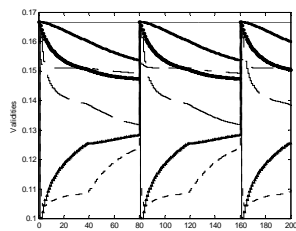


Fig. 4. Normalized validities
Normal mode and free noise case.

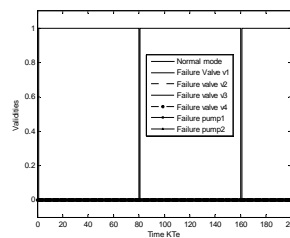


Fig. 5. Reinforced validities
Normal mode and free noise case.

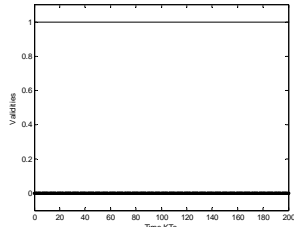


Fig. 6. Sequential clustering Normal mode and free noise case.

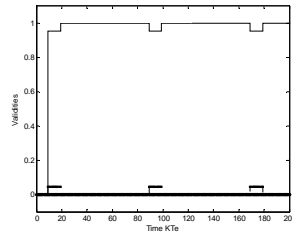


Fig. 7. Exponential validities Normal mode and free noise case.

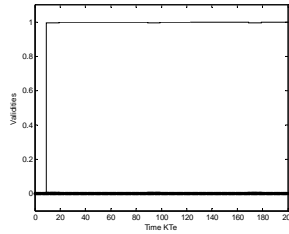
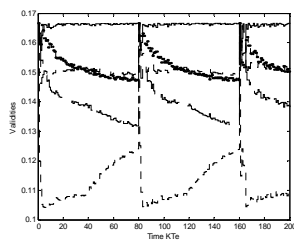


Fig. 8. Reinforced Exponential Normal mode and free noise case.

These figures shows that the model of the normal functioning without failing (continuous line), has the value of the most high validity by all techniques, but never reaching value 1 for the case of the normalized method (figure 4). To analyse the robustness of the validity method, we study the case where system presents a noise of 10 % of the output value presented below.



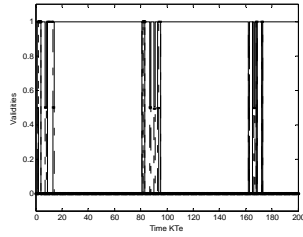


Fig. 11. Sequential clustering Normal mode with noise.

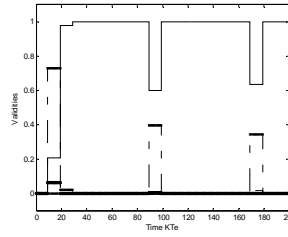


Fig. 12. Exponential validities Normal mode with noise.

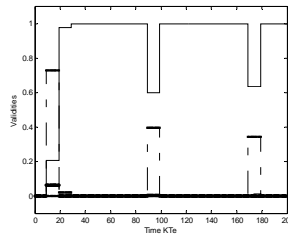


Fig. 13. Reinforced Exponential Normal mode with noise.

We notice that even in the presence of the noise, the validity value allows also to indicate that system is in normal functioning. Note that the discontinuity seeing every “80” iterations are relative for the initializing of models library by the actual states of system in reason to accelerate the detection process.

Studies of the validity failure analysis are similar to the above.

4.3. Failure valve V2

We consider two cases with and without noise where valve V2 is failed at instant 80. The validities values are shown, respectively, in figures (14, 15, 16, 17 and 18) and figures (19, 20, 21, 22 and 23).

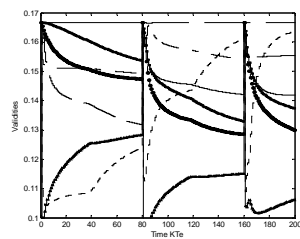


Fig. 14. Normalized validities failure V2 and free noise case.

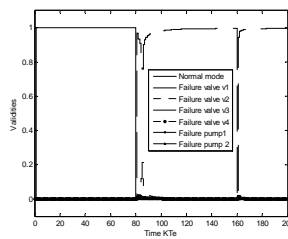


Fig. 15. Reinforced validities failure V2 and free noise case.

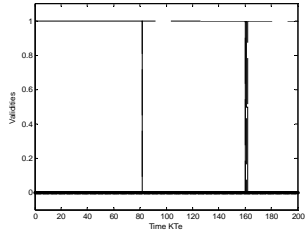


Fig. 16. Sequential clustering failure V2 and free noise case.

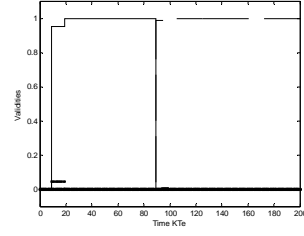


Fig. 17. Exponential validities failure V2 and free noise case.

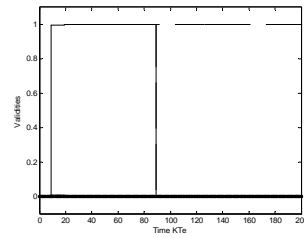
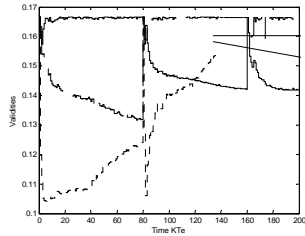


Fig. 18. Reinforced Exponential validities failure V2 and free noise case.

The validity value allows to indicate that system is failing and the failure is referred to the valve V2 ;by reinforced based method at instant 81 , by sequential clustering based method at instant 82, by exponential based method at instant 89 and finally by reinforced last type method at instant 89.



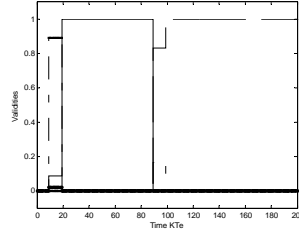


Fig. 23. Reinforced Exponential validities method failure V2, noise case.

We remark that even in the presence of the noise, all techniques of validities indicate the occurrence of studying failure.

Table I presents the result obtained by comparing sequential clustering and exponential validities methods presented in this work and the normalized and reinforced validities methods.

	Advantages	disadvantages
Normalized validities method	- Detection and location of failures	- Very sensitive to the noise - More the number of model is important more the validity remains not exploitable
Reinforced validities method	- Detection and location of failures - Little sensitive to the noise	Sensitive to important noise
Sequential clustering validities method	- Detection and fast location of the failures - Adjustable sensibility face to the noise	Very sensitive to the noise.
Exponential validities method	-Insenible to the noise - Detection and fast location of the failures	The optimization of observation horizon
Reinforced Exponential validities method	-Insenible to the noise - Detection and fast location of the failures	The optimization of observation horizon

Table 1. Advantages and disadvantages of proposed method.

In conclusion of these essays, it stands out:

- 1- That the reinforcement of the validities improves the detection of the good model. Indeed the distance between the various validities increases and the values of the validities are more significant (validity of the good model closer to 1 and the others more close to 0).
- 2- That the method of sequential clustering validities turns out more successful than the other methods. But its defect stays its big sensibility to the noise.
- 3- That the method using the exponential turns out interesting when we take into account measurement noises.

5. Conclusion

In this work, the integration of dynamical models failure in a multimodel supervisor scheme has been presented. This method can recognize the current failure situation of the plant by using a nonlinear analytical library that it can be in both state space and input-output forms. Indeed, the library models are applied to generate residues which are analyzed on-line, by a computation of validity, to indicate the occurrence of failures and locate them. The robustness, towards noises is analyzed and the three-tank-system example is used to show its reliability of the adopted method.

In order to model a complex system in an affordable way, we design a multilevel structure and interpolate among nonlinear local models. The same hierarchical structure can be used to organize the multimodel for multiple failure diagnosis so as to scale up when the number of faults are increased.

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