OPTIMIZING DIAGNOSTIC EFFECTIVENESS OF MIXED TURBOFANS BY MEANS OF ADAPTIVE MODELLING AND CHOICE OF APPROPRIATE MONITORING PARAMETERS

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PURPOSE OF THE WORK

Provide procedures to support selection of appropriate combinations of "health" parameters and measured quantities, in order to optimize the possibility of diagnosing the condition of a turbofan engine

The Principle of GPA Diagnostics

- **Basic relation between measurements and component parameters:**

$$\mathbf{Y} = \mathbf{F}(\mathbf{u},\mathbf{f}) \quad \overset{given \quad operating \quad point}{\Longrightarrow} \quad \mathbf{Y} = \mathbf{F}(\mathbf{f})$$

- **Diagnostic problem :** $\mathbf{f} = \mathbf{F}^{-1}(\mathbf{Y})$

LINEAR METHODS (I)

Based on Determination of Deviations

- **Deviations**
  - Parameters: $$\Delta f_j = \frac{f_j - f_j^{ref}}{f_j^{ref}} \times 100$$
  - Measurements: $$\Delta Y_i = \frac{Y_i - Y_i^{ref}}{Y_i^{ref}} \times 100$$

LINEAR METHODS (II)

Linearized Relations between Deviations

$$\begin{pmatrix} \Delta Y_1 \\ \Delta Y_2 \\ \\ \Delta Y_i \\ \\ \Delta Y_m \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{1j} & a_{1n} \\ a_{21} & a_{22} & a_{2j} & a_{2n} \\ \\ a_{i1} & a_{i2} & a_{ij} & a_{in} \\ \\ a_{m1} & a_{m2} & a_{mj} & a_{mn} \end{pmatrix} \cdot \begin{pmatrix} \Delta f_1 \\ \Delta f_2 \\ \\ \Delta f_j \\ \\ \Delta f_n \end{pmatrix}$$

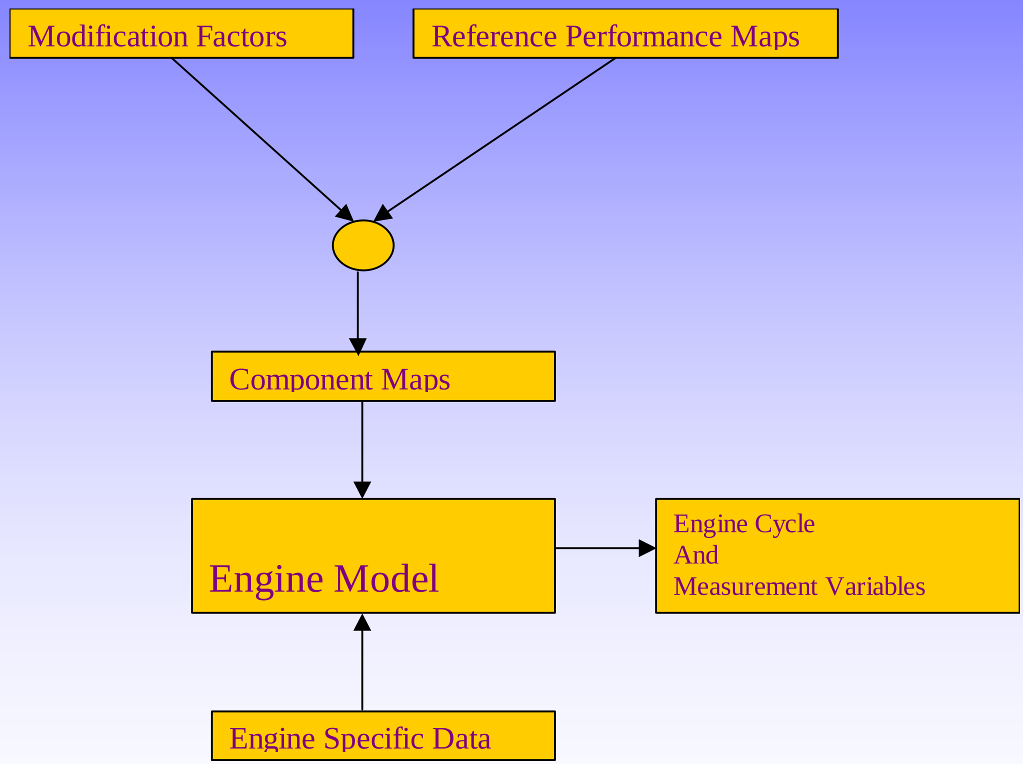
$$\boldsymbol{\Delta Y = J \cdot \Delta f}$$

J is the Jacobian matrix.

NON-LINEAR METHODS: ADAPTIVE MODELLING (I)

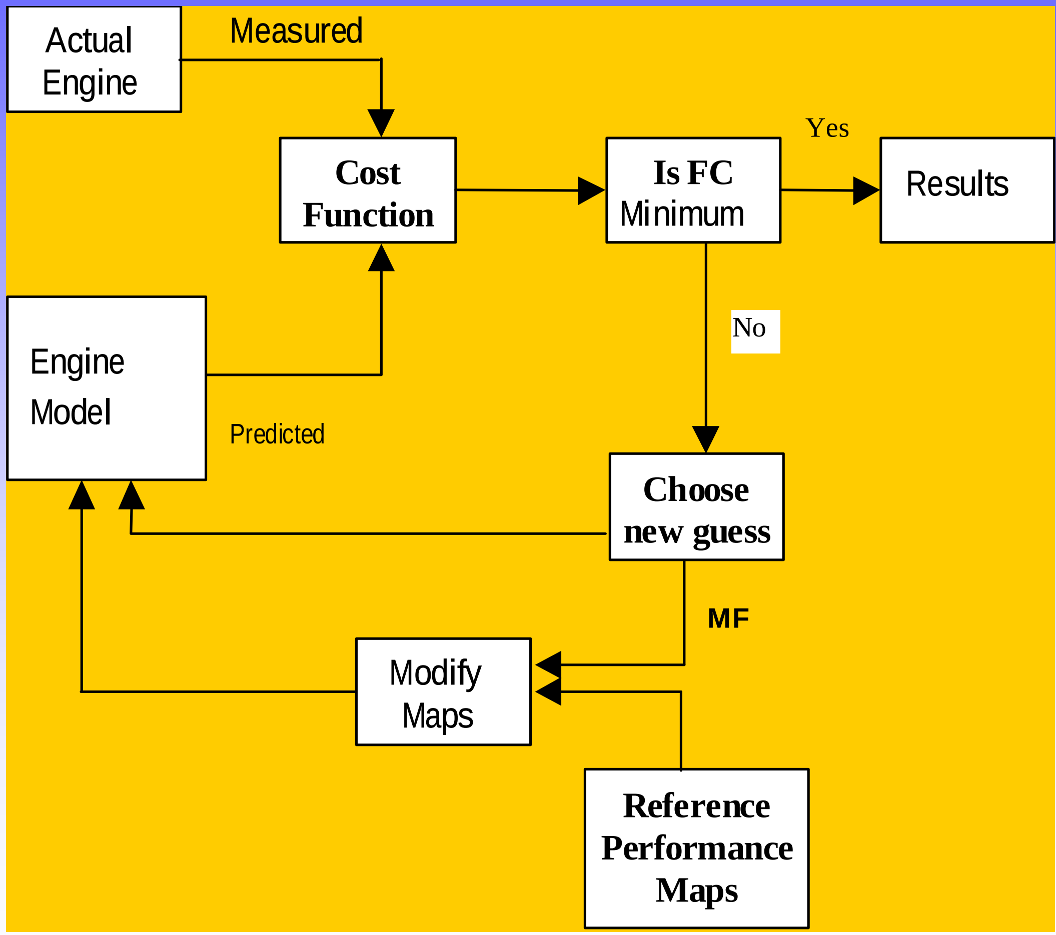
Modification Factors

$$MF = \frac{X_{act}}{X_{ref}}$$



NON-LINEAR METHODS: ADAPTIVE MODELLING (II)

Adaptation to Measurement Data



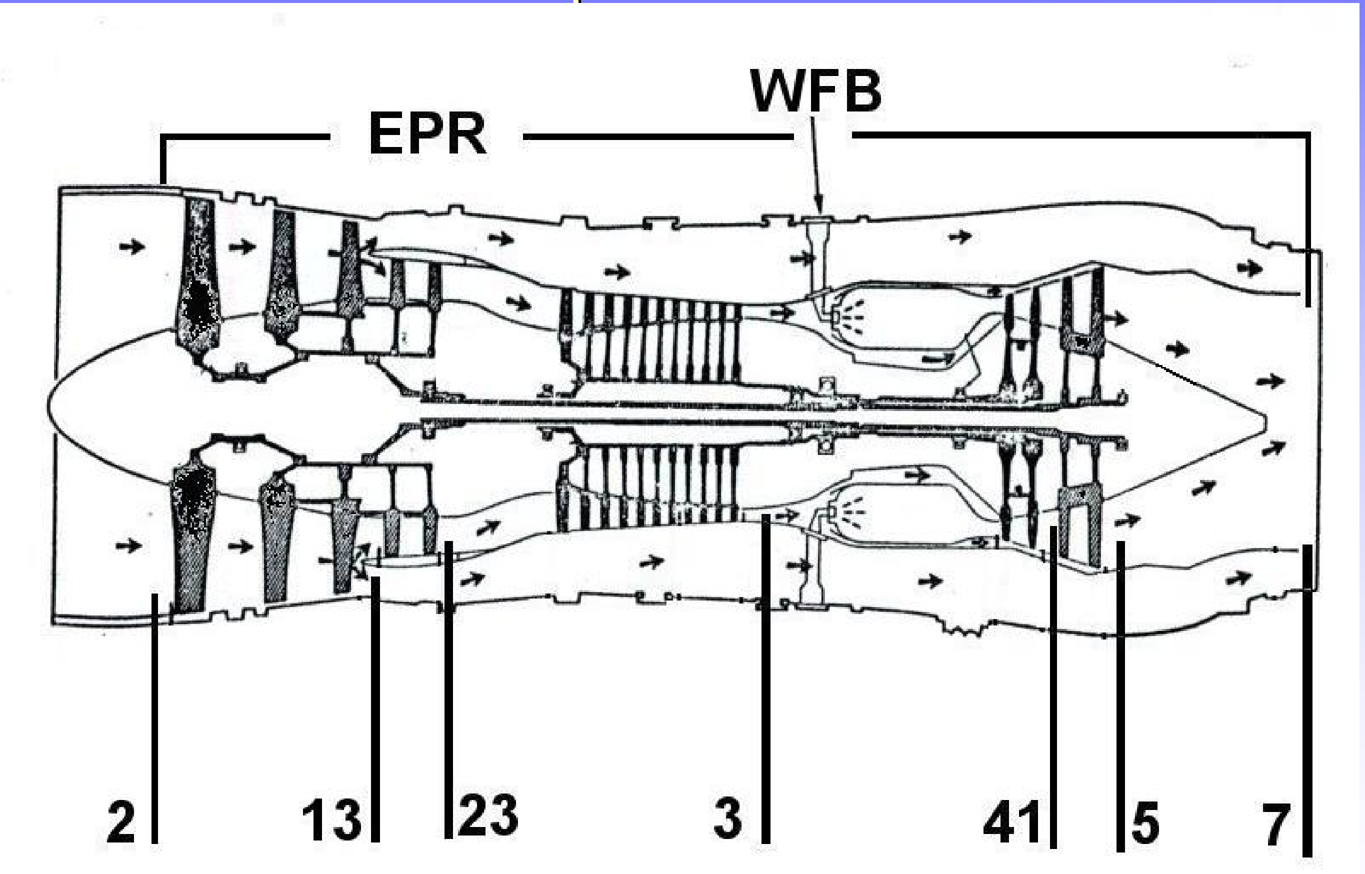
Questions to be answered

- For an engine represented through given set of health parameters, which is the best combination of measurements providing sufficient diagnostic information?

- For an available set of measurements, taken from an operating engine, which is the best combination of health parameters to be estimated?

TEST CASE FOR DEMOSTRATION OF PRESENTED METHODS

A twin spool mixed turbofan



HEALTH PARAMETERS FOR TURBOFAN (I)

Definition

- **Flow capacity:**

$$f_j = \left(\frac{W\sqrt{J}}{\delta}\right)_{actual} \Bigg/ \left(\frac{W\sqrt{J}}{\delta}\right)_{reference}$$

- **Efficiency:**

$$f_j = \eta_{actual} / \eta_{reference}$$

FULL SET OF HEALTH PARAMETERS for engine components

	Considered Health Parameters for mixed turbofan	
	Symbol	Description
1	f_1	Flow capacity factor at FAN
2	f_2	Efficiency factor at FAN
3	f_3	Flow capacity factor at IPC
4	f_4	Efficiency factor at IPC
5	f_5	Flow capacity factor at HPC
6	f_6	Efficiency factor at HPC
7	f_7	Flow capacity factor at HPT
8	f_8	Efficiency factor at HPT
9	f_9	Flow capacity factor at LPT
10	f_{10}	Efficiency factor at LPT

MEASUREMENTS SELECTION

Sensitivity of measurements

- **Most appropriate the measurements with the greater sensitivities**

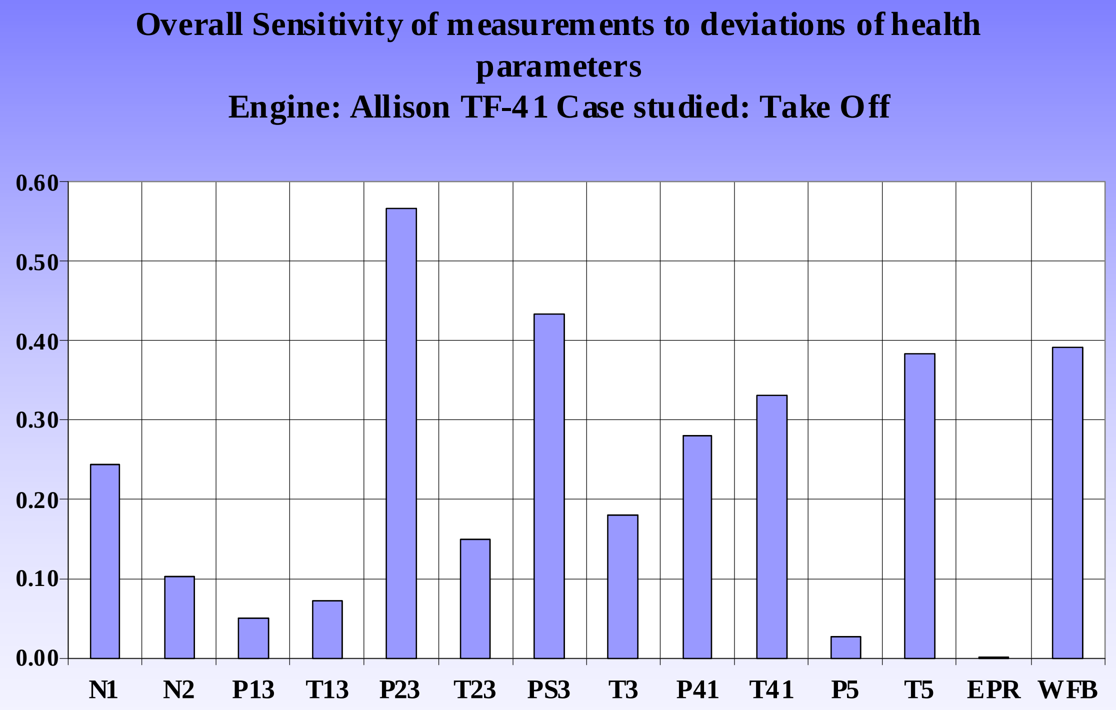
  - On individual parameters: $$\Delta Y_i^{\,j} = \frac{Y_i^{\,j} - Y_i^{ref}}{Y_i^{ref}} \times 100$$

  - Overall: $$S\Delta Y_i = \left[\frac{1}{n} \cdot \sum_{j=1}^{n} \left[\Delta Y_i^{\,j} \right]^2 \right]^{1/2}$$

Necessary condition: Linear Independence

Measurements Selection

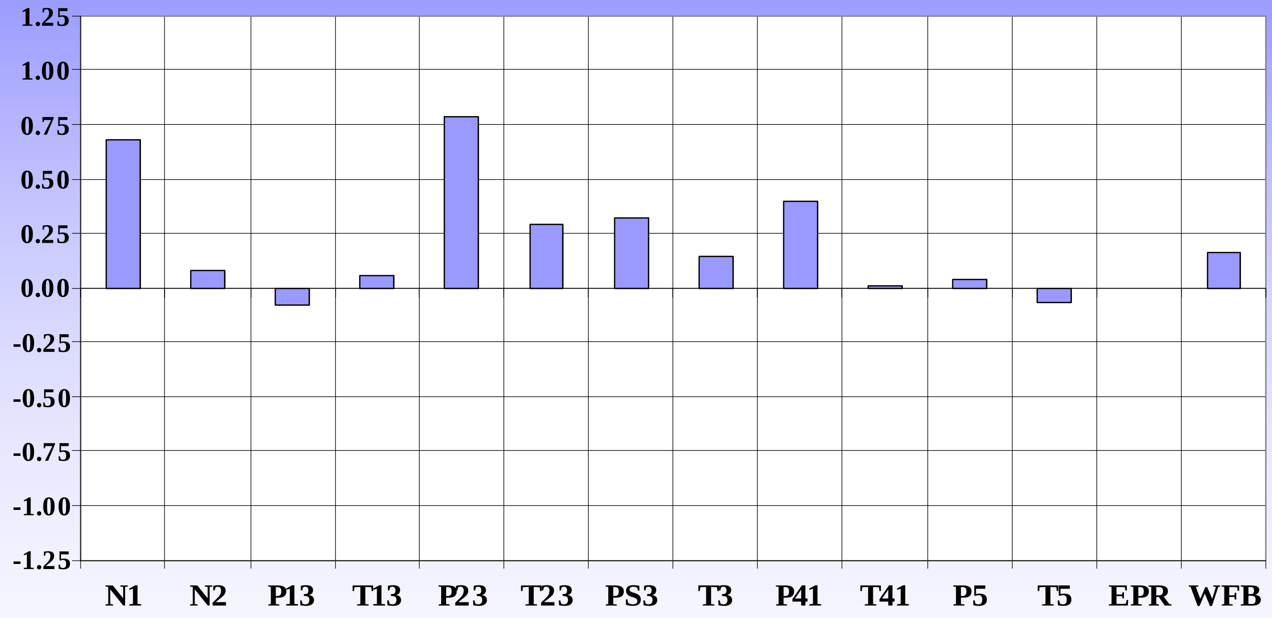
- **Overall sensitivity of each measurement to all health parameters**



- ***Most sensitive measurements : P_{23}, P_{S3}, WFB, T_5, T_{41}, P_{41}, N_1, T_3, T_{23} and N_2.***

SENSITIVITY OF MEASUREMENTS to deviation of flow capacity of Fan

Sensitivity of measurements when health parameter f1 deviates -1% from reference
Engine: Allison TF-41 Case studied: Take Off



Most sensitive P_{23}, N_1, P_{41}, P_{S3}, T_{23} and WFB. Measurements like P_5, T_{41} not suitable.

CONDITION NUMBER OF JACOBIAN
Examination of rows

$$Ncombi = \binom{m}{n} = \frac{m!}{n! \cdot (m-n)!}$$

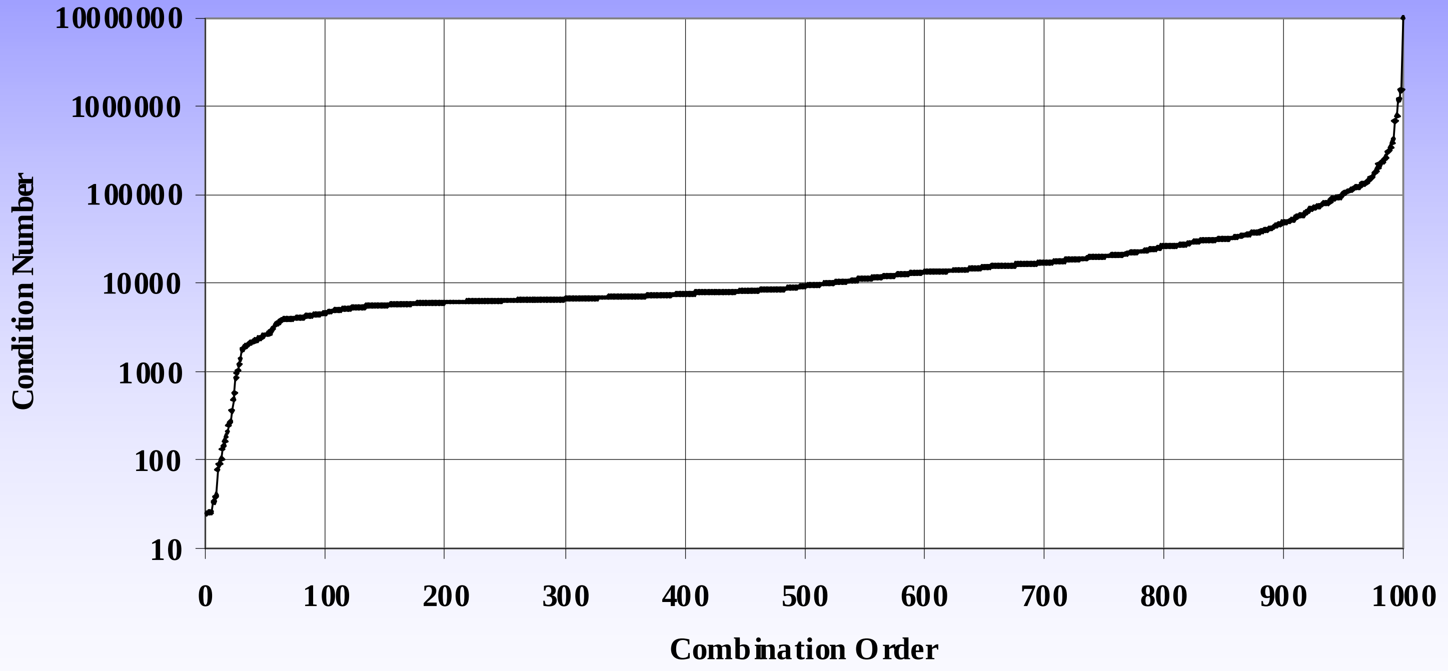
- ***mxn*** **Jacobian formed.**
- **All possible square sub-matrices formed.**
- **Condition number of each sub-matrix is evaluated.**
- **Results are sorted in ascending order**

Engineering Judgment on the outcome

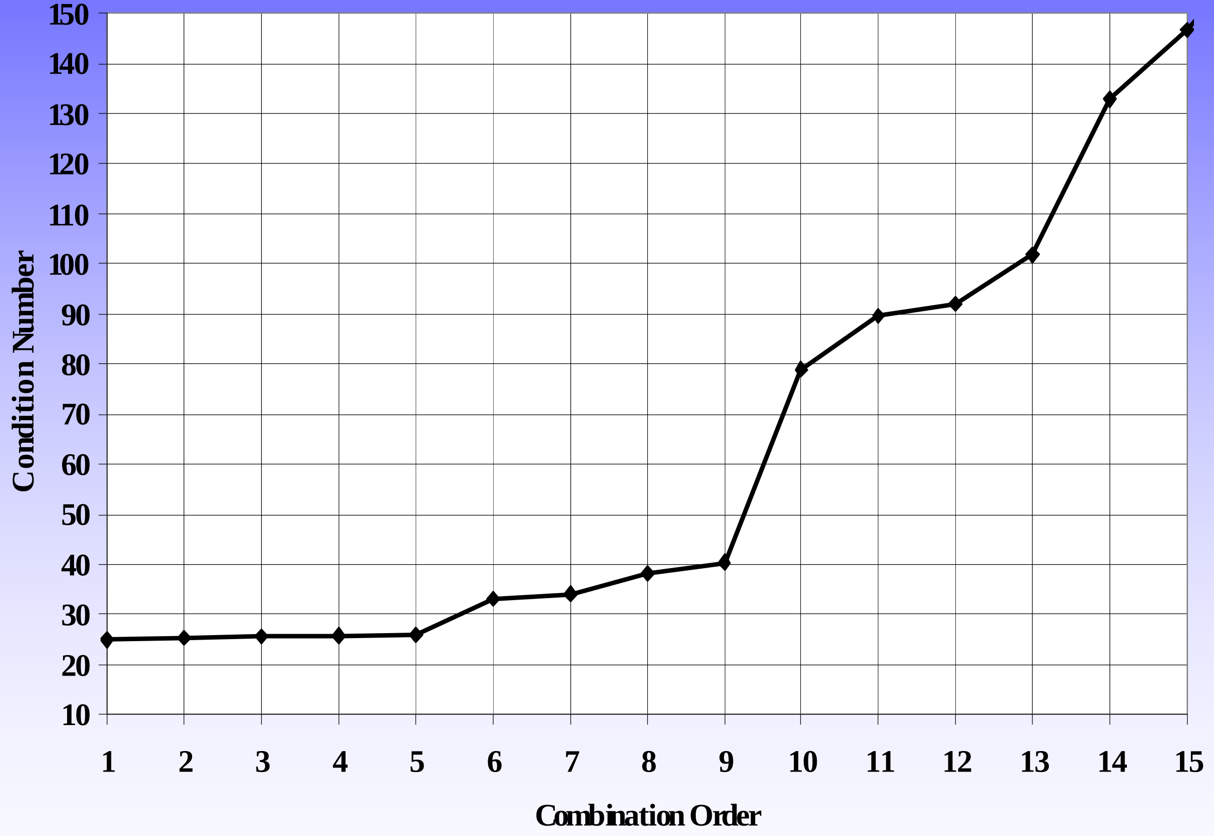
(E.G. Desire to measure in the cold section of an engine)

Condition Number values for all combinations.

Condition number of Jacobians which are formed using all the possible combinations of 14 measurements taken 10 at time



THE SMALLEST CONDITION NUMBERS



CORRESPONDING MEASUREMENT SETS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
N_1															
N_2															
P_{13}															
T_{13}															
P_{23}															
T_{23}															
P_{S3}															
T_3															
P_{41}															
T_{41}															
P_5															
T_5															
EPR															
WFB															

MEASUREMENT INTERRELATIONS

Method Developed by Provost (1994)

	N1	N2	P13	T13	P23	T23	PS3	T3	P41	T41	P5	T5	EPR	WFB
N1	0	78	70	85	62	57	75	85	60	66	74	61	87	70
N2	78	0	59	66	71	90	63	55	87	79	61	80	87	88
P13	70	59	0	85	87	83	60	66	78	77	9	81	77	79
T13	85	66	85	0	81	71	87	65	83	70	84	75	87	69
P23	62	71	87	81	0	33	85	79	58	85	87	87	77	86
T23	57	90	83	71	33	0	89	84	54	77	83	87	79	83
PS3	75	63	60	87	85	89	0	51	79	70	62	72	75	83
T3	85	55	66	65	79	84	51	0	86	83	64	82	88	72
P41	60	87	78	83	58	54	79	86	0	81	80	75	84	80
T41	66	79	77	70	85	77	70	83	81	0	86	11	45	25
P5	74	61	9	84	87	83	62	64	80	86	0	90	70	70
T5	61	80	81	75	87	87	72	82	75	11	90	0	43	21
EPR	87	87	77	87	77	79	75	88	84	45	70	43	0	38
WFB	70	88	79	69	86	83	83	72	80	25	70	21	38	0

HEALTH PARAMETERS SELECTION

- **For a given set of measured quantities, Parameters Chosen such that:**
  - There is minimum uncertainty in their evaluation
  - They are in agreement with existing experience

SINGULAR VALUE DECOMPOSITION ANALYSIS Of Jacobian Matrix

- **Jacobian with**
  - *m* rows corresponding to measurements
  - *n* columns (*n*>*m*) corresponding to health parameters.

- **1. *mxn* Jacobian is formed.**
- **2. Decomposed using SVD analysis**
- **3. Singular values shorted in descending order**

Results are inspected to select combinations with maximum projections.

Condition number of Jacobian Examination of columns

- **Approach based on condition number of Jacobian can also be used for parameter selection.**

-mxn Jacobian is formed.

-All possible square sub-matrices of Jacobian are formed.

- Condition number of Each sub-matrix evaluated.

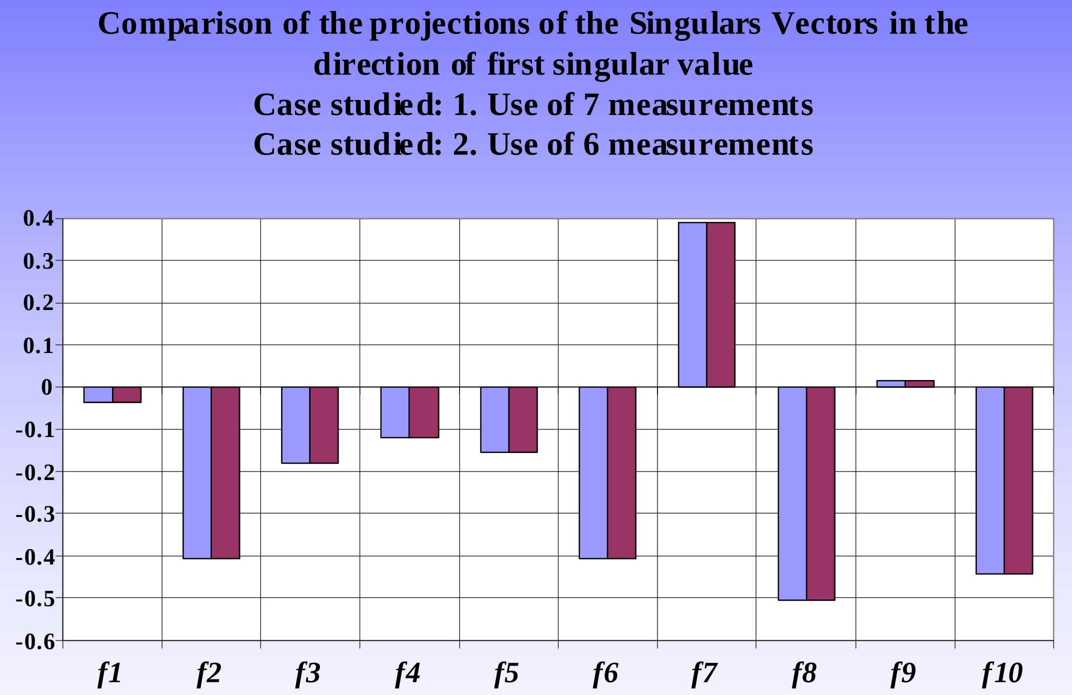
-Results are sorted in ascending order of condition number.

The smaller the condition number, the more suitable the combination.

Engineering judgment should also be applied: C*ertain parts of the engine are more prone to damage than others. Corresponding health indices should be included in the set to be defined while others could be kept constant.*

HEALTH PARAMETERS SELECTION

- Projections of Singular vectors in the direction of first singular value

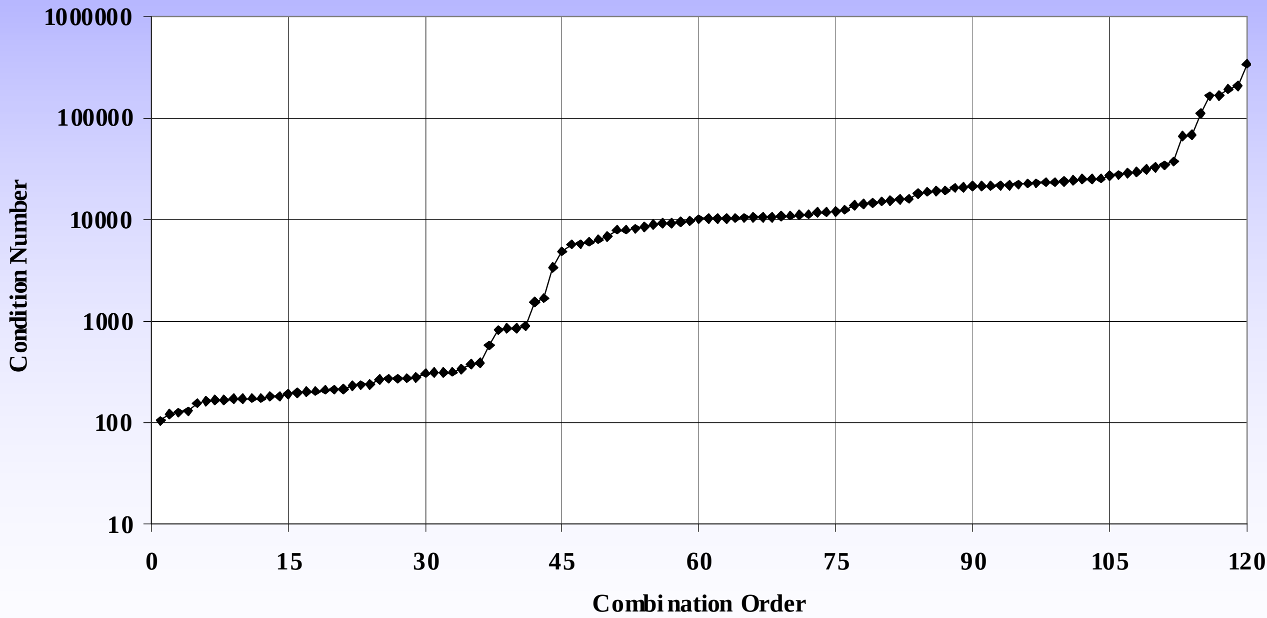


- First six projections correspond to the following health parameters: $f_8, f_{10}, f_2, f_6, f_7, f_3$.

SELECTION OF PARAMETERS using Jacobian condition number

- **Condition Numbers in Ascending order**
- **7 available measurements**

Condition Number of Jacobians which are formed using all the possible combinations of 10 health parameters taken 7 at time



MEASUREMENT SETS FOR SMALLEST CONDITION NUMBERS 7 measurements , 10 parameters

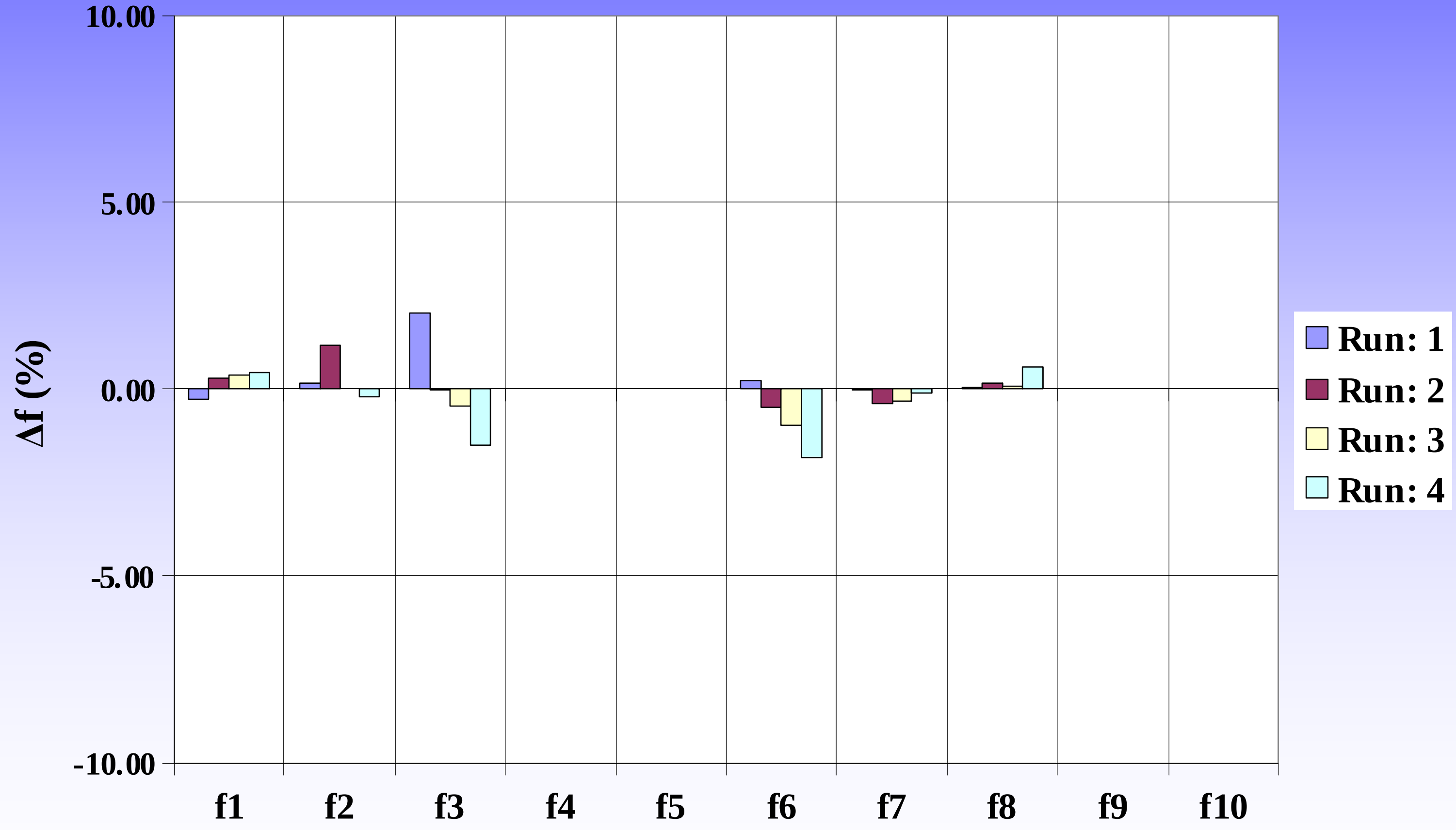
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
f_1	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
f_2	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
f_3			■		■		■		■		■				
f_4						■	■	■	■	■		■	■	■	■
f_5	■	■	■	■	■	■	■			■		■	■		
f_6	■	■	■	■	■			■	■		■	■		■	■
f_7	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
f_8		■		■	■					■			■	■	■
f_9	■	■				■		■		■	■			■	
f_{10}	■		■	■		■	■	■	■		■	■	■		■

CONDITION ASSESSMENT OF A TURBOFAN, FROM TEST CELL DATA

- **Combination Nr 6 chosen:** ***f_1, f_2,. f_3, f_6, f_7, f_8.***

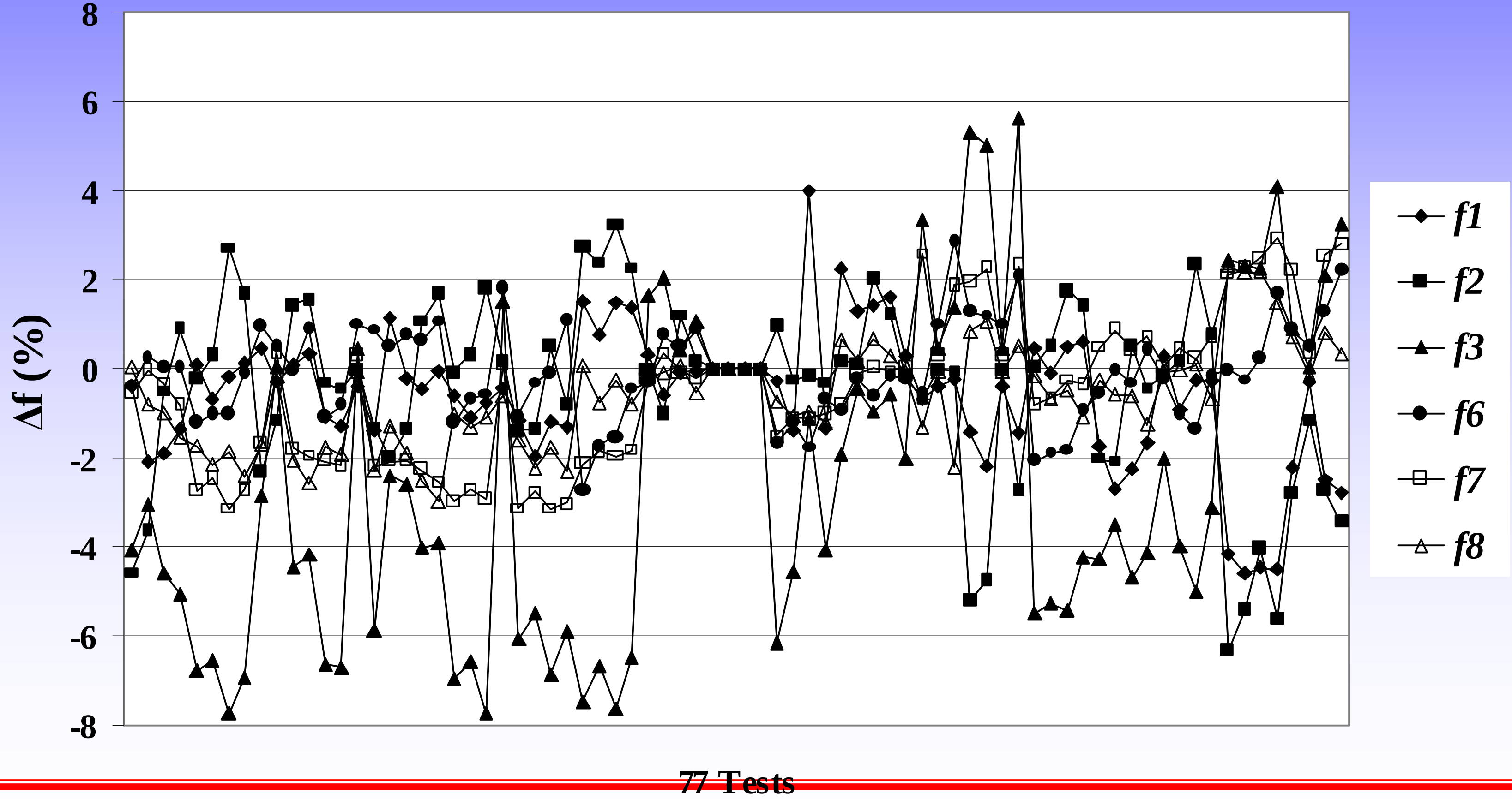
(Contains parameters expressing the condition -flow capacity and efficiency- of two components of the engine namely fan and HPT, which are more inclined to faults)

Results of adaptation procedure for reference engine



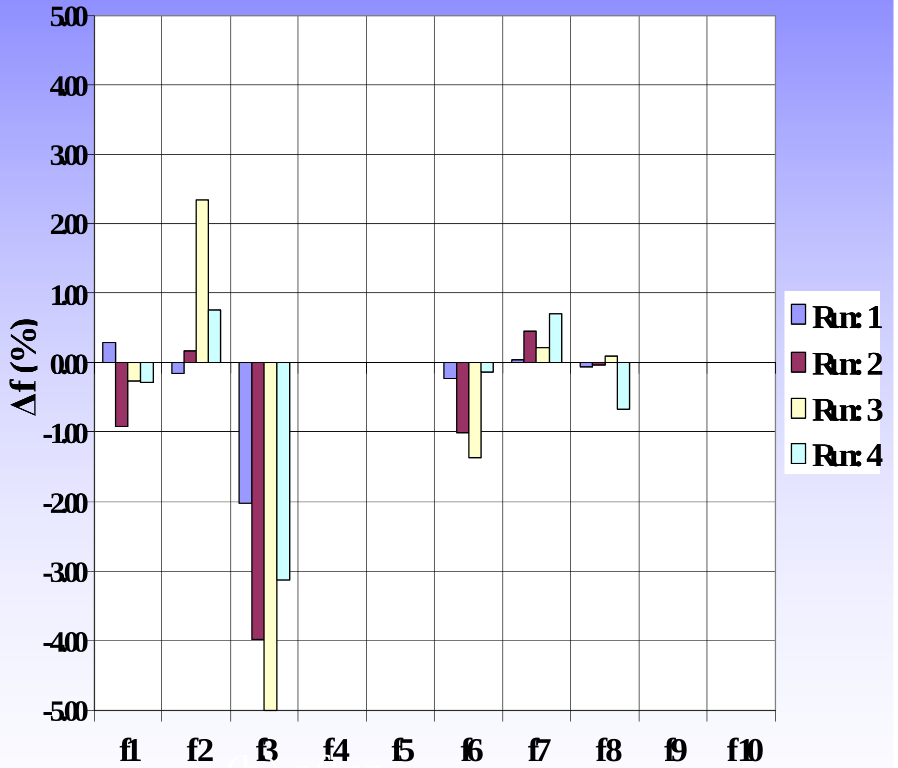
HEALTH PARAMETERS for different engines and operating points

- Results of diagnostic procedure from 77 tests



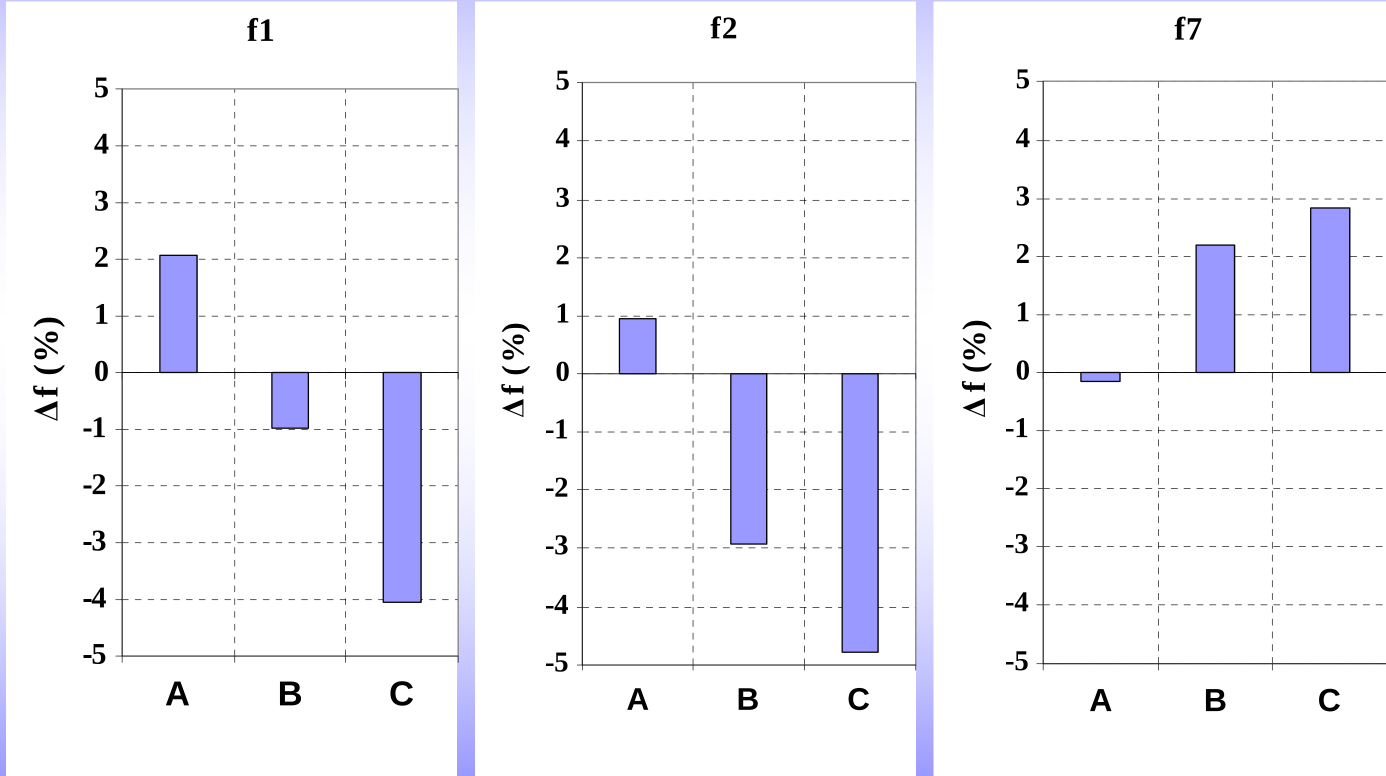
RESULTS OF DIAGNOSTIC PROCEDURE
before and after maintenance

(a) before



(b) after

EFFECT OF DETERIORATION



(A: "New" Engine, B: 1200 hours of operation, C: 5000 hours of operation)

SUMMARY-CONCLUSIONS

- **Methods for the optimal selection of measurements and health parameters for diagnosis in aircraft gas turbines presented.**
  - Measurements selection
  - Health indices selection

- **Application to an existing turbofan showed that**
  - Scattering of values for different engines indicates that each individual engine has to be followed separately.
  - Effect of engine overhaul can be quantified.
  - Effect of deterioration can be assessed.