MULTIPOINT NON-LINEAR METHOD FOR ENHANCED COMPONENT AND SENSOR MALFUNCTION DIAGNOSIS

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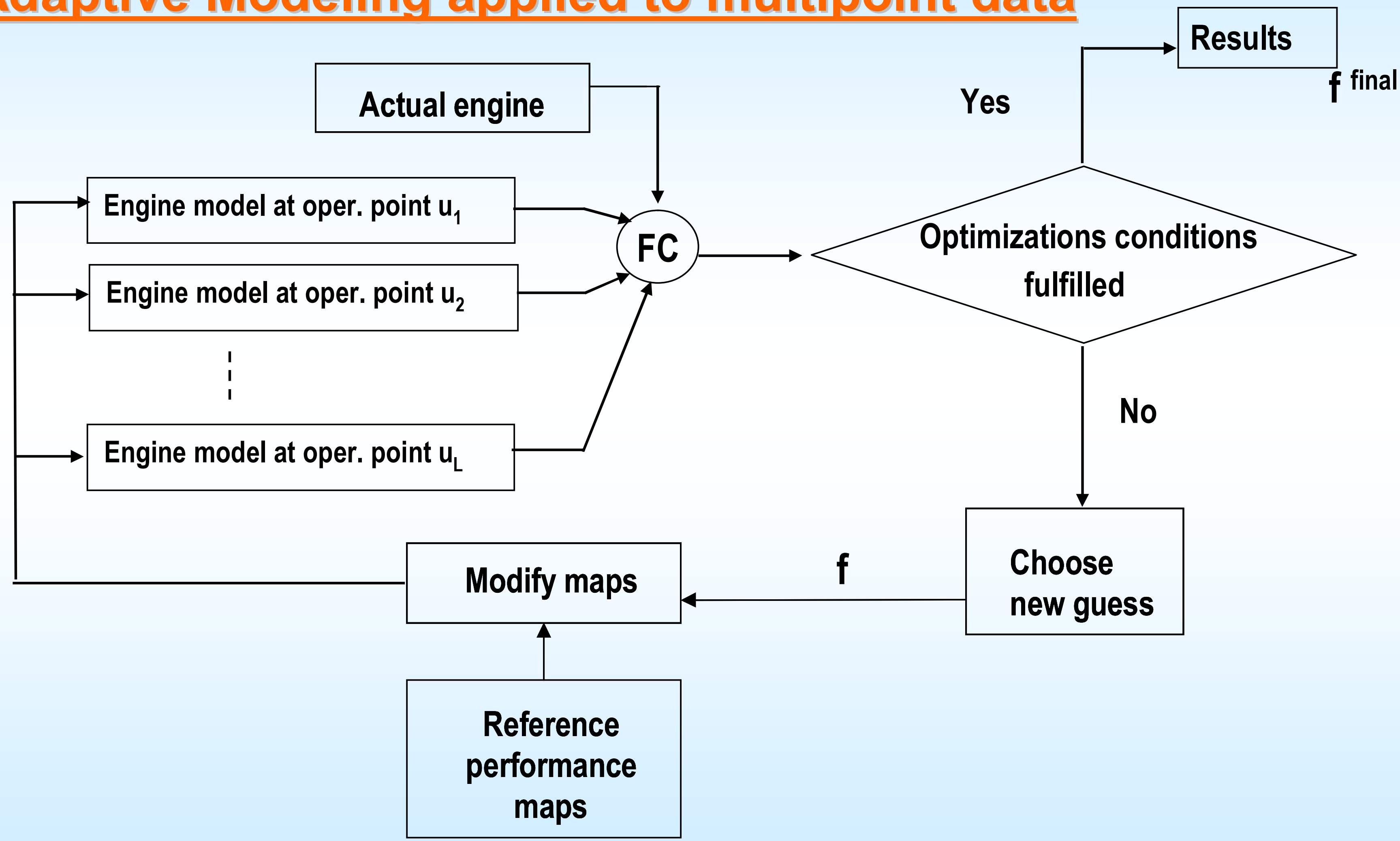
MULTIPOINT NON-LINEAR METHOD FOR ENHANCED COMPONENT AND SENOSOR MALFUNCTION DIAGNOSIS

- **Diagnosis through the use of adaptive modeling with application to multipoint aerothermodynamic data**
- **Multipoint method definitions and operating points selection**
- **Method application to noisy data**
- **Evolution of the method to deal with sensor faults**
- **Implementation aspects of multipoint method**
- **Conclusions**

Adaptive Modeling applied to multipoint data



Formulation of the non-linear diagnostic problem

Investigation on the ability to derive solutions

The possibility to derive a unique solution for f depends on the relation between *(the number of measurements) M* and *(the number of health parameters) N*

- **If *N≤M* : A Unique solution exists**
- **If *N>M*, An Infinite number of solutions exists.**

The multipoint aerothermal diagnostic method

The engine operation can be observed using an adaptive model.

$$\mathbf{Y_k} = \mathbf{F}(\mathbf{u_k}, \mathbf{f_c})$$

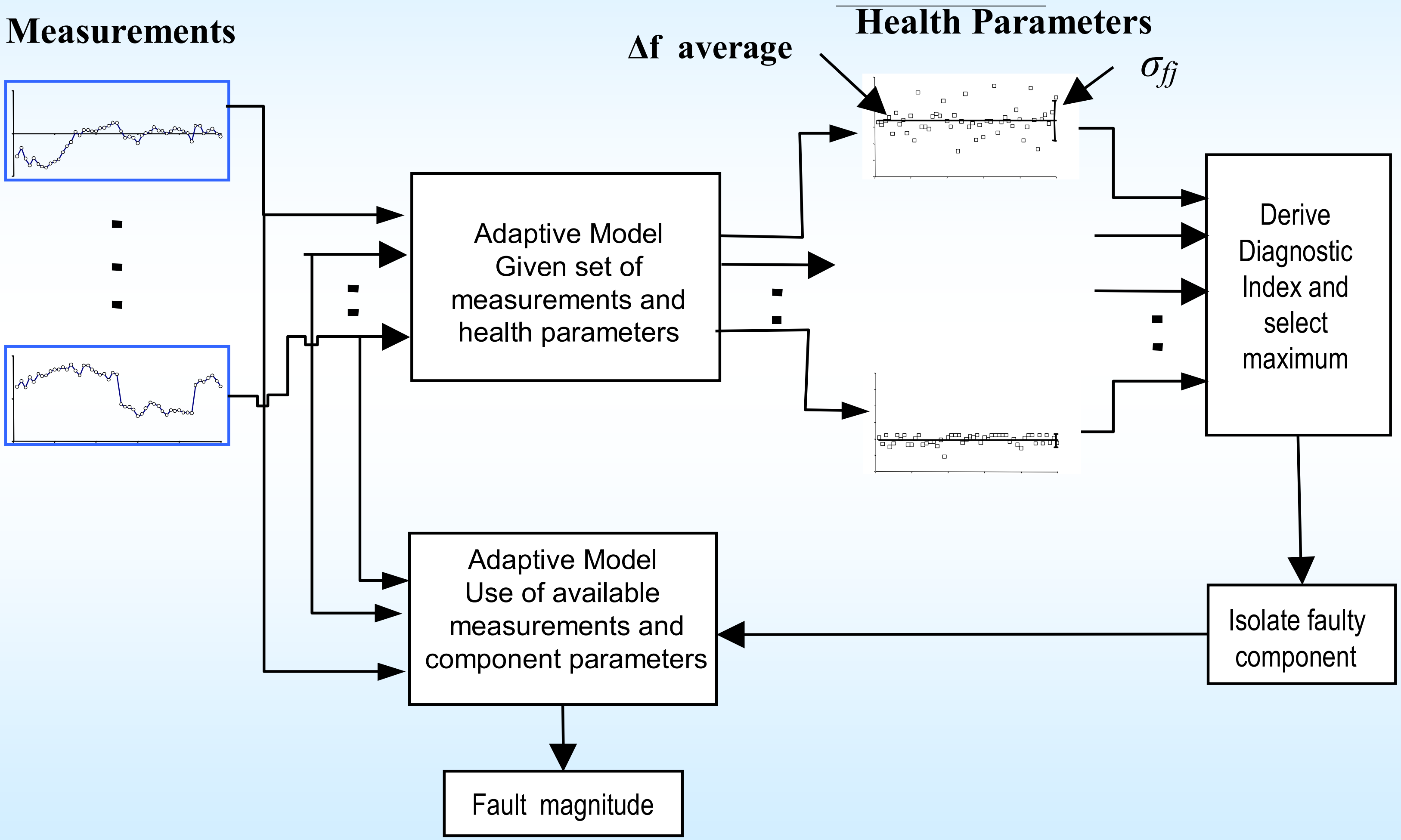
Diagnosis could be performed by forming a cost function of this type if the estimated parameters are less or equal to available measurements.

$$FC_k(\mathbf{f}) = \sum_{i=1}^{M} \left[\frac{\Delta Y_{ik}^{meas} - \Delta Y_{ik}(\mathbf{u_k}, \mathbf{f})}{\sigma_{Yik}^{norm}} \right]^2$$

In case of limited information from an engine the diagnostic procedure can be extended at several different operating points.

$$FC(\mathbf{f_c}) = \sum_{k=1}^{L} FC_k(\mathbf{f_c}) = \sum_{k=1}^{L} \sum_{i=1}^{M} \left[\frac{\Delta Y_{ik}^{meas} - \Delta Y_{ik}(\mathbf{u}_k, \mathbf{f_c})}{\sigma_{Yik}^{norm}} \right]^2$$

Diagnostic Procedure Flow Chart

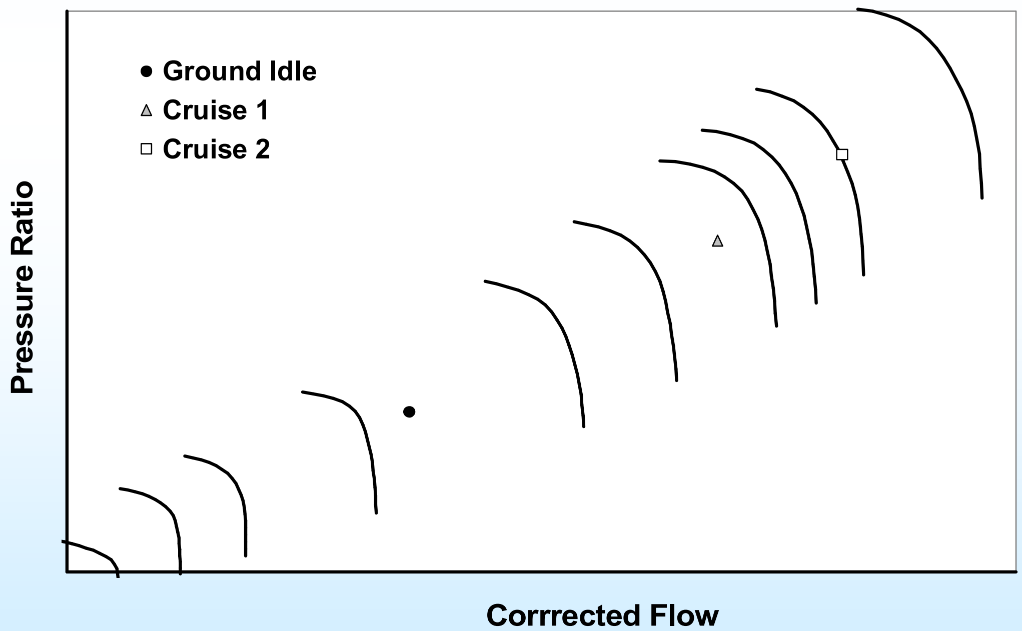


Operating points selection for multipoint procedures

The operating points selected among available for the constitution of the method must ensure:

Operating points for turbofan

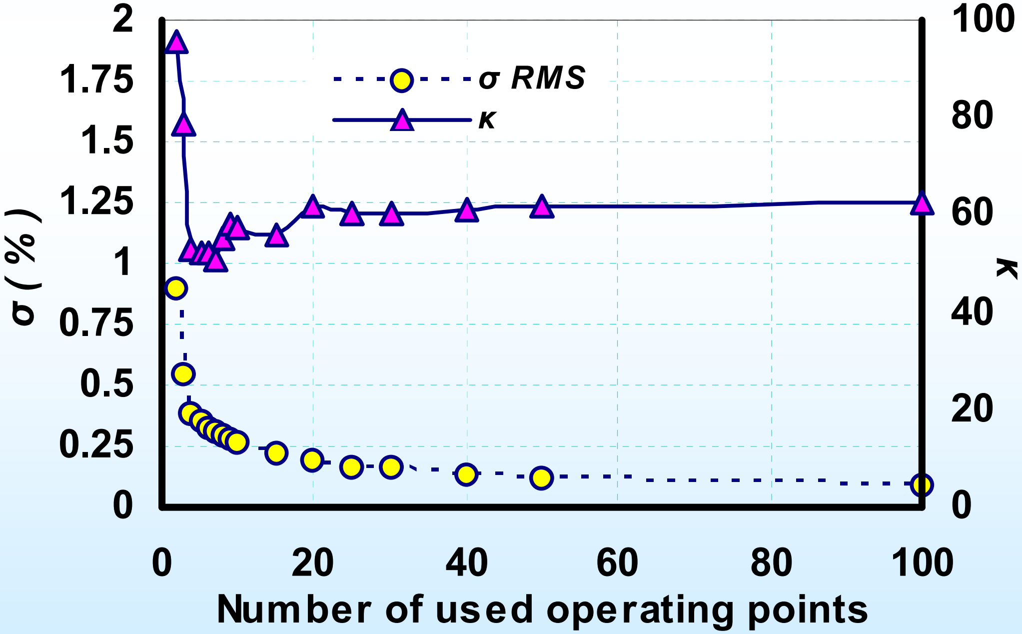
- **Robust behaviour of the numerical procedure supporting the diagnosis**
- **Minimum amplification of measurements noise to estimated health parameters**



Criteria for optimal selection of operating points

The method of condition number is applied to the extended system matrix of the equivalent linear system

Low condition number and low noise amplification is ensured



Increase of operating points taken in to account:

- **Results to low condition number**
- **Reduces the estimation uncertainty**

Application Test Case

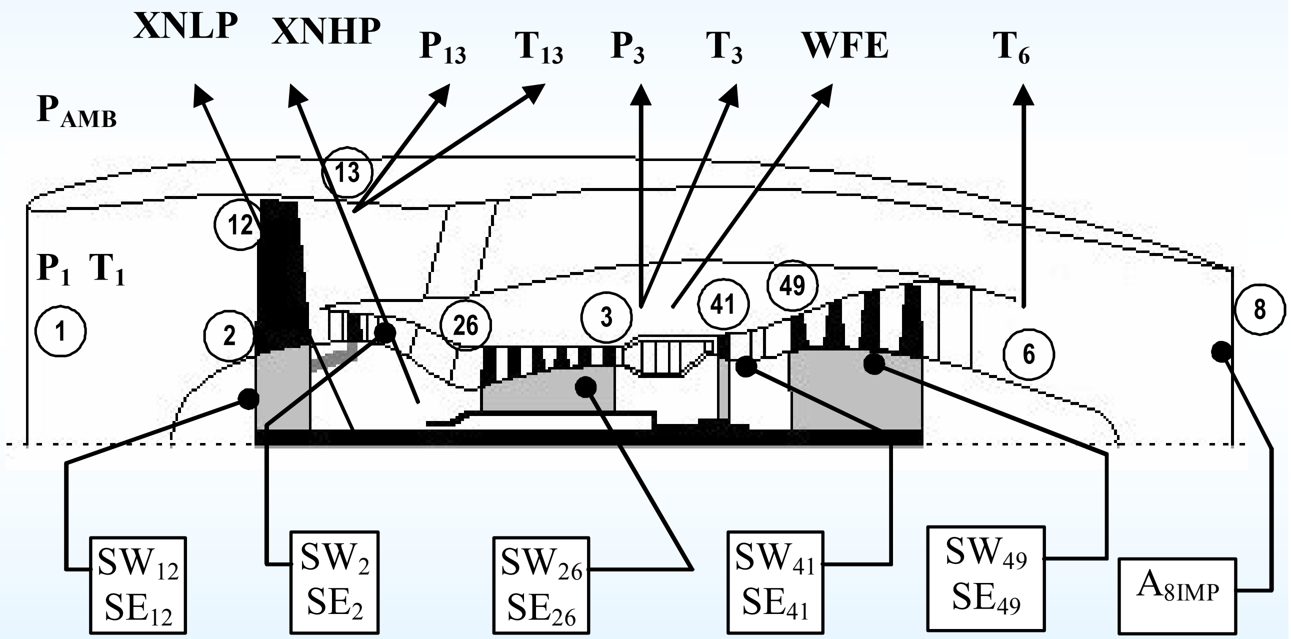
A large civil turbofan

4 OP definition variables

7 measurements are available to

estimate

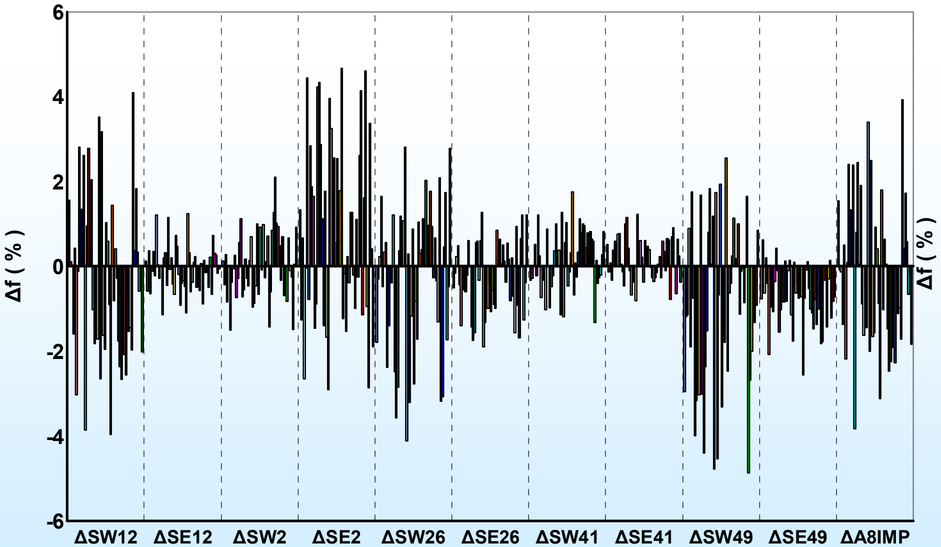
11 health parameters



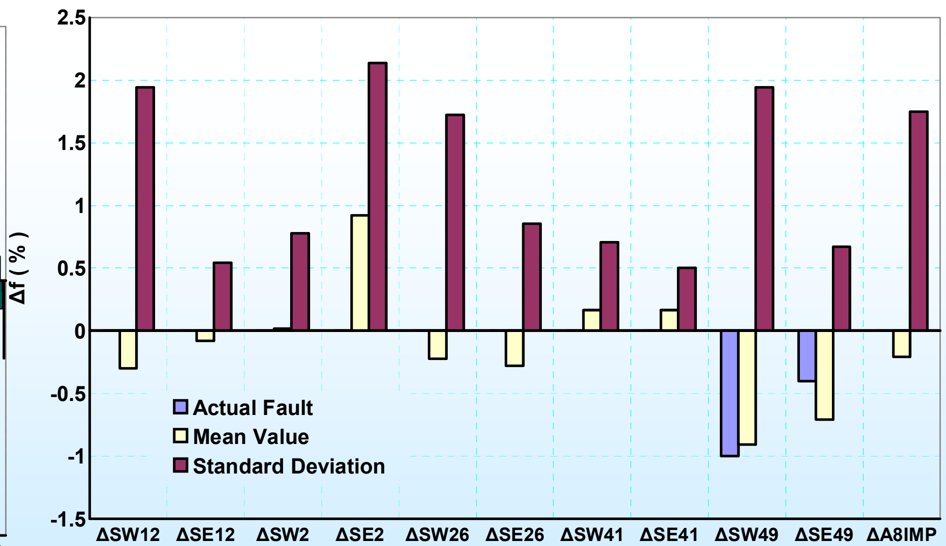
Application of the method to noisy data – Row estimations

The method has been applied to a set of single component faults defined through European project OBIDICOTE.

Row estimations from a sequence of 50 records



Fault localization

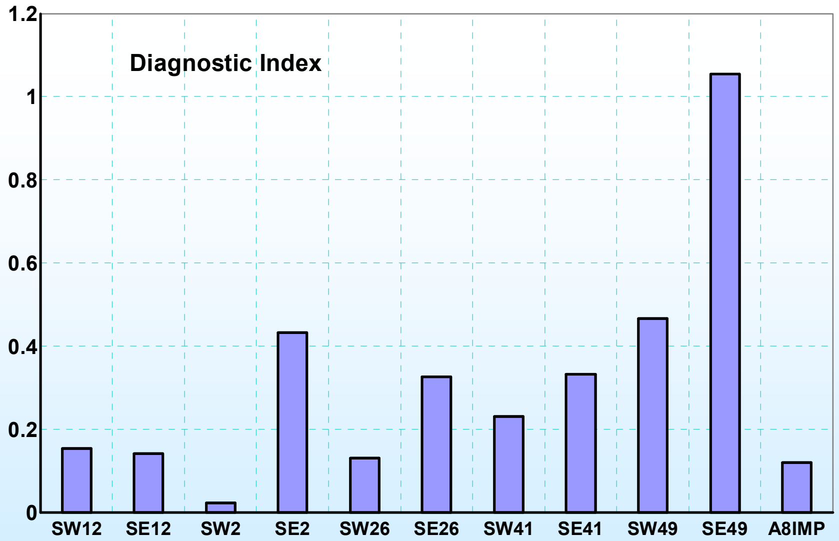


Application of the method to noisy data
Detection of faulty component

Mean Value and Standard Deviation based on the sample are derived used for Diagnostic Index application

DI

$$DI_j = \frac{\left|\Delta f_{cj}^{mean}\right|}{\sigma_{fj}}$$



	Correct detection of faulty component	
Fault	Single Point	Multi point
A	√	√
B	√	√
C		√
D	√	√
E	√	√
F	√	√
G	√	√
H	√	√
I	√	√
J		√
K	√	√
L	√	√
M	√	
N	√	√
O	√	√

Extension of Multipoint method to deal with sensor faults

Nominal value for a measurement

$$\mathrm{F_i}(\mathbf{u_k},\mathbf{f_c}) = Y_{\mathrm{ik}}^{\mathrm{exp}} = a_{\mathrm{i}}^{\mathrm{ref}} + \beta_{\mathrm{i}}^{\mathrm{ref}} \cdot V_{\mathrm{ik}}$$

Component parameters $\mathbf{f_c}$

Sensor parameters $\mathbf{f_y}$

Health parameters for measurement sensor

$$f_{\mathrm{y\,i\alpha}} = \frac{a_{\mathrm{i}}}{a_{\mathrm{i}}^{\mathrm{ref}}} \qquad f_{\mathrm{y\,i\beta}} = \frac{\beta_{\mathrm{i}}}{\beta_{\mathrm{i}}^{\mathrm{ref}}}$$

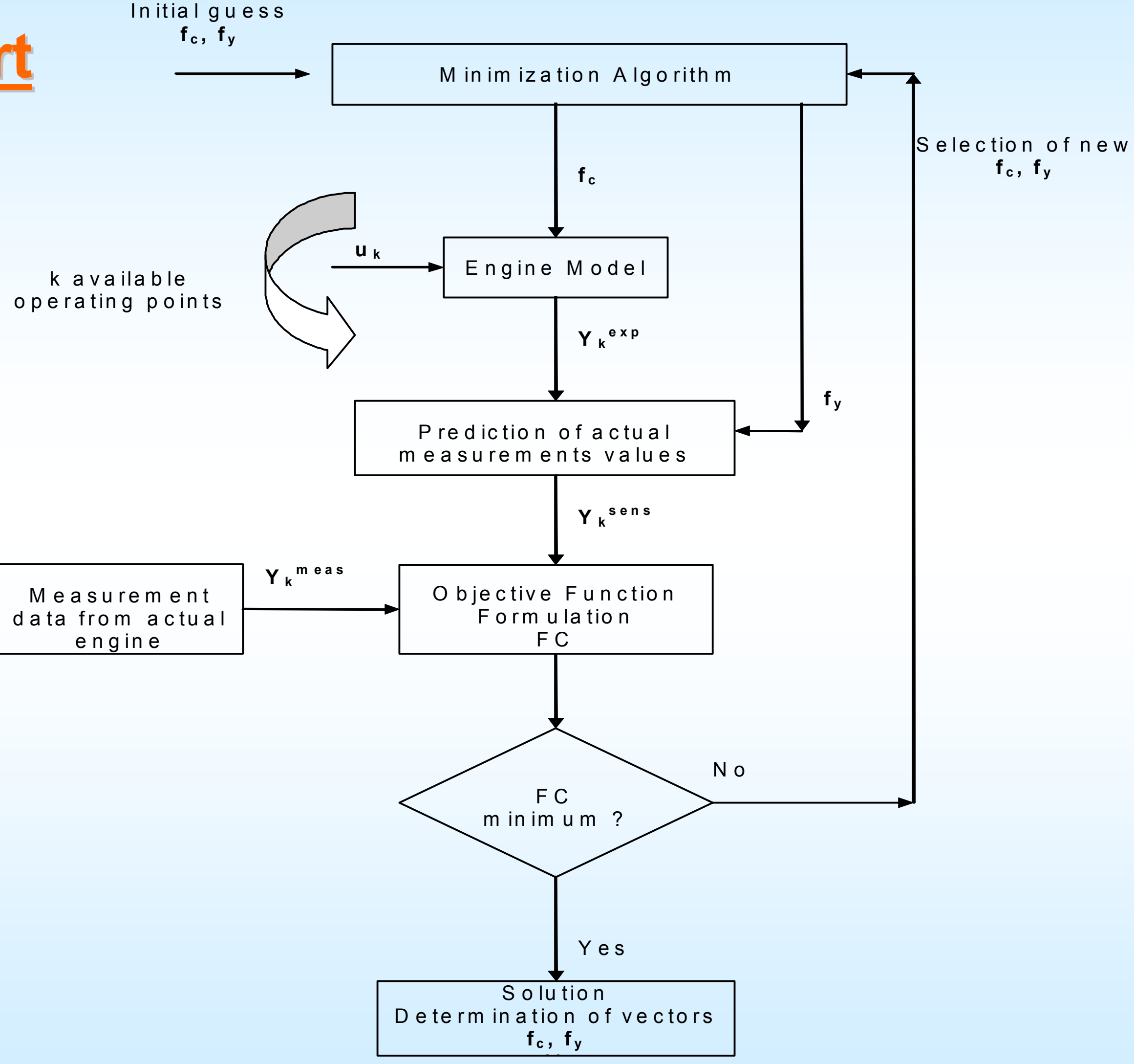
The vector $\mathbf{f}$ of estimated health parameters consists on:

$$\mathbf{f} = \begin{bmatrix} \mathbf{f_c} \\ \mathbf{f_y} \end{bmatrix}$$

Measurement value provided by a sensor

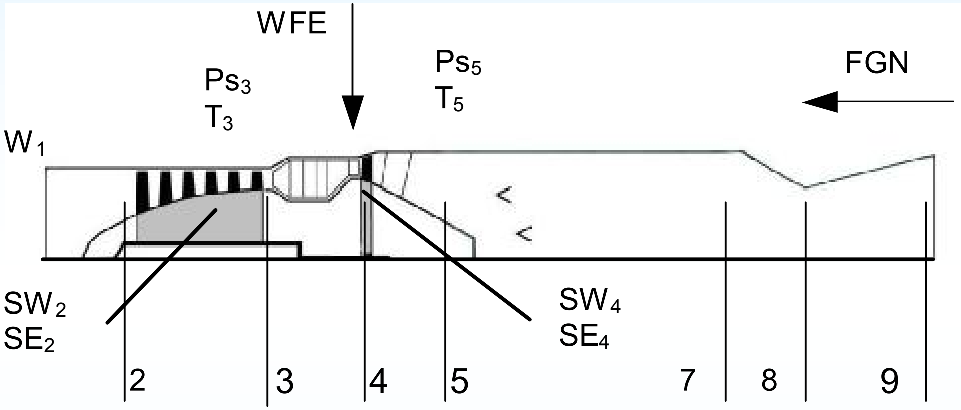
$$Y_{\mathrm{ik}}^{\mathrm{sens}} = f_{\mathrm{y_{i\beta}}} \cdot \mathrm{F_i}(\mathbf{u_k},\mathbf{f_c}) + a_{\mathrm{i}}^{\mathrm{ref}} \cdot \left(f_{\mathrm{y_{i\alpha}}} - f_{\mathrm{y_{i\beta}}}\right)$$

Procedure Flow Chart



Application to a turbojet test case

Estimation of compressor and turbine state: SW_2,SE_2, SW_4, SE_4 using P_{s3}, T_3, T_5, W_1.



For each used measurement two health parameters are considered:

$SP_{s3\alpha}$, $SP_{s3\beta}$, $ST_{3\alpha}$, $ST_{3\beta}$, $ST_{5\alpha}$, $ST_{5\beta}$, $SW_{1\alpha}$, $SW_{1\beta}$.

The number of unknowns rise to 12 while the number of known is 4. Thus 3 operating points are used. The resulting system exhibit bad condition number.

Introduction of a heuristic search rule

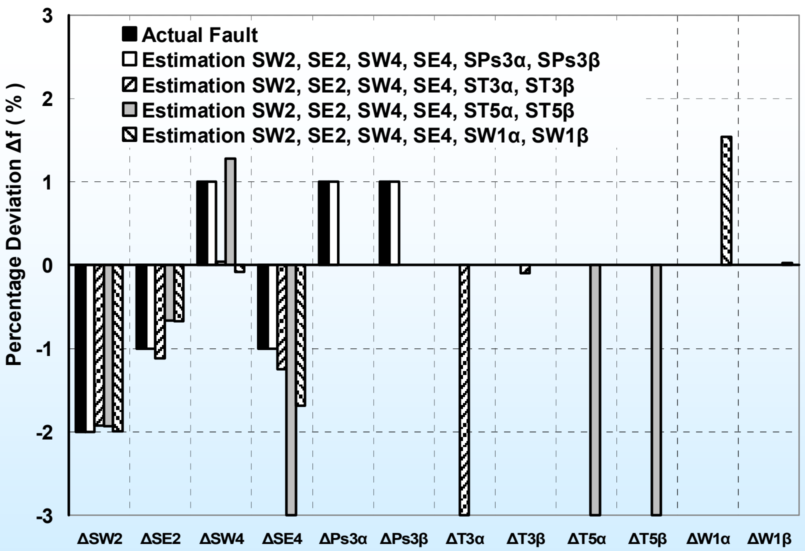
A reasonable assumption:

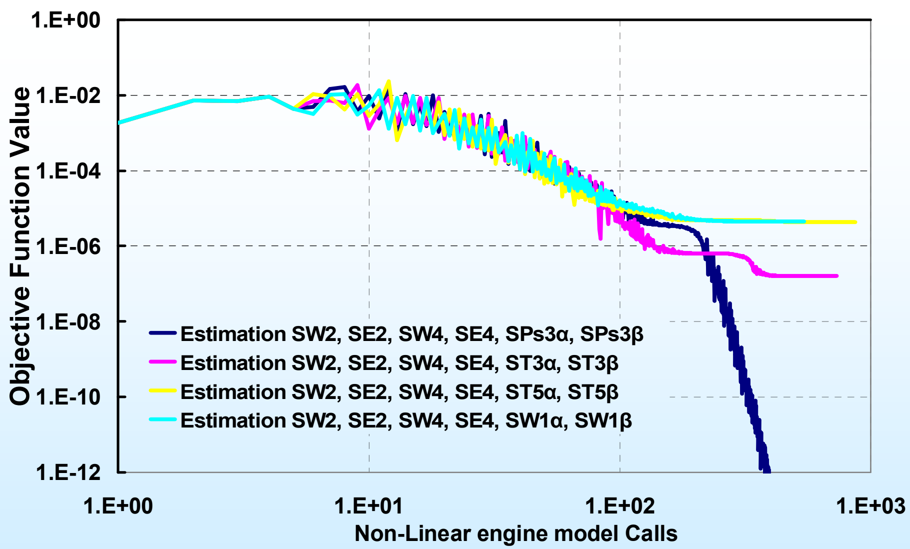
Only 1 sensor among 4 available can present malfunction at the time

A criterion for effective diagnosis:

The solution producing the minimum cost function value will considered as accurate

The procedure is repeated 4 times



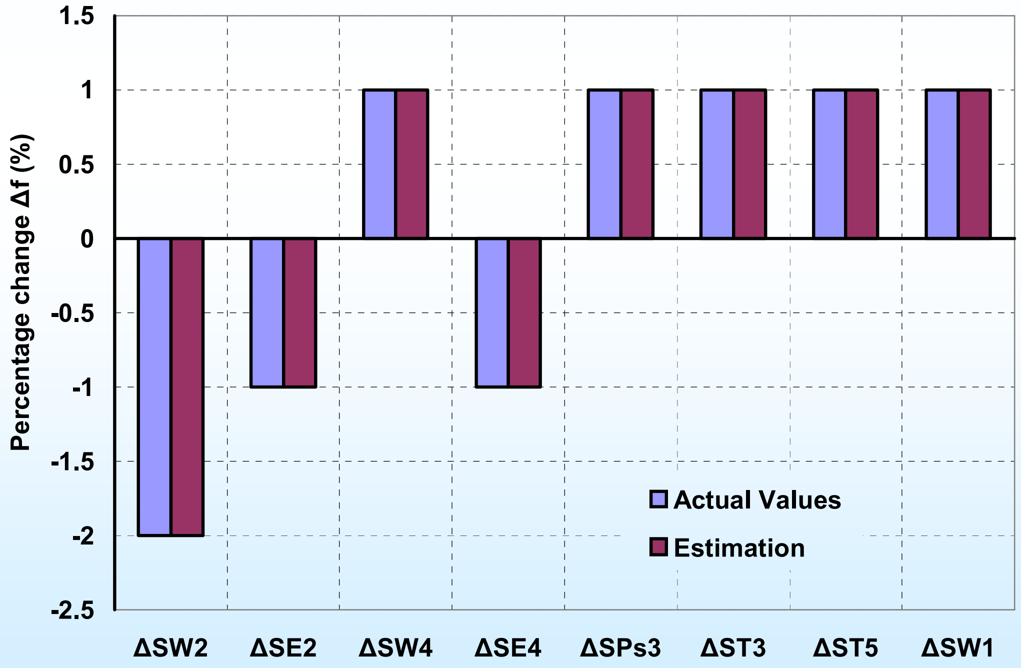


Sensor fault problem simplification

If the offset α is equal to 0, the sensor diagnosis problem is simplified with the significant reduction of the unknowns. The resulting expression is the mainly used up to date for sensor diagnosis.

$$Y_{ik}^{sens} = f_{y_{i\beta}} \cdot F_i(\mathbf{u_k}, \mathbf{f_c})$$

Application to turbojet test case

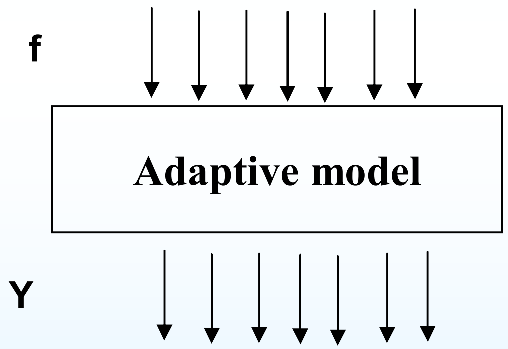


Classification of Diagnostic Problems

with respect to the relation between measurements and health parameters

Problems of MxM

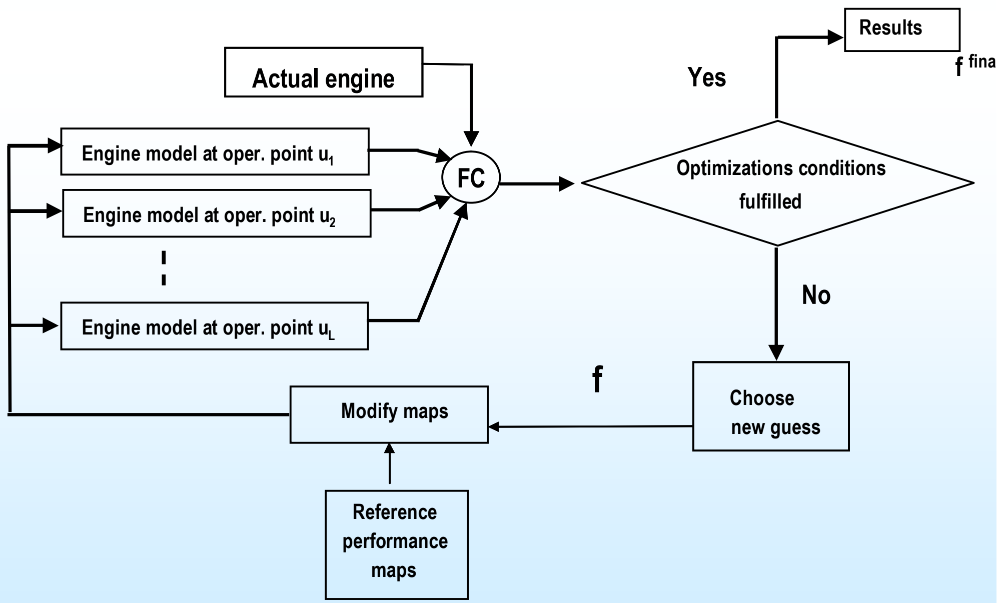
Results to a Non-Linear system of equations



$$\begin{cases} Y_1^{given} - Y_1^{est}(\mathbf{f}) = 0 \\ \vdots \\ Y_M^{given} - Y_M^{est}(\mathbf{f}) = 0 \end{cases}$$

Problems of MxN

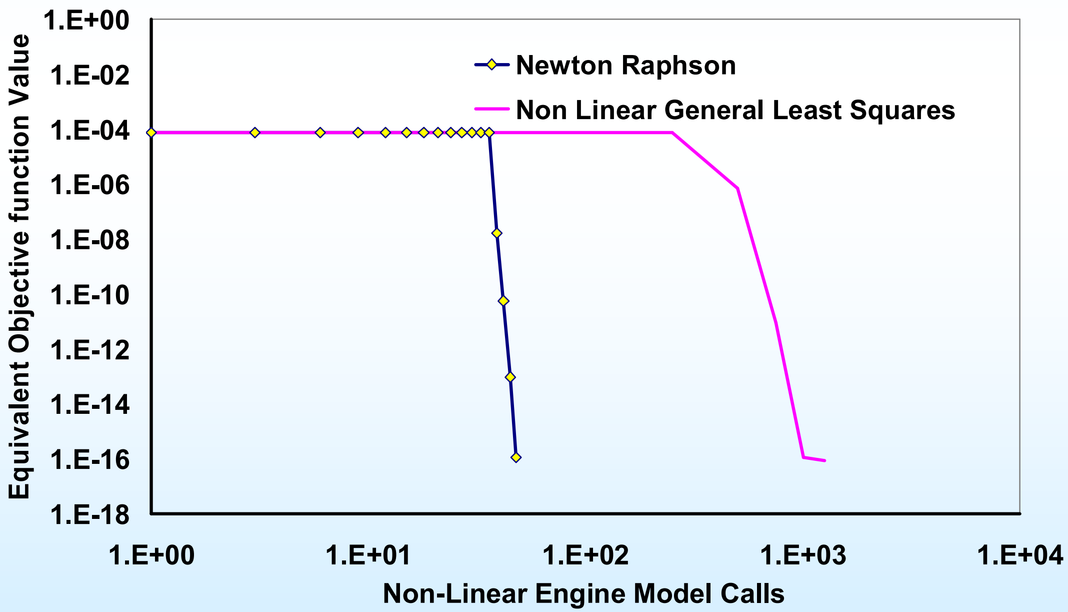
Results to a Non-Linear function minimization



Reduction of the computational cost

Selection of the appropriate measurements from the available operating points to form a square system of non-linear equations instead of cost function minimization.

Non-Linear systems are very rapidly solved with dedicated methods



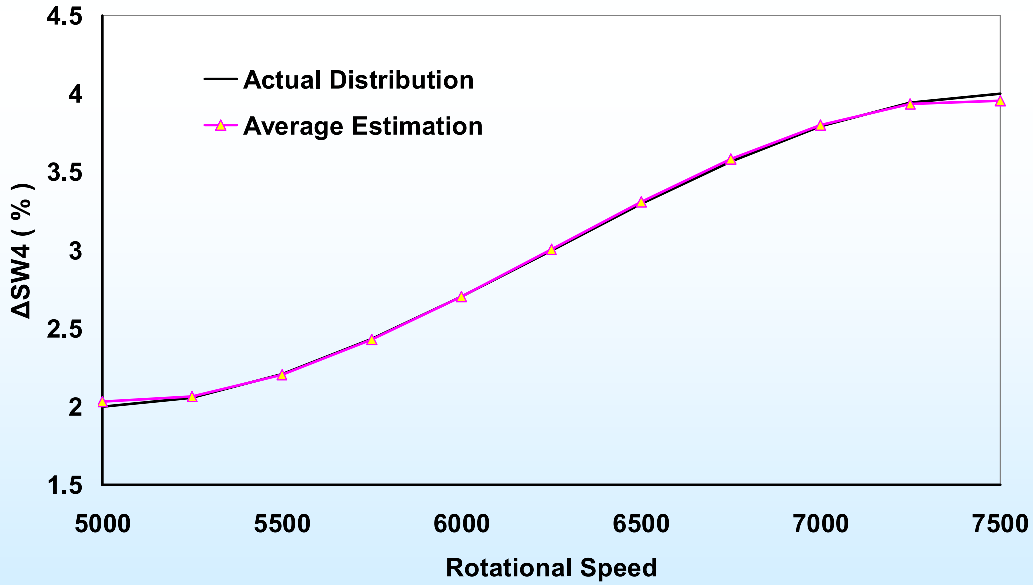
Tracking health parameters deviations manifested as function of the operating point

For the cases where health parameters deviations are considered as function of the operating point, the multipoint method can be applied.

Application test case: Turbojet

Use of noisy data

$$f_j(u_k) = \sum_{z=1}^{Z} b_{jz} \cdot u_k^{z-1}$$



Conclusions

The successful application of the non-linear multipoint method to the condition diagnosis of a turbofan engine has been demonstrated.

An extension of the multipoint method in order to be able to accommodate the simultaneous diagnosis of engine components and sensors state has been presented. Successful results from method application to the case of a turbojet engine has been presented.

A way for the significant reduction of the computational cost of multipoint procedure has been presented.

The dependence of health parameters values from the operating point has been considered and the multipoint method has been used for the detection of this variation.