

Fault Detection using Parameter Estimation applied to a Winding Machine

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Outline

Objective

Identification

- Choice of a model structure
and an estimation method
- Consequence of a fault on parameter estimates
- Actuator fault example

Diagnosis

- Residual generation **for detection**
- Residual fuzzyfication
- Signature table generation **for isolation**
- Symptom Aggregation
- Isolation Function by **fuzzy inference**
- Isolation Function by **distance computation**
- Diagnosis task architecture

Application

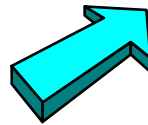


Objective



Diagnosis using Parameter estimation

applied to a complex process!

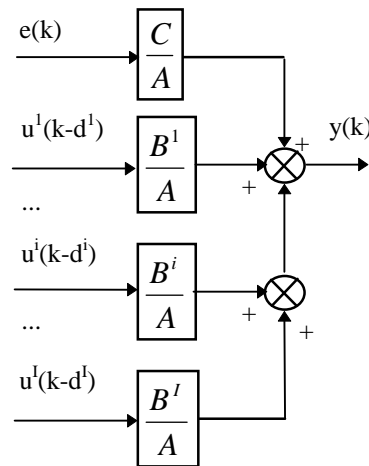


- ▶ No physical parameters
- ▶ No additive signal !
- ▶ A fast and simple estimation method



Choice of a model structure and an estimation method

▶ **ARMAX MISO** discrete model



$$A(q^{-1}) \cdot y(k) = \sum_{i=1}^l B^i(q^{-1}) \cdot u^i(k - d^i) + C(q^{-1}) \cdot e(k)$$

☺ **transfer function** parameter estimation

☺ **low complexity**
and no biased parameters

▶ **RELSE** with forgetting factor achieved by **Orthonormal Transformation**

☑ **on line** variance and parameter estimation

☑ **good numerical properties**



Consequence of a fault on parameter estimates

Two kinds of faults

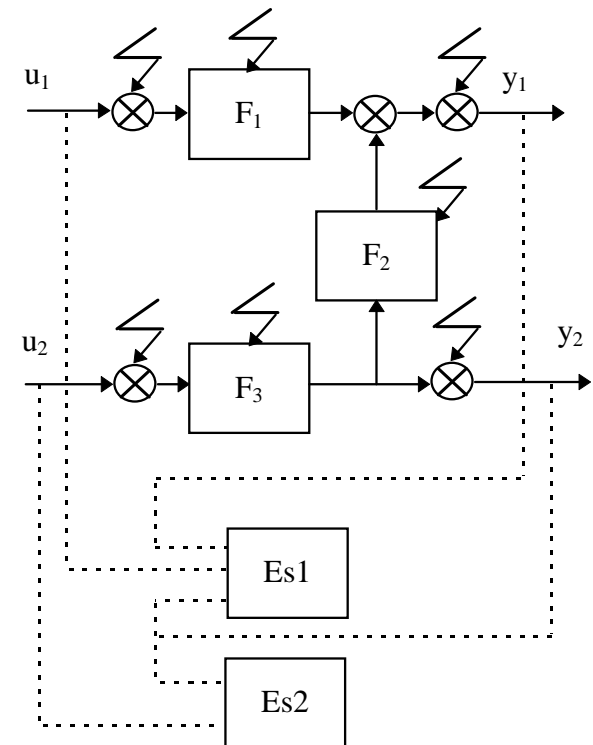
$$y_1 = F_1 u_1 + F_2 y_2$$
$$y_2 = F_3 u_2$$

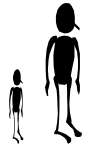
- ☑ process fault

variation of static or dynamic characteristics

- ⇒ ☑ *actuator or sensor fault*

***a global perturbation of all parameters
and variance increase***





Residual generation for detection

The reference model

$$Es^l = \left[\Theta_1 \quad \dots \quad \Theta_p \right]$$

long horizon
estimate vector with $\lambda = 1$

The tracking model

$$Es^s = \left[\theta_1 \quad \dots \quad \theta_p \right]$$

short horizon
estimate vector with $\lambda = 0.99$

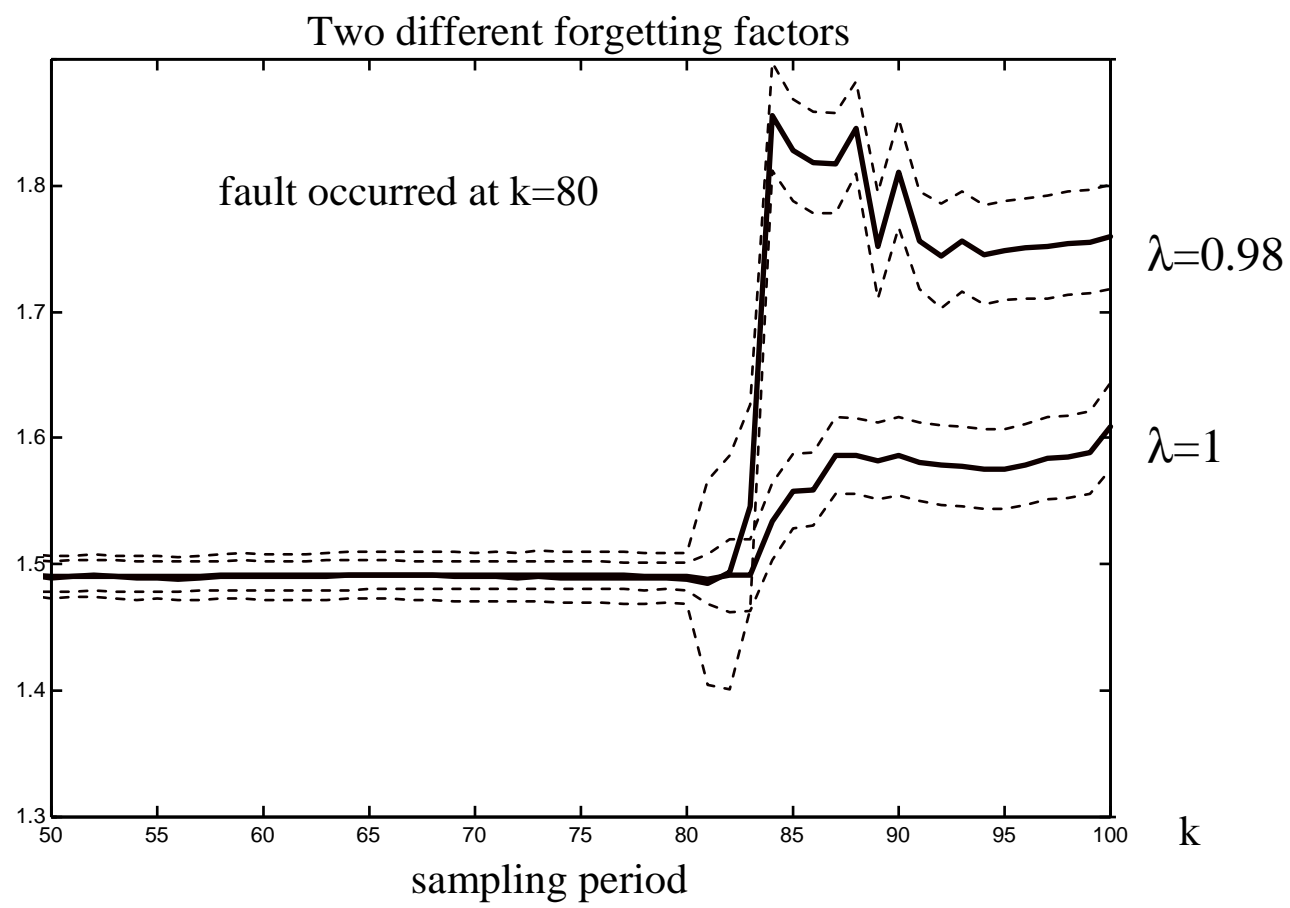
RESIDUALS

$$r_j = \Theta_j - \theta_j$$

$$E \{ r_j \} = E \{ \Theta_j \} - E \{ \theta_j \} \longrightarrow 0 \text{ if no fault occurred !}$$

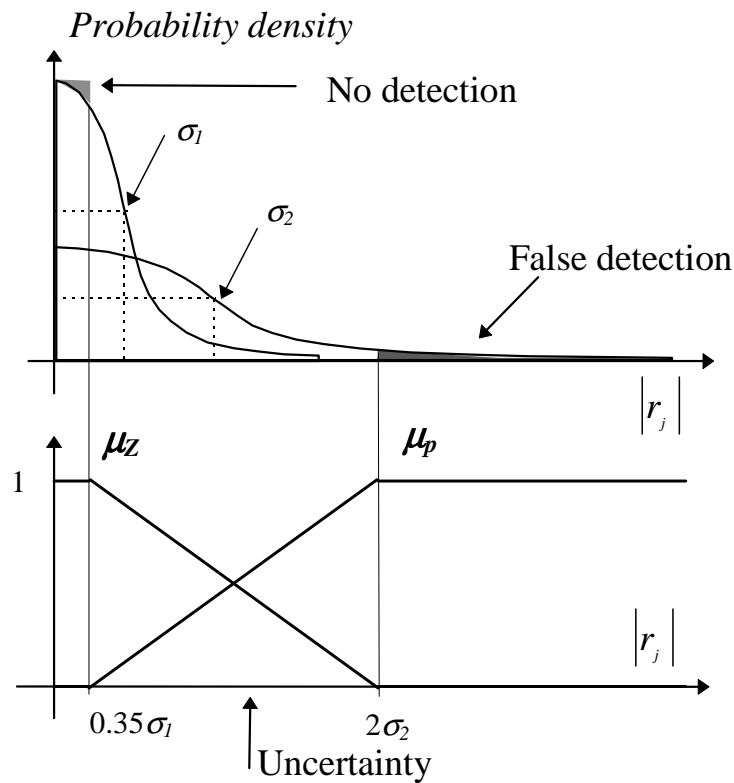


Actuator fault example





Residual fuzzyfication



Membership functions

Variance $\sigma_1^2 \leq \sigma_{r_j}^2 \leq \sigma_2^2$

$$\sigma_1^2 = \sigma_{\theta_j}^2 + \sigma_{\theta_j}^2 \quad \sigma_2^2 = \left(\sigma_{\theta_j} + \sigma_{\theta_j} \right)^2$$

The membership function of the fuzzy sets

POSITIVE residual and ZERO residual :

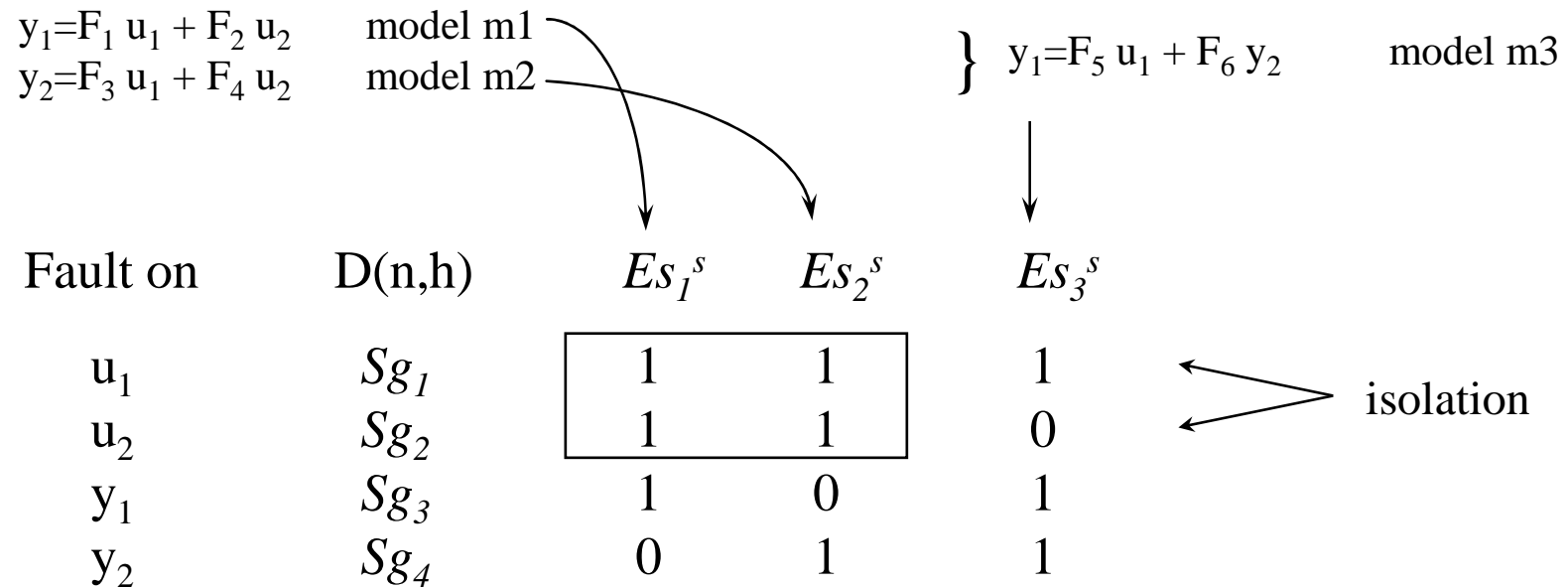
$$\mu_p(|r_j|) = \min \left(1, \max \left(0, \frac{|r_j| - 0.35 \cdot \sigma_1^2}{2 \cdot \sigma_2^2 - 0.35 \cdot \sigma_1^2} \right) \right)$$

$$\mu_z(|r_j|) = 1 - \mu_p(|r_j|)$$



Signature table generation for isolation

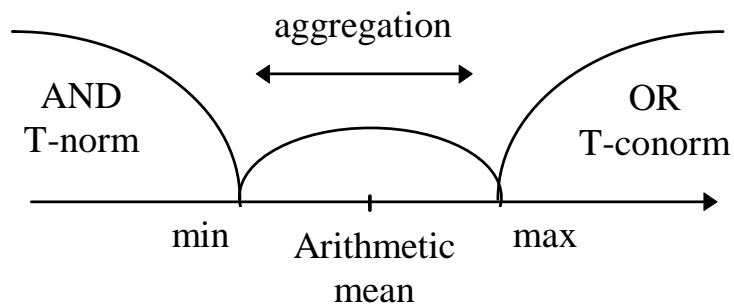
The signature table $D(n,h)$ defines the relation between faults and short estimate vector Es_h^s





Symptom Aggregation



FAULT  a global perturbation of residuals for the model m_h



The symptom s_{m_h} is based on the residual vector :

$$\left[\left| r_1^h \right| \dots \left| r_{p^h}^h \right| \right]$$

The symptom is defined by two complementary fuzzy sets :

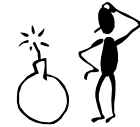
Gp  Globally perturbed
 Np  Not perturbed

The membership functions for each model are computed by an aggregation

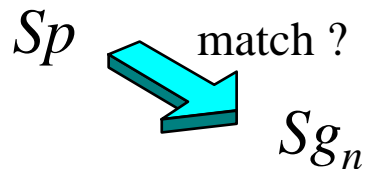
$$\mu_{Gp}(s_{m_h}) = \frac{1}{p^h} \sum_{j=1}^{p^h} \mu_P(|r_j^h|) \quad \text{and} \quad \mu_{Np}(s_{m_h}) = 1 - \mu_{Gp}(s_{m_h})$$

Aggregated symptom vector

$$Sp = \left[\mu_{Gp}(s_{m_1}) \dots \mu_{Gp}(s_{m_H}) \right]$$



Isolation function by fuzzy inference (in single fault case)



$\mu_{F_n}(Sp) = 0$ no fault F_n
 $0 < \mu_{F_n}(Sp) < 1$ fault F_n suspicion
 $\mu_{F_n}(Sp) = 1$ fault F_n

D(n,h)	Es_1^s	Es_2^s	Es_3^s	
Sg_1	1	1	1	Np
Sg_2	1	1	0	Np
Sg_3	1	0	1	Gp
Sg_4	0	1	1	Gp

The rule for Sg_2

IF s_{m1} is Gp
 and s_{m2} is Gp
 and s_{m3} is Np
 THEN the fault is F_2

and is a T-norm computed by a min operator, the rule becomes :

$$\mu_{F_2}(Sp) = \min \{ \mu_{Gp}(s_{m1}), \mu_{Gp}(s_{m2}), \mu_{Np}(s_{m3}) \}$$

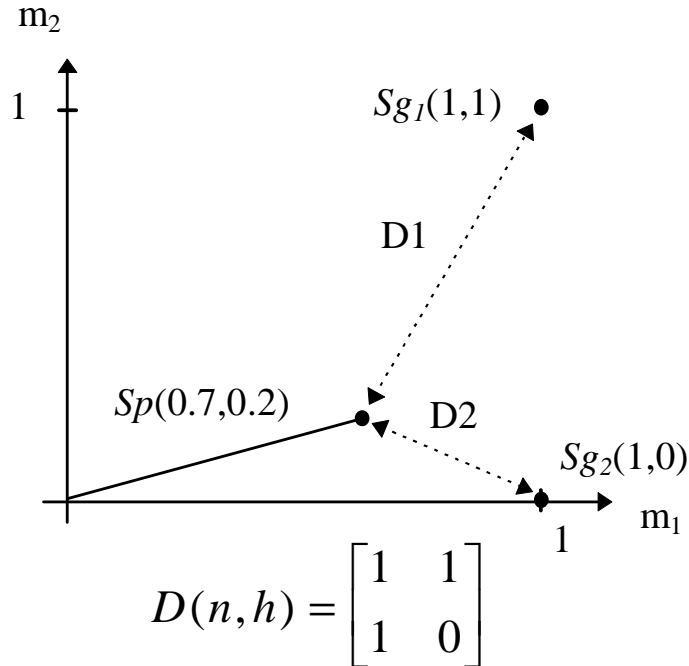
Isolation function by distance computation

The Isolation Function $F(Sp, Sg_n)$ represents a degree of **likeness** between Sp and the fault signature Sg_n

$$F(Sp, Sg_n) = 0 \quad \text{no fault } n$$

$$0 < F(Sp, Sg_n) < 1 \quad \text{fault } n \text{ suspicion degree}$$

$$F(Sp, Sg_n) = 1 \quad \text{fault } n$$



General formula by distance computation

$$F(Sp, Sg_n) = 1 - \frac{1}{\omega} \left(\sum_{h=1}^H |\mu_{Gp}(s_{m_h}) - D(n, h)|^q \right)^{\frac{1}{q}}$$

Hamming distance $q=1$ ω =space dimension

$$F(Sp, Sg_n) = 1 - \frac{1}{H} \sum_{h=1}^H |\mu_{Gp}(s_{m_h}) - D(n, h)|$$

Isolation function by distance computation

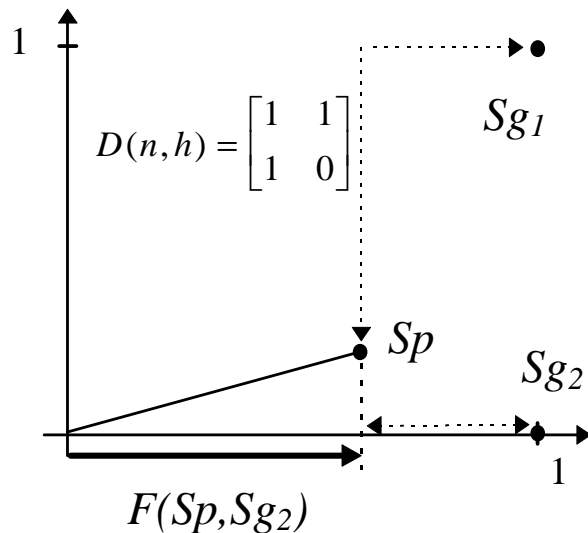
No fault

$$Sp = [0 \quad 0] \quad \Rightarrow \quad F(Sp, Sg_2) = 1 - \frac{1}{2}[|0 - 1| + |0 - 0|] = 0.5$$



eliminate insensitive dimensions

$$F(Sp, Sg_n) = 1 - \frac{1}{W_n} \sum_{h=1}^H \{ |\mu_{Gp}(s_{mh}) - D(n, h)| \cdot D(n, h) \}$$



$$Sp = [0 \quad 0] \quad F(Sp, Sg_1) = 0$$

$$F(Sp, Sg_2) = 0$$

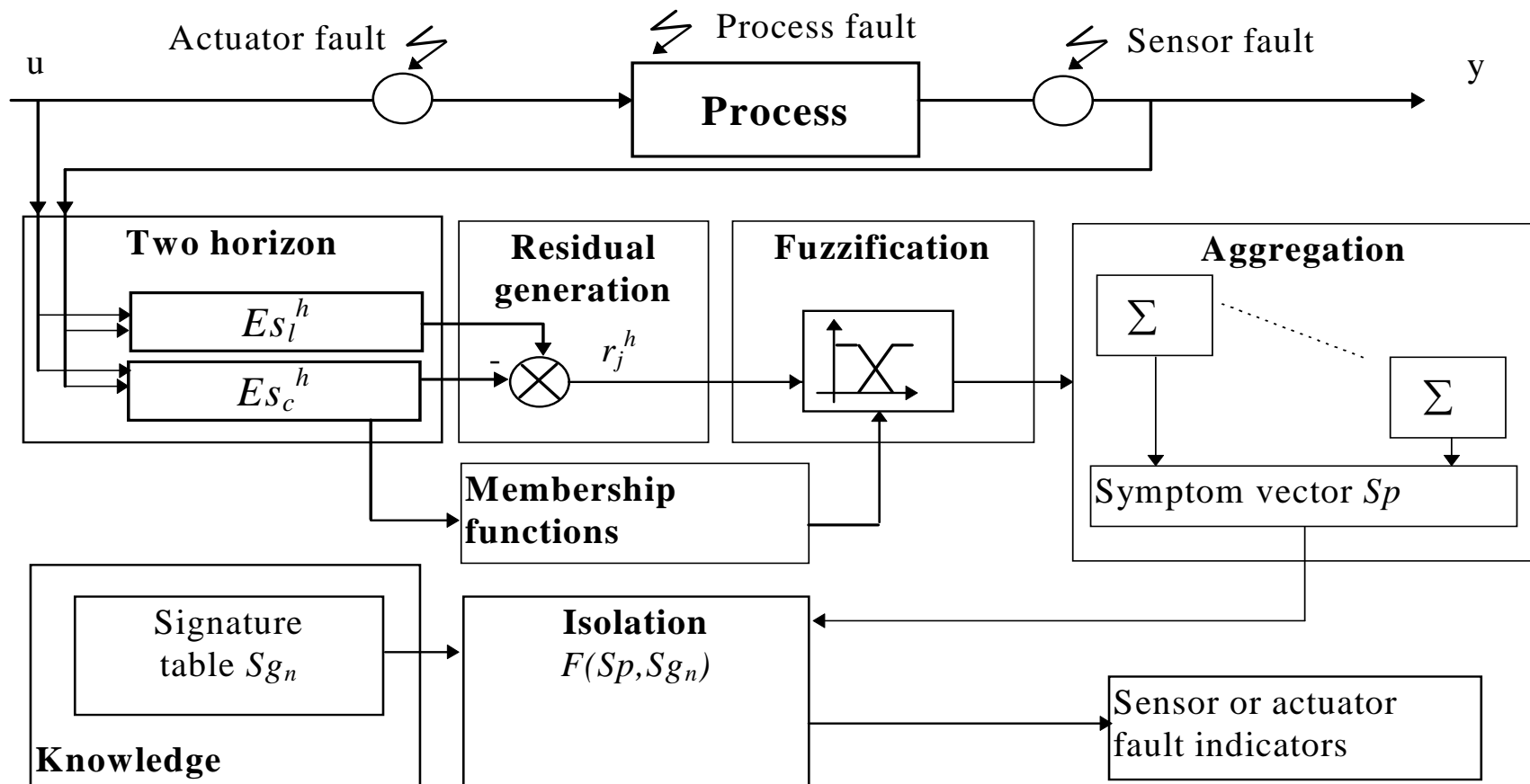
$$Sp = [0.7 \quad 0.2] \quad F(Sp, Sg_1) = 0.45$$

$$F(Sp, Sg_2) = 0.7$$

\Rightarrow Useful too for multiple fault analysis



Diagnosis task architecture



Application

After off line parameter estimation:

$$A_1(q^{-1}).T_1(k)=B_{12}(q^{-1}).\Omega_2(k-d_{12})+B_{1u1}(q^{-1}).u_1(k-d_{1u1})$$

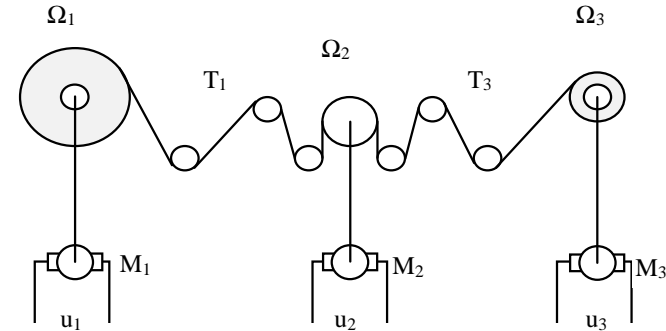
$$A_2(q^{-1}).\Omega_2(k)=B_{2u2}(q^{-1}).u_2(k-d_{2u2})$$

$$A_3(q^{-1}).T_3(k)=B_{32}(q^{-1}).\Omega_2(k-d_{32})+B_{3u3}(q^{-1}).u_3(k-d_{3u3})$$

Redundant transfer function generation:

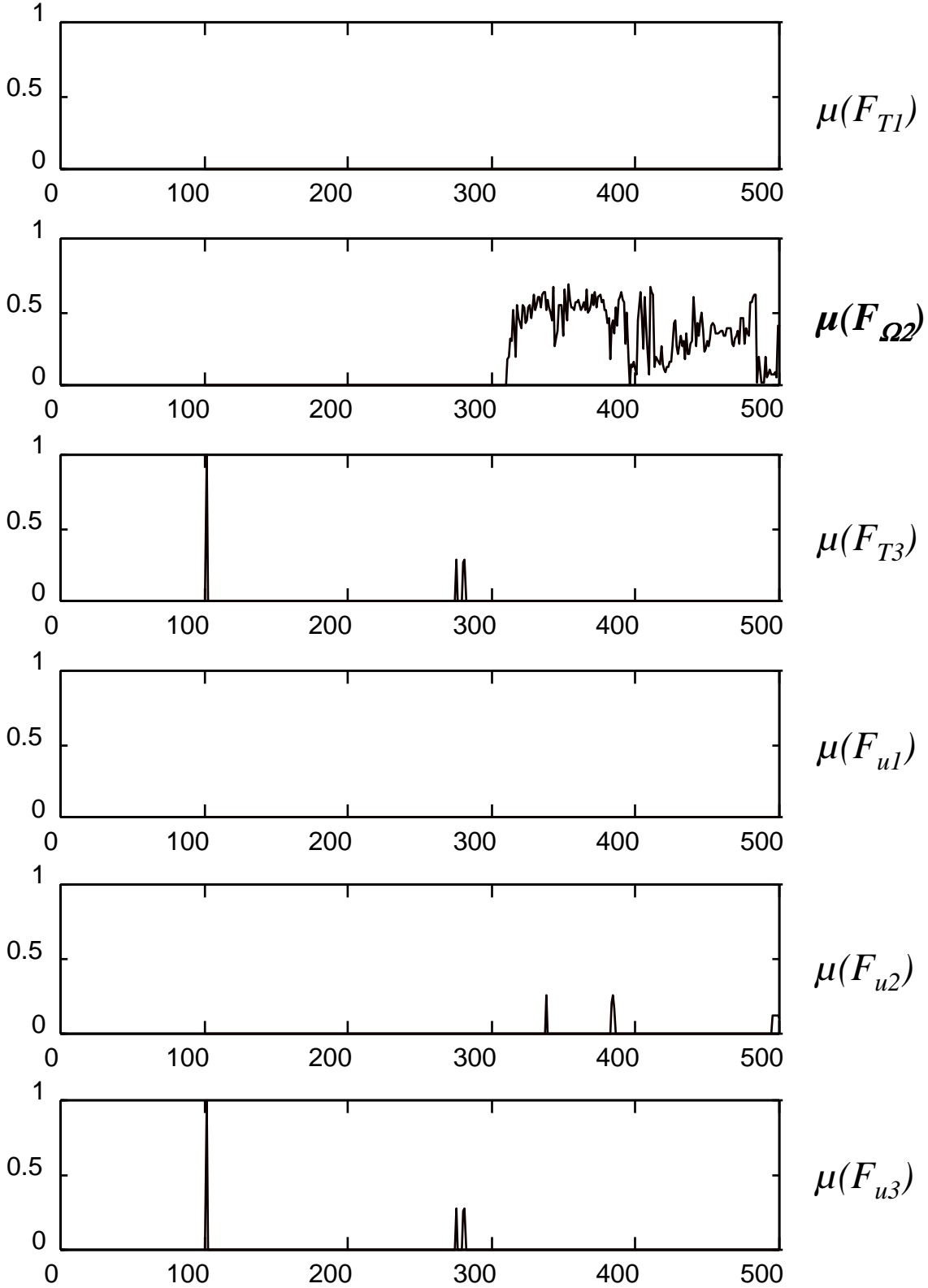
$$A_{11}(q^{-1}).T_1(k)=B_{11u2}(q^{-1}).u_2(k-d_{11u2})+B_{11u1}(q^{-1}).u_1(k-d_{1u1})$$

$$A_{33}(q^{-1}).T_3(k)=B_{33u2}(q^{-1}).u_2(k-d_{33u2})+B_{33u3}(q^{-1}).u_3(k-d_{3u3})$$

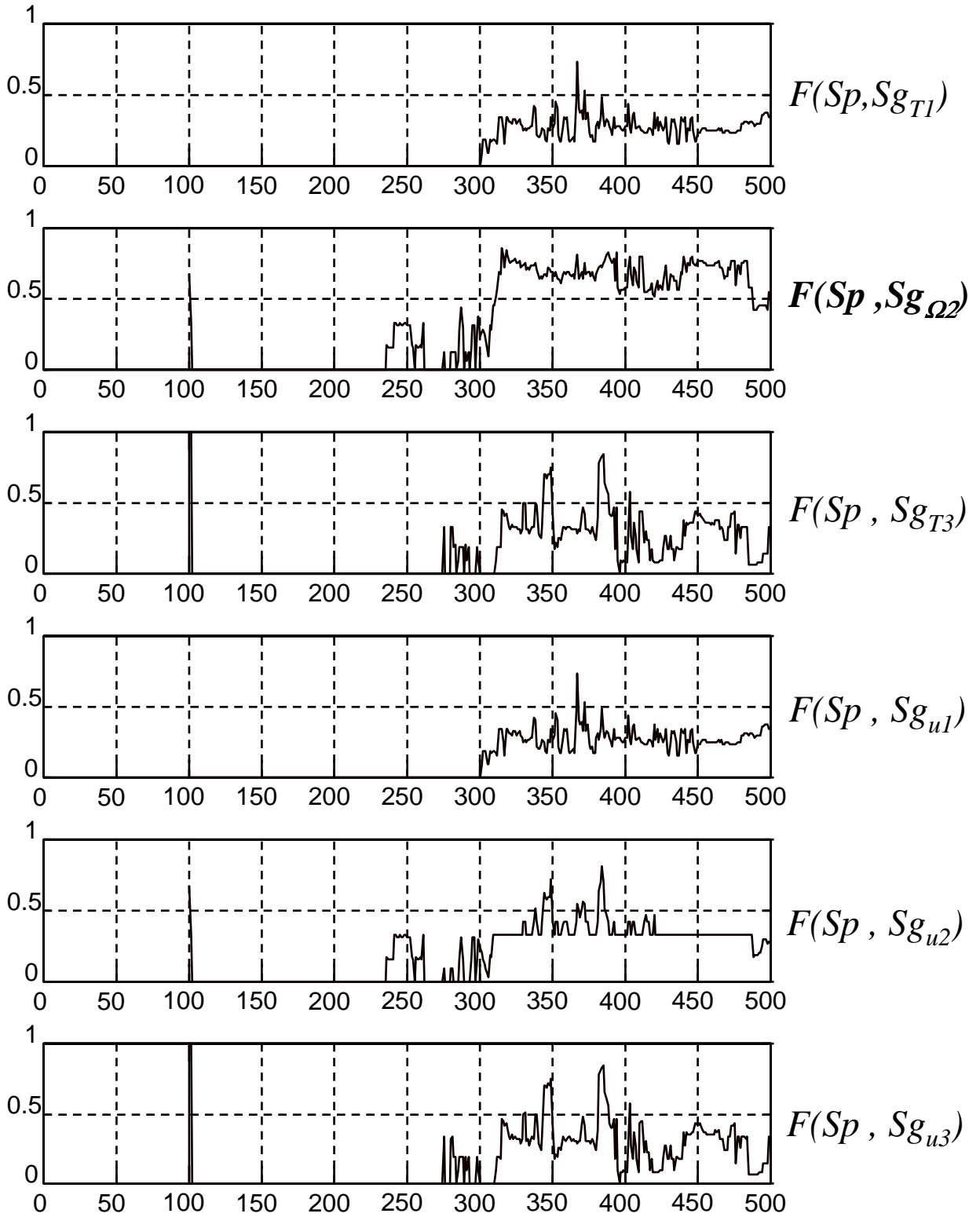


Bias on	D	Es ₁	Es ₂	Es ₃		Es ₄	Es ₅
T ₁	Sg _{T1}	1	0	0		1	0
Ω_2	Sg _{Ω_2}	1	1	1		0	0
T ₃	Sg _{T3}	0	0	1		0	1
u ₁	Sg _{u1}	1	0	0		1	0
u ₂	Sg _{u2}	0	1	0		1	1
u ₃	Sg _{u3}	0	0	1		0	1

Fault suspicion degree using fuzzy rules



Fault isolation function evolution



Conclusion

Fault detection and isolation of sensor or actuator FAULTS

- transfer function redundancy \Rightarrow better isolation performance
- fuzzy residual evaluation \Rightarrow taking uncertainty into account
- symptom aggregation \Rightarrow allows comparison with the fault signature table
- the result with a classical fuzzy inference system in a single fault case
 \Rightarrow method validation
- the result with distance computation for classification
 \Rightarrow possibility of multiple faults isolation

Future work

Parameter estimation method with adaptive forgetting factor

using information like

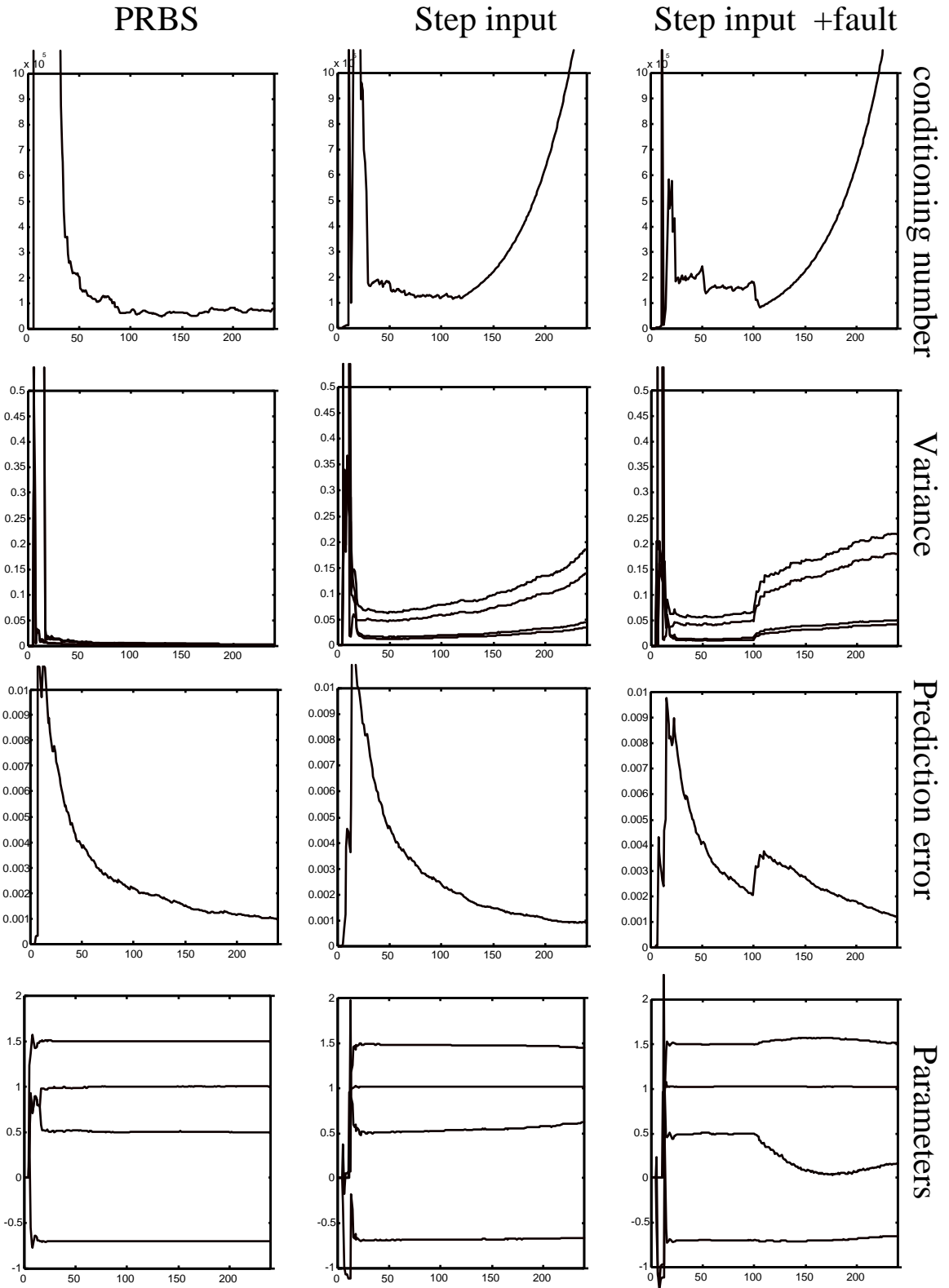
condition number,

prediction error,

to solve the non-persistent excitation problem

Find an optimal signature table

Closed loop application



On line conditioning number evolution

