2000 SAFEPROCESS

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Fuzzy evaluation of residuals in FDI methods
Application to a urban water supply network

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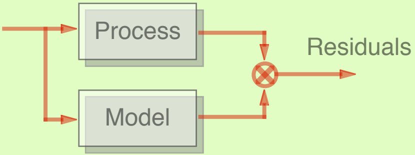
Fuzzy evaluation of residuals in FDI methods



- Problem statement
- Recall about classical approaches
- Non Boolean approach
- Enhancements
- Application
- Conclusion

Problem statement

FDI method

Generation of residuals

- Sensitive to faults to be detected
- Insensitive to model uncertainties
- Insensitive to perturbations

Evaluation of residuals

Statistical decisions → Boolean
→ Non Boolean

Classical approach

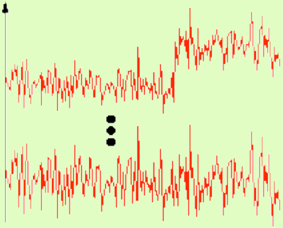
Set of residuals

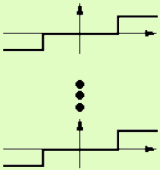
$$\begin{cases} r_1 = f_1(+x_1, -x_2) \\ r_2 = f_2(-x_1, +x_3) \\ r_3 = f_3(-x_1, -x_2, +x_3) \\ r_4 = f_4(+x_2, -x_3) \end{cases}$$

Theoretical ternary fault signature matrix

$$\Sigma = \begin{pmatrix} +1 & -1 & 0 \\ -1 & 0 & +1 \\ -1 & -1 & +1 \\ 0 & +1 & -1 \end{pmatrix}$$

Comparison





$$\begin{matrix} 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & -1 \end{matrix}$$

Experimental residuals

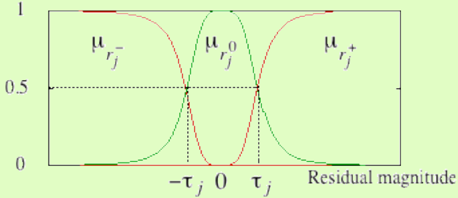
Experimental signatures

Non Boolean evaluation

Three fuzzy sets per residuals :

"negative" : r_i^- "null" : r_i^0 "positive" : r_i^+

Shape of membership functions :



Fault localization :

Conjoined analysis of residuals and theoretical ternary fault signature matrix

Non Boolean evaluation

Signature matrix → Rule base

Example :

Fault signature : $\begin{pmatrix} 1 & -1 & 0 \end{pmatrix}^T$

Corresponding rule : if $r_1(k)$ is r_1^+ and $r_2(k)$ is r_2^- and $r_3(k)$ is r_3^0 then f_1^+

premises conclusion

$r_1(k)$ is r_1^+ —quantification→ $\mu_{r_1^+}$ Membership grade

and → Conjonction or aggregation operator

Non Boolean evaluation

if $r_1(k)$ is r_1^+ and $r_2(k)$ is r_2^- and $r_3(k)$ is r_3^0 then f_1^+

Combination of the membership grades of the premises

⇓

Truth degree of the rule

For example : product operator $\mu_{f_1}(k) = \mu_{r_1^+}(k)\mu_{r_2^-}(k)\mu_{r_3^0}(k)$

Fault localization

Highest truth degree of a rule ⇒ Most likelihood fault

Enhancements of the method

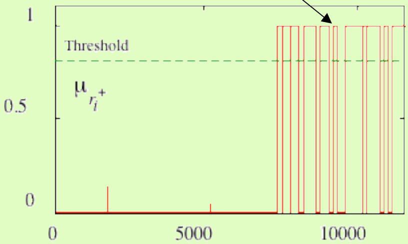
Calculus of a persistence index

$N(\mu)$

number of values of the membership grade which go beyond a given threshold on a window of L observations

$$p_i = \frac{N(\mu_{r_i})}{L}$$

Unceasing switch



Modified membership grades taking into account the persistence indexes

$$\tilde{\mu}_{r_i}(k) = f\left(\mu_{r_i}(k), p_i(k)\right)$$

For example, using product conjunction operator

$$\tilde{\mu}_{r_i}(k) = \mu_{r_i}(k)\, p_i(k)$$

Enhancements of the method

Integration of the sensitivity of the residuals with regard to faults

d_{ij} magnitude of the fault on the jth variable that implies a deviation of the ith residual greater than a given threshold S

(for example $S = \tau_j$ ⇒ membership grade equal to 0.5)

Calculus of a kind of "normalized sensitivities"

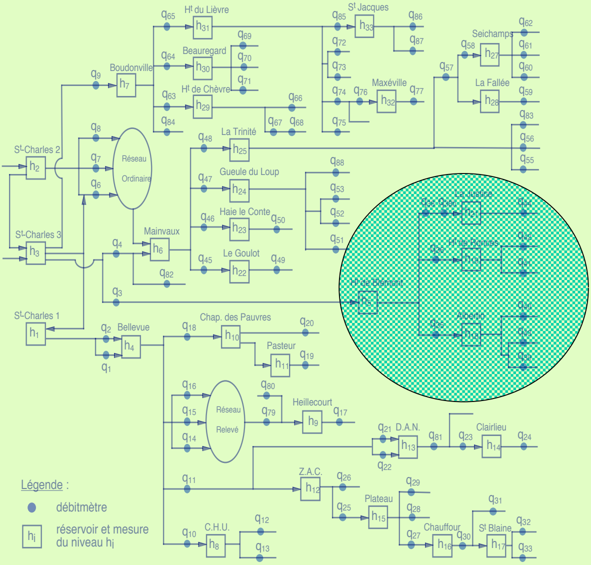
$$\delta_{ij} = \frac{\frac{1}{d_{ij}}}{\sum_j \frac{1}{d_{ij}}}$$

Modified truth degree of fault hypotheses

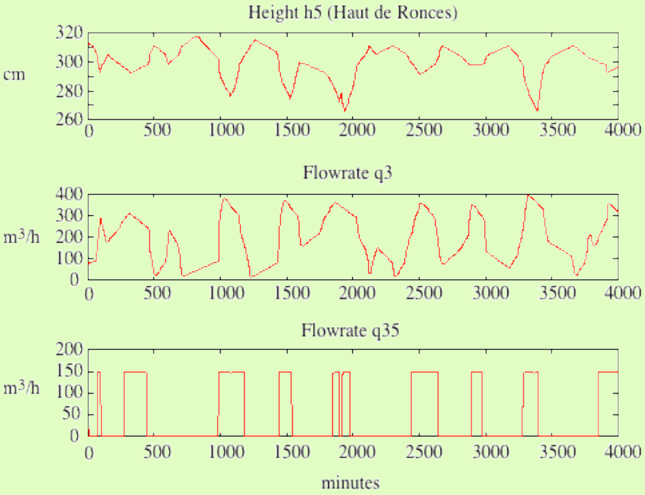
if $r_1(k)$ is r_1^+ and $r_2(k)$ is r_2^- and $r_3(k)$ is r_3^0 then f_1^+

$$\mu_{f_1^+} = \frac{\mu_{r_1^+}(k) + \mu_{r_2^-}(k) + \mu_{r_3^0}(k)}{3} \Rightarrow \mu_{f_1^+} = \frac{\delta_{11}\mu_{r_1^+}(k) + \delta_{21}\mu_{r_2^-}(k) + \mu_{r_3^0}(k)}{\delta_{11} + \delta_{21} + 1}$$

Application : urban water supply network



Application : urban water supply network



Measurements

- ♦Water level of the tanks
- ♦Flowrate
- ♦State of the pumps
- ♦Pressure

Application : urban water supply network

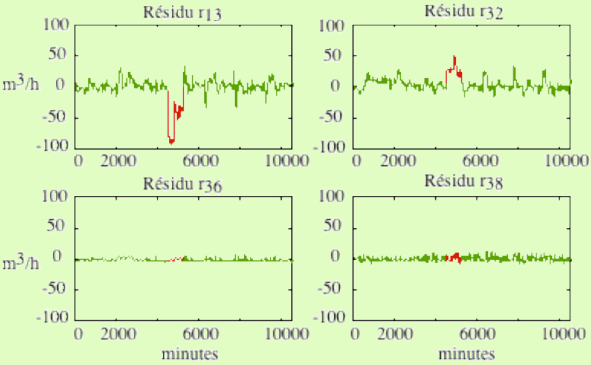
Set of residuals

$$r_{13} = \mathcal{K}_1(-q_{39}, -q_{40}, -q_{41}, -q_{42}, +q_{44})$$

$$r_{32} = \mathcal{K}_2(+q_{39}, -q_{40})$$

$$r_{36} = \mathcal{K}_3(+q_{40}, -q_{41})$$

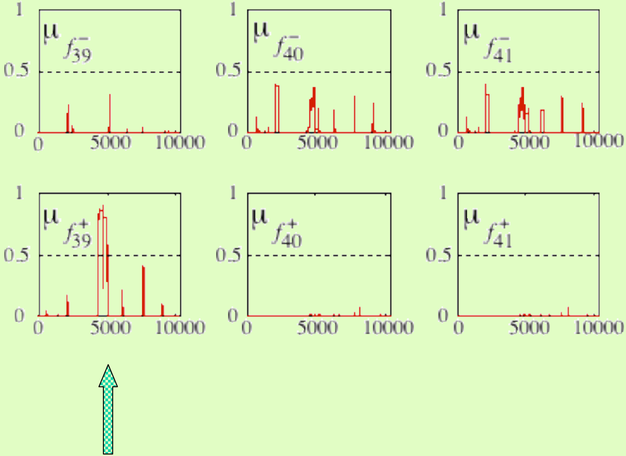
$$r_{38} = \mathcal{K}_4(+q_{41}, -q_{42})$$



→ The measurement of q_{39} is strongly suspected

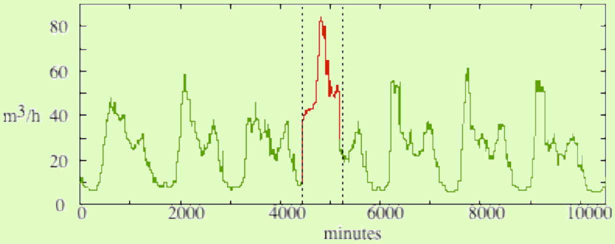
Application : urban water supply network

Truth degrees of fault hypotheses



Application : urban water supply network

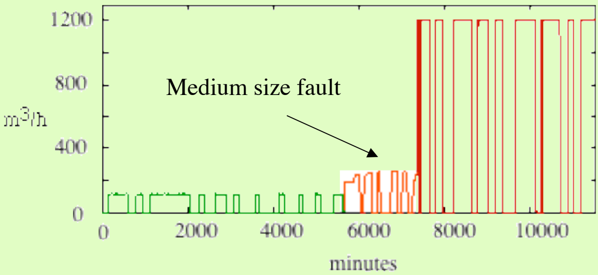
Temporal evolution of the flowrate q_{39}



A posteriori analysis → Leak during about 12 hours

Application : urban water supply network

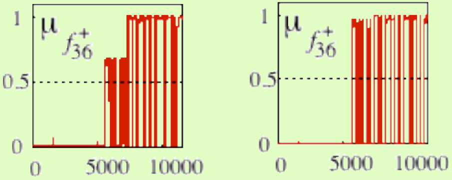
Importance of the integration of residual sensitivity to the different faults



Objective : detection-localization of the fault as soon as possible

Application : urban water supply network

Truth degrees of fault hypotheses



without with

taking into account the sensitivity of the residuals

→ Early detection of small magnitude fault

Conclusion

- Enhancement of now classical approach of fuzzy evaluation of residuals
- Flexible method : ability to integrate many type of information (magnitude of residual deviation, persistence index, sensitivity, and so on)
- Incremental changes in the plant state results in incremental changes in degrees of belief of fault hypotheses
- Ranking of probable faults
- Early detection of small magnitude faults