Turbofan performance deterioration tracking using non-linear models and optimization techniques

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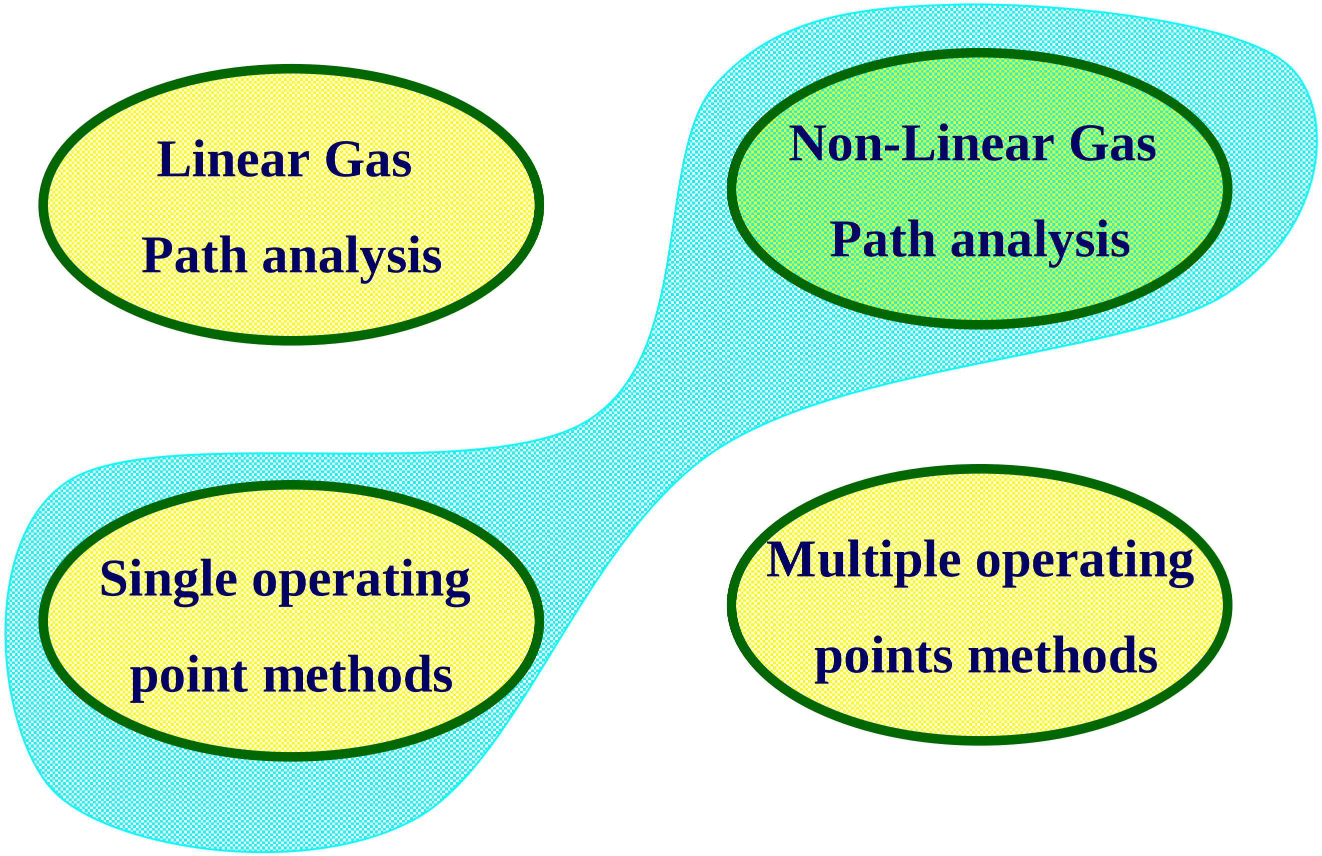
Turbofan performance deterioration tracking using non-linear models and optimization techniques

- §Key features of the method - The diagnostic problem
- §Deterioration Mechanisms
- §Overall structure of diagnostic procedure
- §A performance model as a tool supporting the diagnosis
- §Formulation of the non-linear diagnostic problem
- §Implementation of a solution algorithm
- §Results presentation
- §Discussion
- §Conclusions

Key features of the Method



Definition of the Problem

Types of Faulty Situations:

I.Engine Deterioration: all individual engine components degrade with time

II.Engine Component Faults: changes in one or more components leading to degradation of their performance

III.Individual Engine Identification: determination of the performance of all individual components of a particular engine

The present method is dealing with Problem of identifying Situation I

Deterioration Mechanisms on Compressors and Turbines

- **Tip clearance increase**
- **Air foil shape change**
- **Surface quality change**
- **Other mechanisms**

Effects on

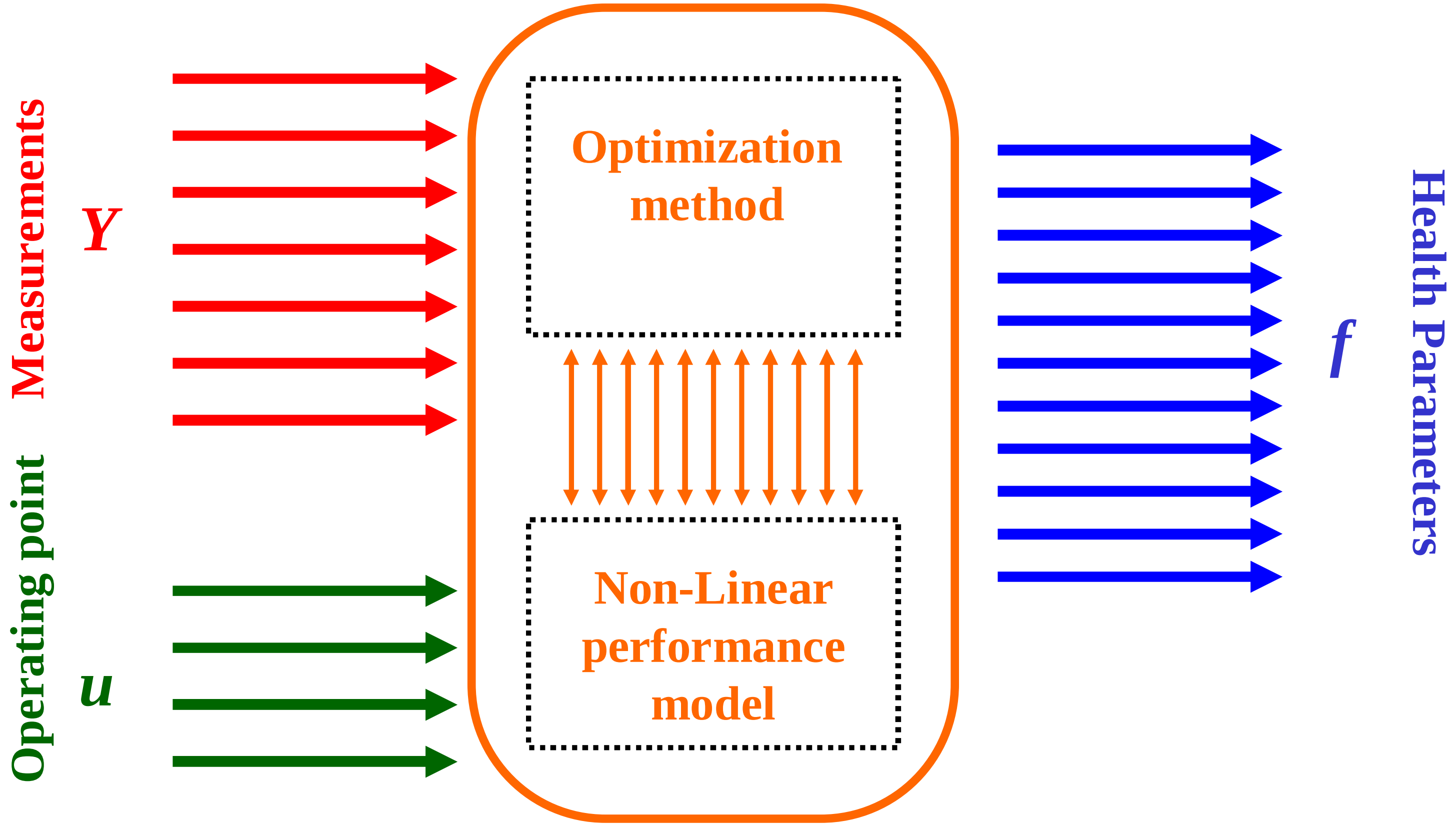
Compressors

- Decrease of pumping capacity
- Decrease of efficiency

Turbines

- Decrease or Increase of swallowing capacity
- Decrease of efficiency

Overall structure of diagnostic procedure



A performance model as a tool supporting the diagnosis (I)

Input parameters

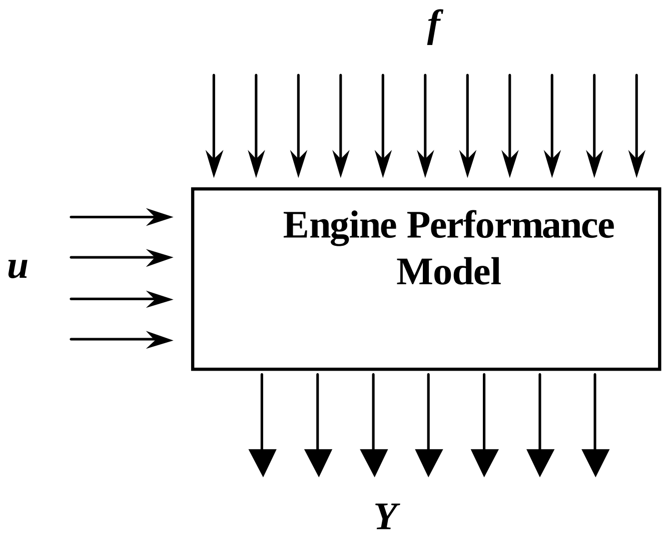
- **Quantities defining the operating condition (*u* vector)**

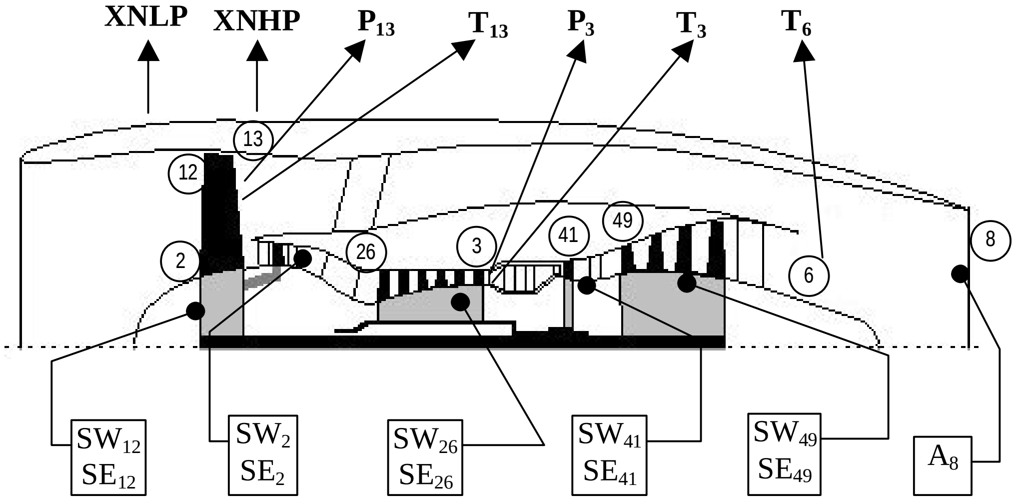
- **Quantities expressing the condition of individual components (*f* vector)**

Output parameters

- **Quantities expressing the measured variables from the engine (*Y* vector)**

A performance model as a tool supporting the diagnosis (II)





Schematic representation of an engine performance model and layout of a turbofan engine with station numbering for positions of interest.

Formulation of the non-linear diagnostic problem (I)

•Objective:

The estimation of components health parameters (vector ***f***) using the measurements (vector ***Y***) for given operating conditions (vector ***u***)

•Condition to be fulfilled

Measured quantities on the engine $\boldsymbol{Y^g(u)}$ should be reproduced by engine model $\boldsymbol{Y^{calc}=Y(u,f)}$ in the best possible way:

$$OF_Y = \sum_{i=1}^{M}\left(a_i \, \frac{Y_i^{calc} - Y_i^{g}}{Y_i^{g}}\right)^2$$

$\boldsymbol{OF_Y}$ must be minimum

Formulation of the non-linear diagnostic problem (II)

Investigation on the ability to derive solutions

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

- If $N \leq M$: Unique solution
- If $N > M$, Infinite number of solutions exists.

Formulation of the non-linear diagnostic problem (III)

Our case

Situation Considered:

N (number of health indices) > *M* (available measurements)

Additional Information exploited

•All Health parameters decrease, apart from turbine flow functions

Flow capacity –

Efficiency –

•Changes are gradual, (slow with time, no abrupt changes expected)

$$OF_f = \sum_{j=1}^{N} \left(b_j \frac{f_j - f_j^r}{f_j^r} \right)^2$$

Formulation of the non-linear diagnostic problem (IV)

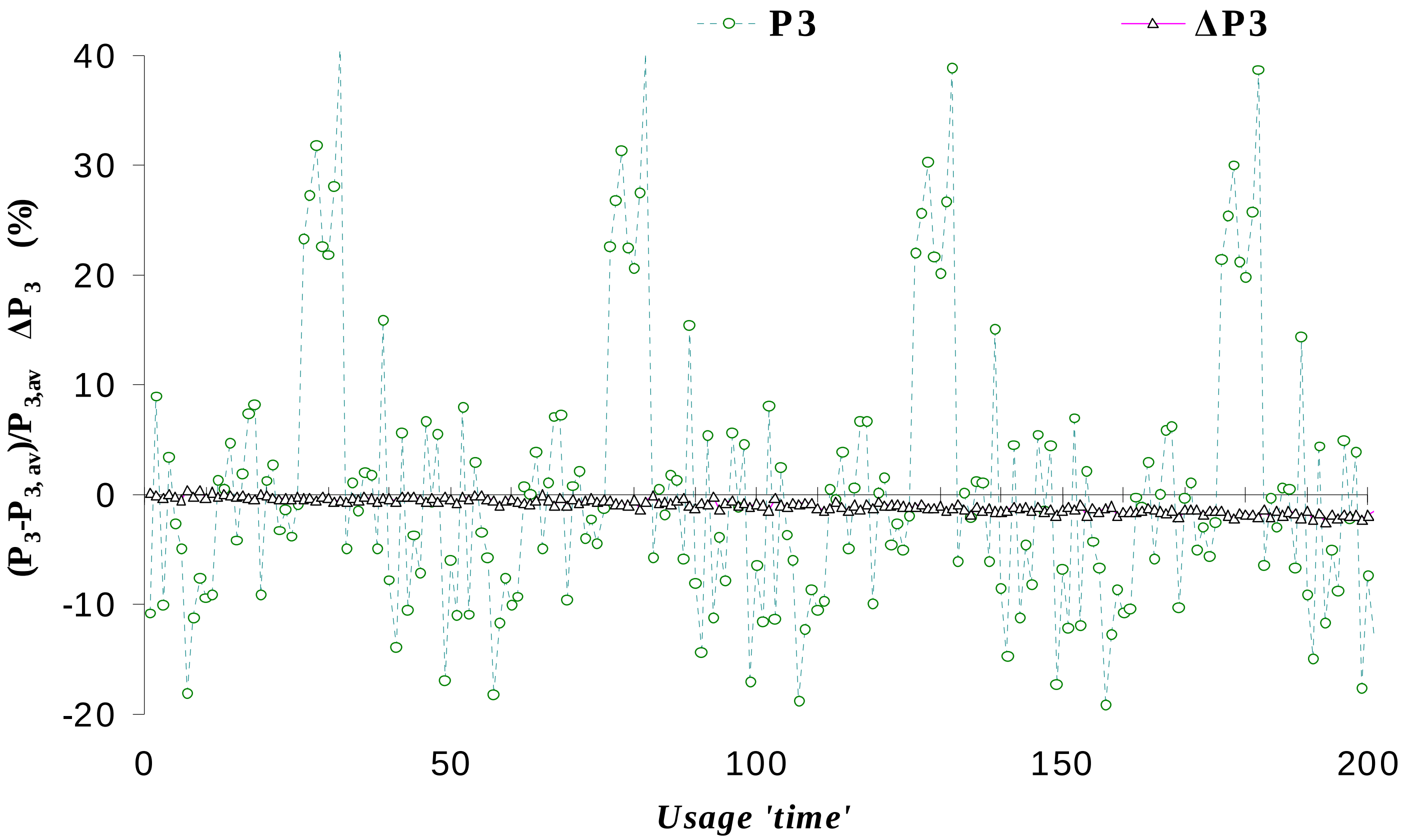
Final form of the used Objective function

$$OF = \sum_{i=1}^{M}\left[\frac{Y_i^{calc}(\boldsymbol{f}) - Y_i^g}{Y_i^g \sigma_{Y_i}}\right]^2 + C_A \cdot \sum_{j=1}^{N}\left|\frac{f_j - f_j^r}{f_j^r \sigma_{f_j}}\right| + C_S \cdot \sum_{j=1}^{N}\left[\frac{f_j - f_j^r}{f_j^r \sigma_{f_j}}\right]^2$$

- **Inclusion of three groups of terms with weight factors**
- **Inclusion of Standard deviations σ_Y, σ_f**
- **First guess for f^r is f^0 from "healthy" engine**

Implementation of a solution algorithm (I)

Why apply smoothing on measurements deltas ?



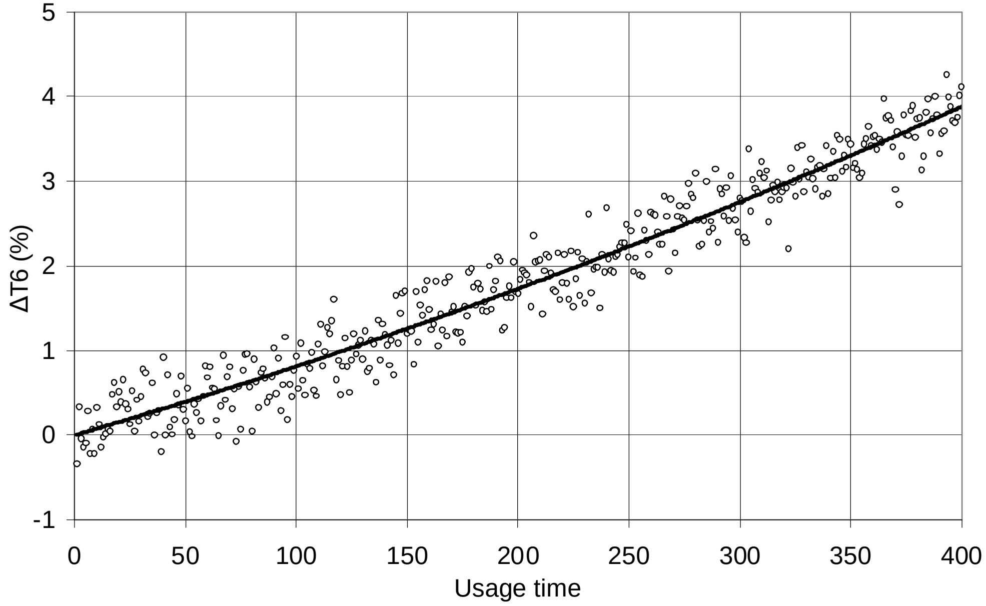
Implementation of a solution algorithm (II)

•Smoothing procedure

Definition of Deltas

$$DU = 100 \times \frac{U - U^0}{U^0}$$

Smoothing the deltas



Smoothed measurements reproduction

$$Y_i^{smooth} = Y_i^0 \cdot \left(1 + \frac{\Delta Y_i^{smooth}}{100}\right)$$

Implementation of a solution algorithm (III)

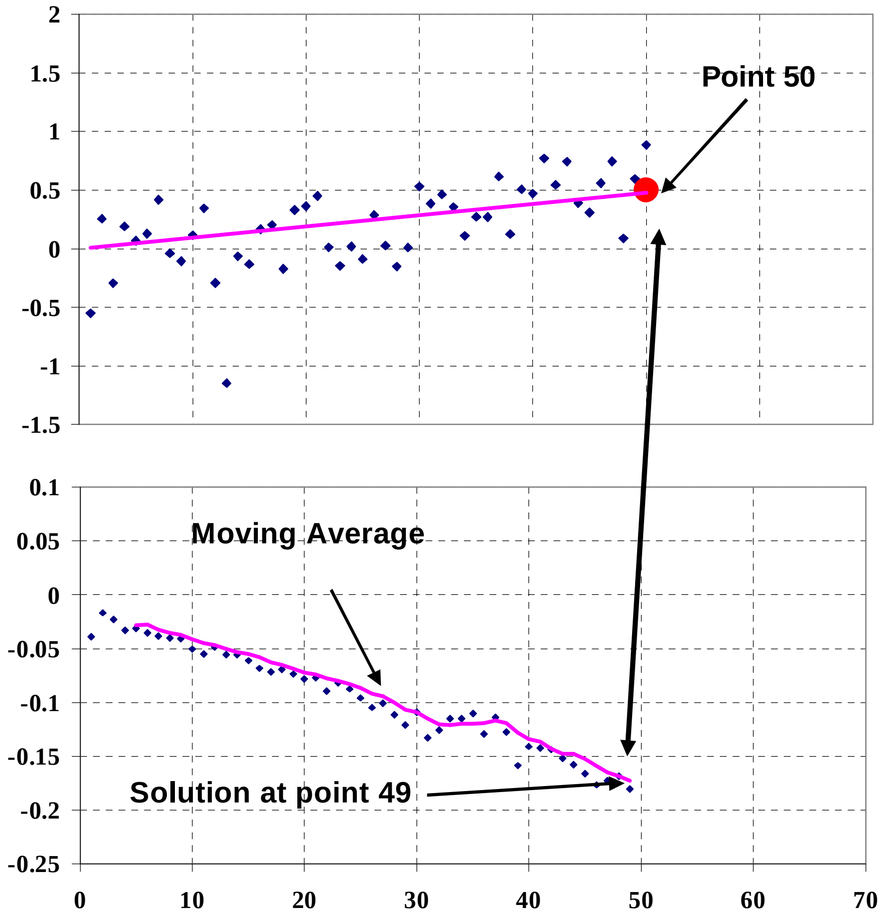
- **Choice of reference values f^r**

  Appropriate selection of f^r : *Crucial for accurate estimation*

- Initial guess for f^r: The values referred to "healthy" engine f^0

- Successive update of f^r based on the derived estimations

Implementation of a solution algorithm (IV)

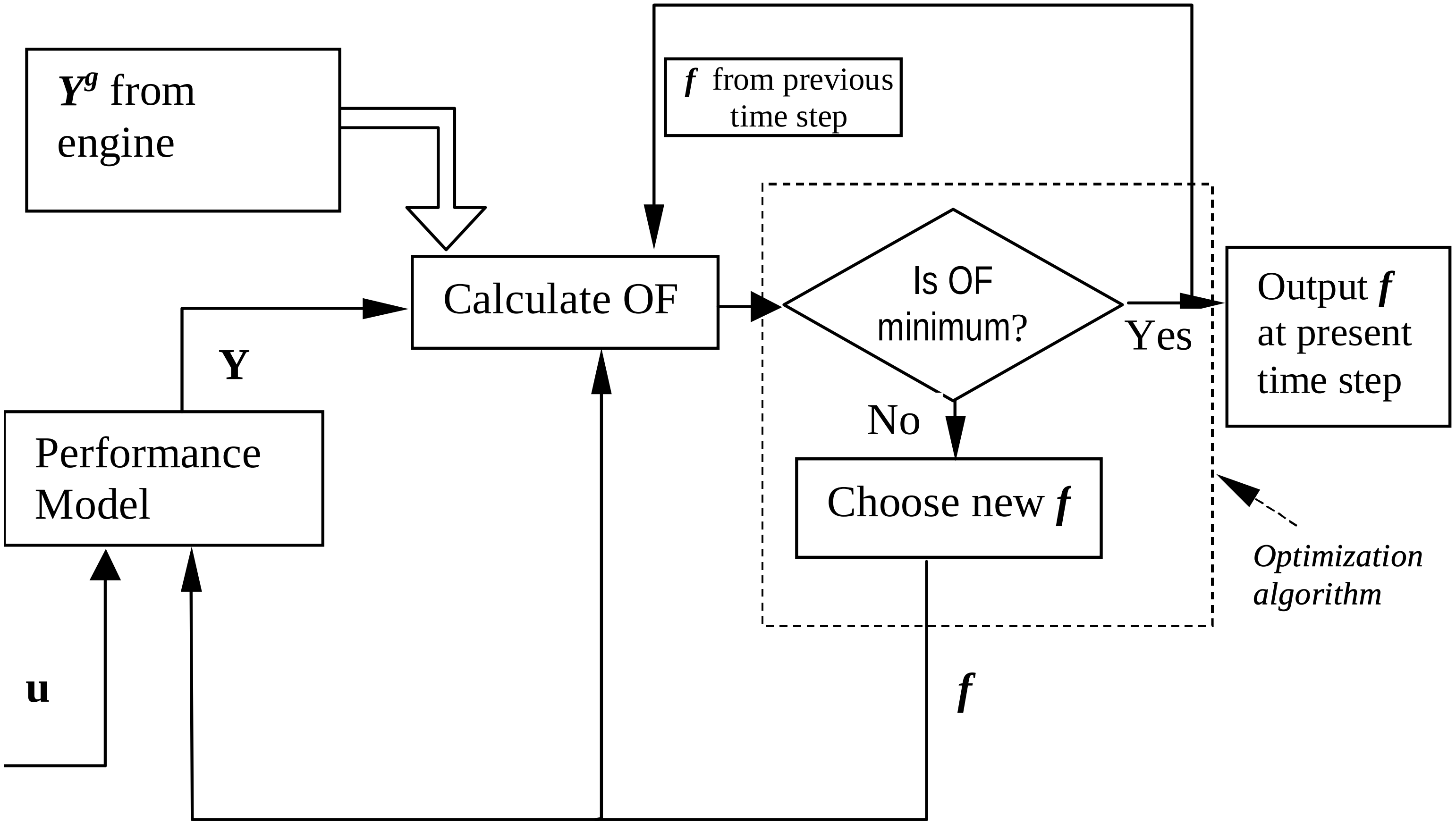


Inputs: Measurements

Output: Parameters

Implementation of a solution algorithm (V)

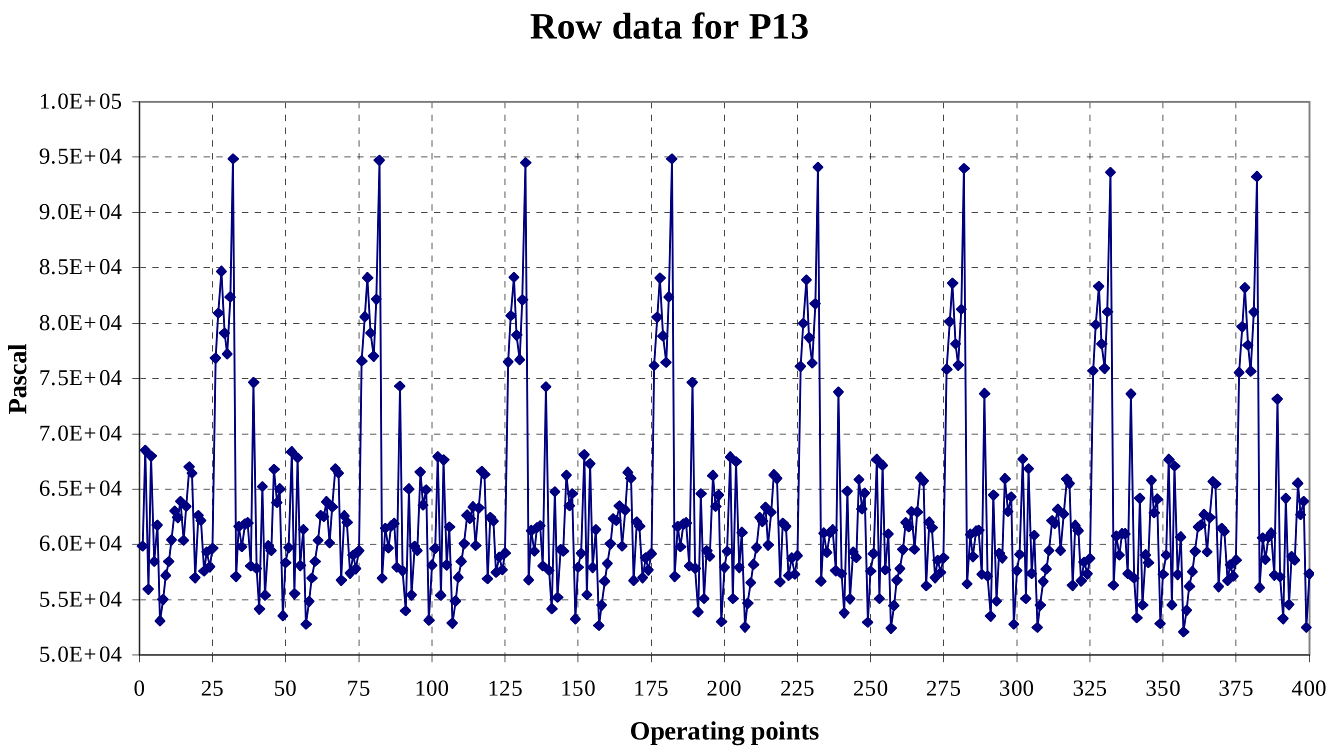
•Procedure for Derivation of “health” Parameters



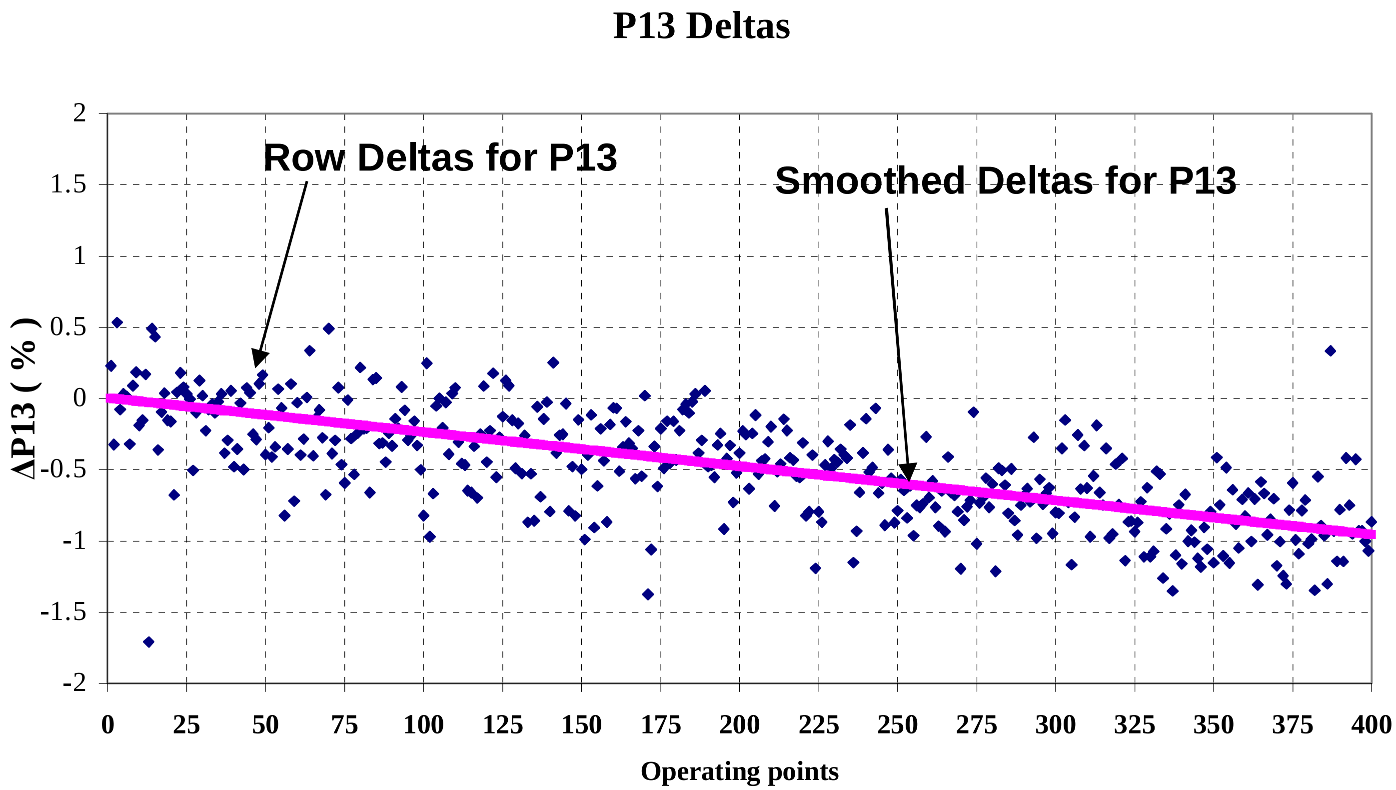
Sample Results from method implementation

- **Raw Data used**
- **Deltas and their smoothing**
- **Health parameters evolution**
- **Estimations at the final point**
- **Assessment of diagnostic ability**

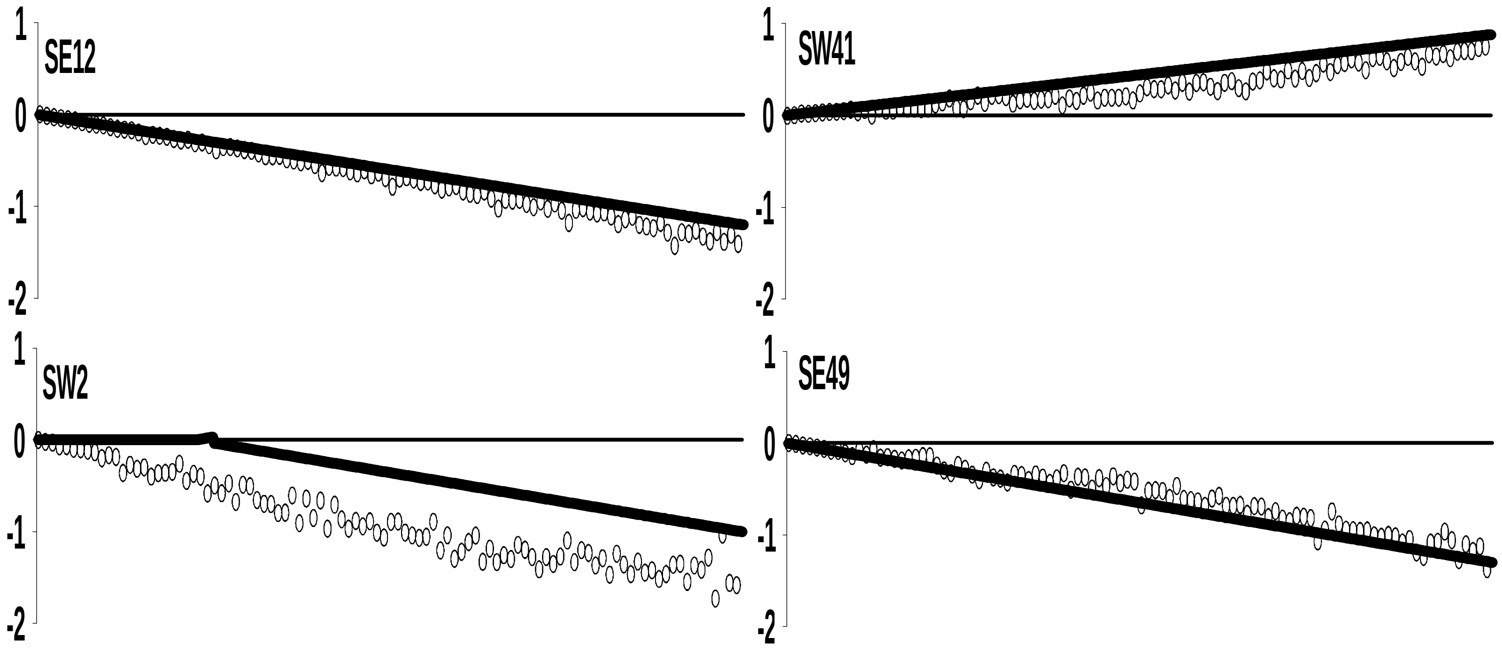
Row data used



Deltas and their smoothing

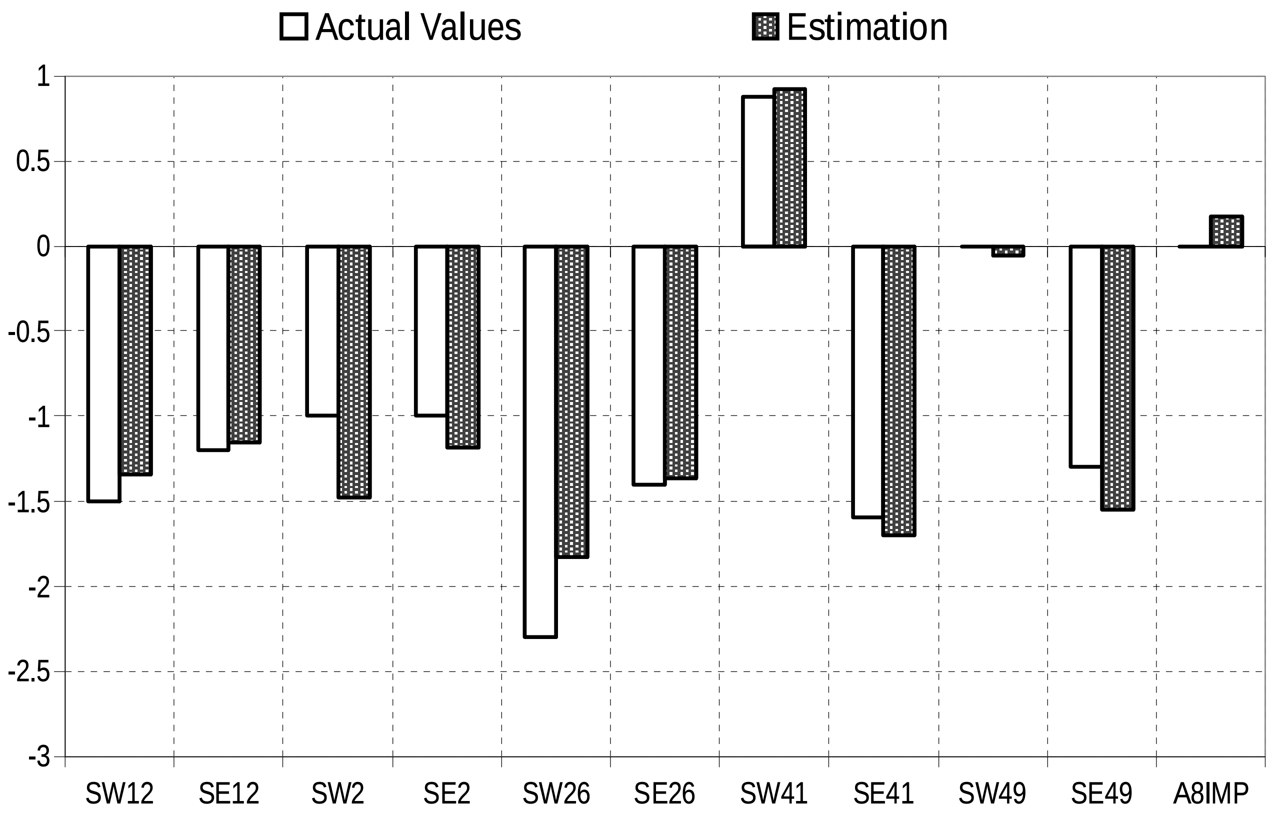


Health parameters evolution



Time evolution of estimated health parameters

Estimations at the Final point

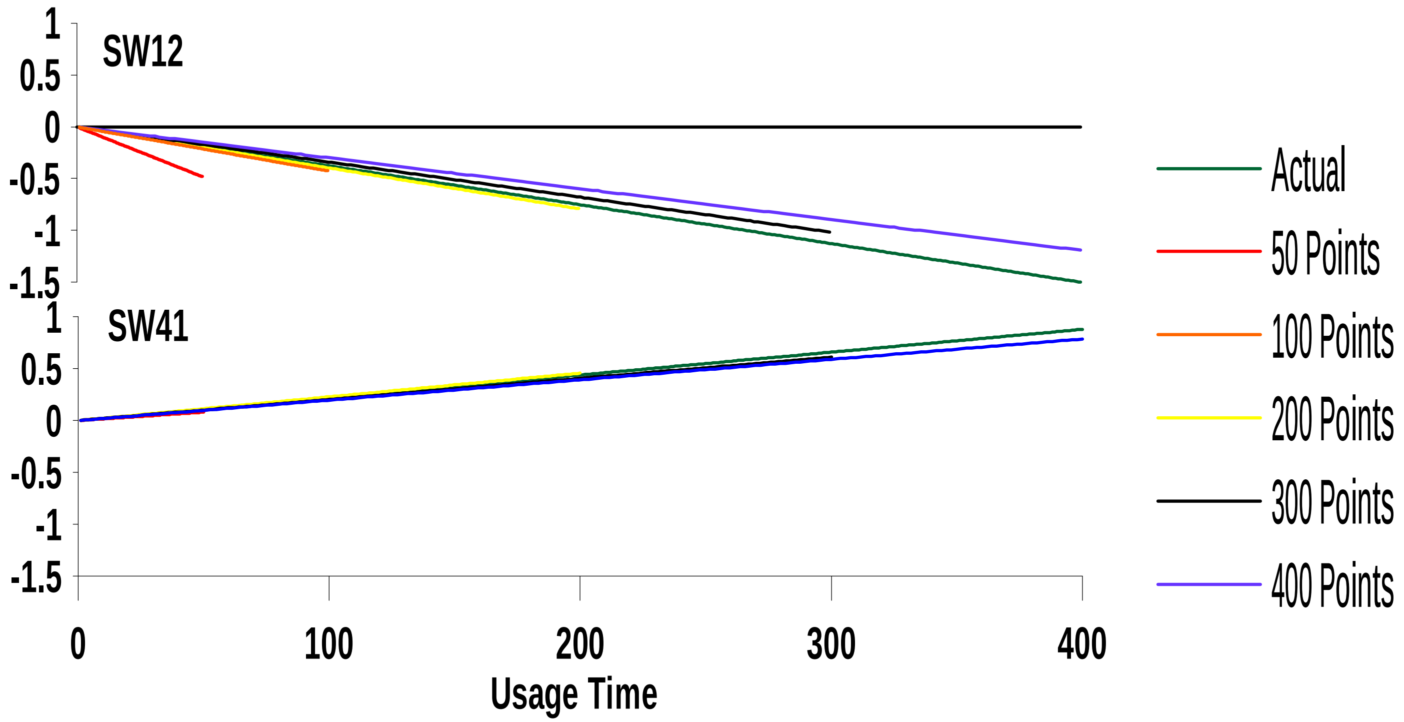


Assessment of Diagnostic Ability for individual parameters

Disturbed Parameter	Estimated values										
	SW12	**SE12**	**SW2**	**SE2**	**SW26**	**SE26**	**SW41**	**SE41**	**SW49**	**SE49**	**A8IMP**
f1 : **SW12**	-1.006	0	-0.001	0	0	0	-0.001	0	0	-0.001	-0.006
f2 : **SE12**	0	-1.000	0	0	0	0	0	0	0	0	0.001
f3 : **SW2**	-0.127	0	-0.051	-0.006	-0.453	-0.145	0.054	-0.002	-0.389	-0.003	-0.104
f4 : **SE2**	0	0	-0.824	-0.338	-0.280	-0.277	-0.001	-0.001	0.250	-0.004	0.000
f5 : **SW26**	-0.001	0	-0.001	0	-0.999	0	0	0	0.001	0.000	-0.001
f6 : **SE26**	0	0	-0.001	0	0	-1.000	0	0	0	-0.001	0
f7 : **SW41**	-0.001	-0.005	0	0	0	0	-1.000	0	0	0	-0.002
f8 : **SE41**	0	-0.005	-0.007	0	0	0	-0.001	-0.955	-0.081	-0.047	-0.003
f9 : **SW49**	0	0	0	0	0	0	0	0	-0.999	-0.001	0.001
f10 : **SE49**	-0.006	0	-0.001	0	0	0	-0.001	-0.002	0.004	-0.999	-0.006
f11 : **A8IMP**	0	0	0	0	0	0	0	0	0	0	-1.000

Diagnostic Response matrix

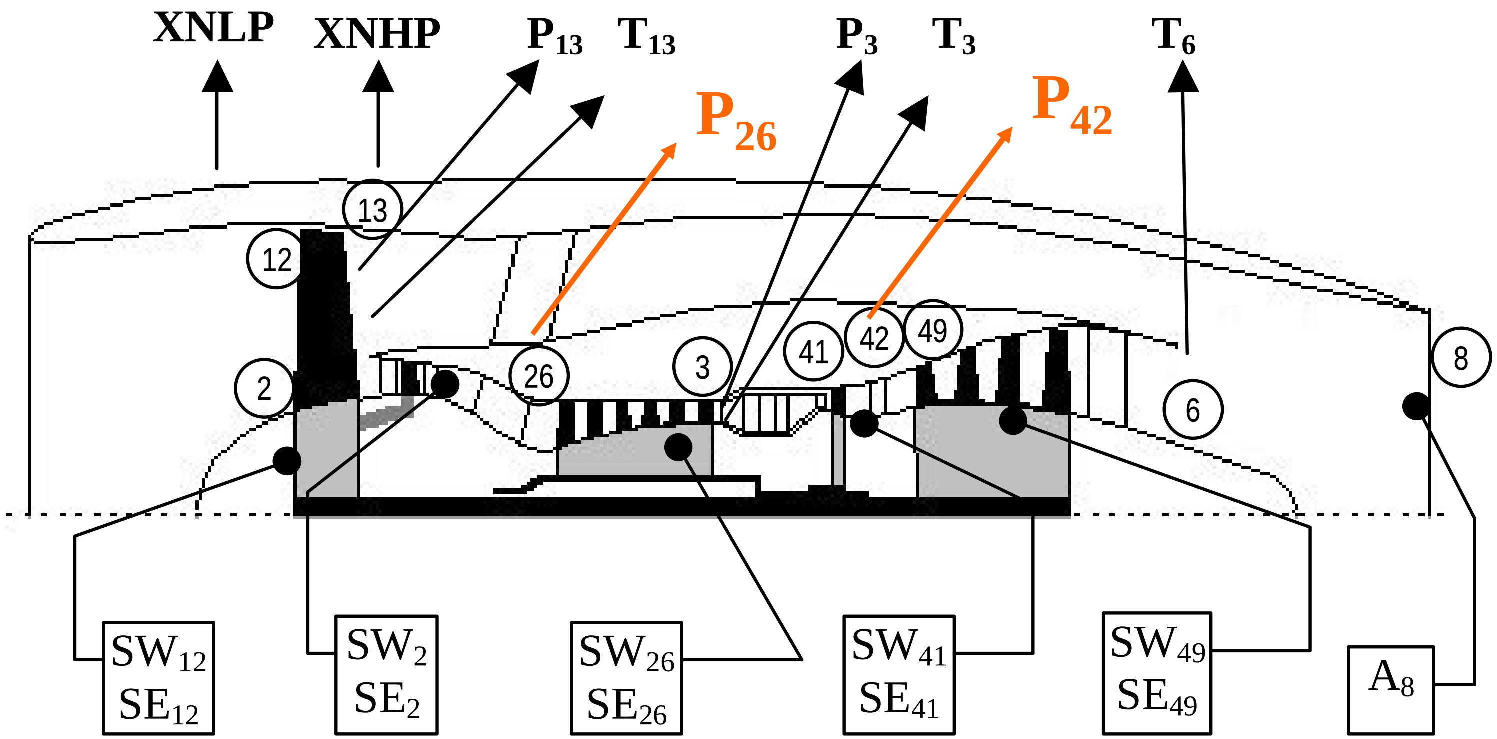
Estimations for increasing number of available points



Effectiveness improves with number of points

Augmented Measurement set

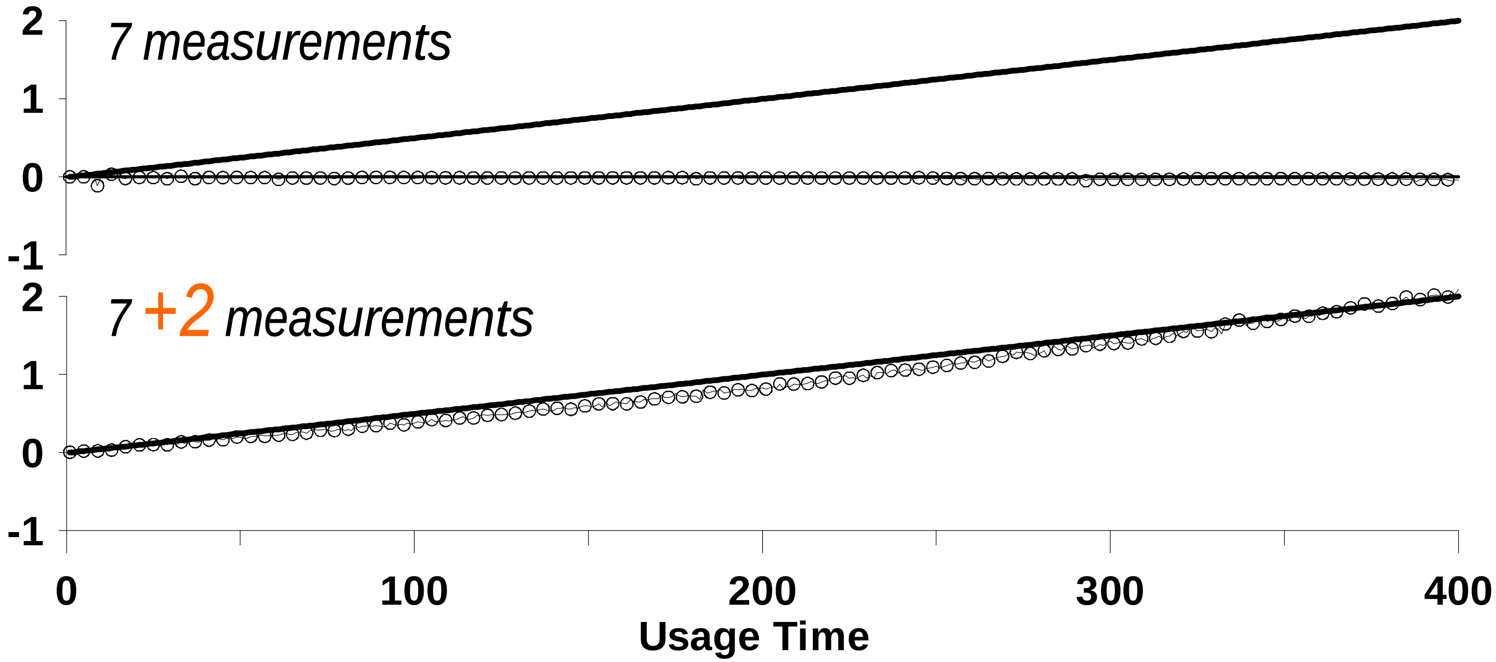
(to Increase of identification capability)



Extension of measurement set

Improved Estimation Capability

with augmented measurement set



Example: SW49 Low Pressure Turbine swallowing capacity

Conclusions

- An efficient method for the detection of engine deterioration has been presented.
- Main feature of the method: ability to derive accurate estimations for health parameters even if limited information is available.
- Key features for the success of the method: appropriate smoothing and parameter update.
- The method is able to detect at an early stage the engine deterioration.
- The method can be used to produce a performance model adapted to a particular engine in its current condition