ENHANCED FAULT LOCALIZATION USING PROBABILISTIC FUSION WITH GAS PATH ANALYSIS ALGORITHMS

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- The problem of GPA fault diagnosis
- Description of the diagnostic procedure
  - o Engine Partitioning
  - o Statistical Processing - PDF integration
  - o Fault Isolation Criteria
  - o Fusion mechanism
- Method implementation
  - o Diagnosis of component faults on a turbofan engine
    1. Individual diagnostic methods
    2. Fusion Procedure
- Summary - Conclusions

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The problem of GPA fault diagnosis

***u*: variables defining operating point.**

***f*: set of *health parameters*, representing health condition of the engine.**

***Y*: set of measured variables (speeds, pressures, temperatures etc).**

$$Y = F(u, f)$$

- **The diagnostic procedure obtains solution for the inverse problem.**
- **Usually system of equations underdetermined**

The problem of GPA fault diagnosis

Y= F(u, f)

- **Unique solution for *f* is derived with minimization of OF (GPA optimization)**

$$OF = C_1 \sum_{i=1}^{K} \left[\frac{Y_i^m(f) - Y_i^g}{Y_i^g \sigma_{Y_i}} \right]^2 + C_2 \sum_{i=1}^{K} \left| \frac{Y_i^m(f) - Y_i^g}{Y_i^g \sigma_{Y_i}} \right|$$

$$+ C_3 \sum_{j=1}^{L} \left| \frac{f_j - f_j^r}{f_j^r \sigma_{f_j}} \right| + C_4 \sum_{j=1}^{L} \left[\frac{f_j - f_j^r}{f_j^r \sigma_{f_j}} \right]^2$$

- **Weight factors C_i represent relative importance of each term**
- **Factors C_i are defined based on application**

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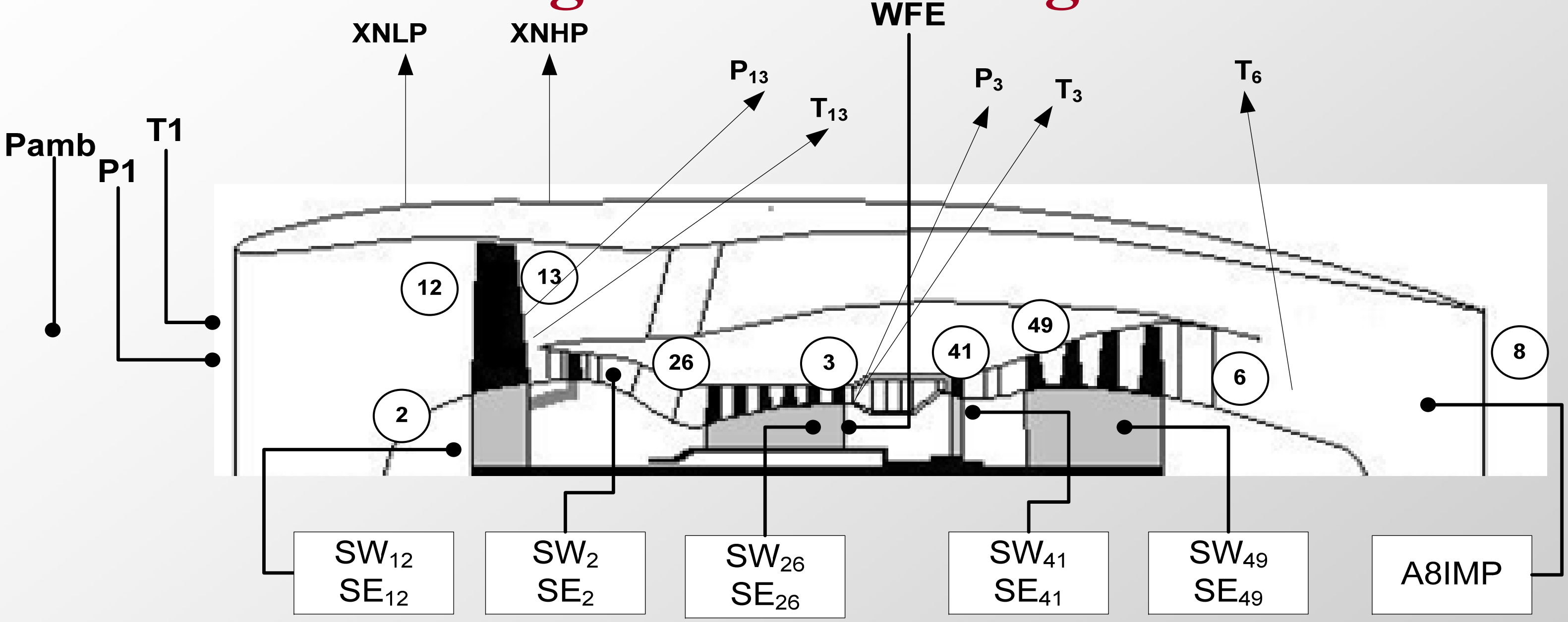
Engine Partitioning



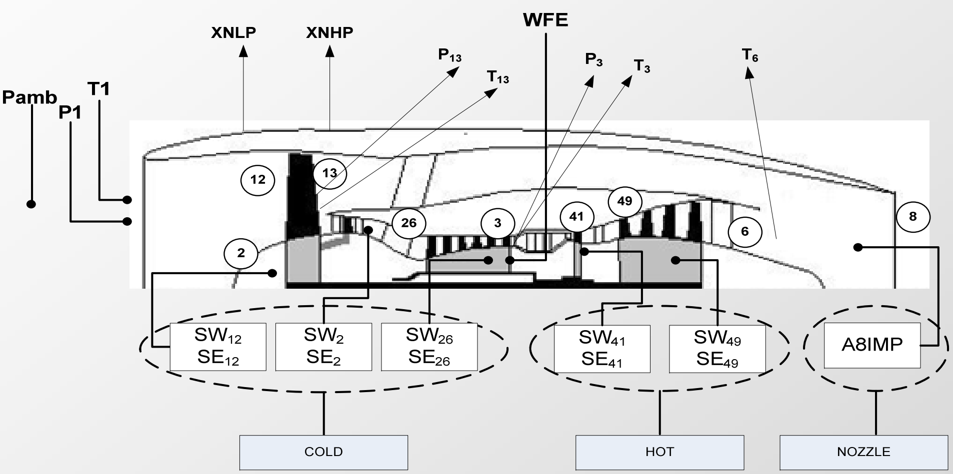
High-by-Pass ratio, partially mixed, turbofan engine utilized

- *Health Parameters > Measurements*
- Underdetermined system
- Engine Partitioning reduces number of unknowns (Health Parameters)

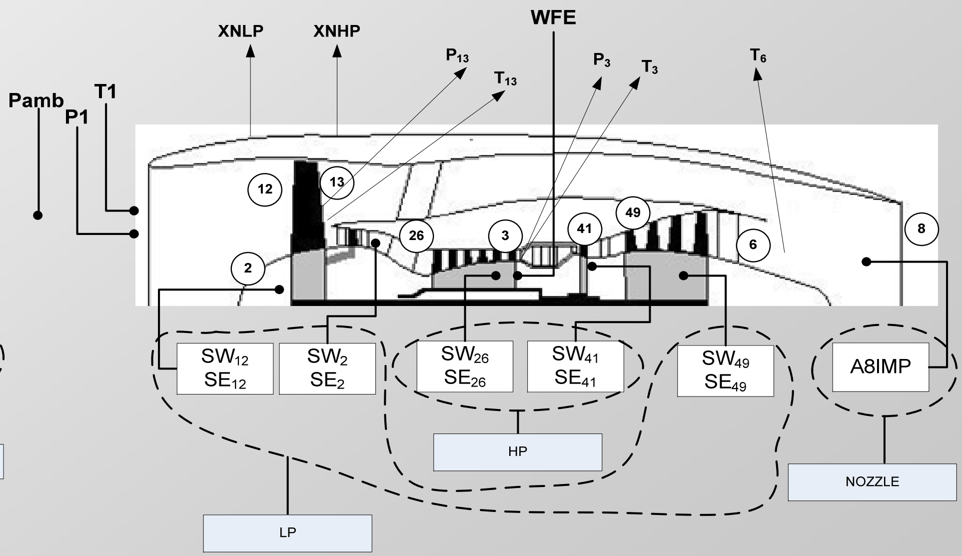
Engine Partitioning

Two different modes of partitioning: (based on layout and physics of operation)

- COLD-HOT-NOZZLE
- LP-HP-NOZZLE



COLD-HOT-NOZZLE

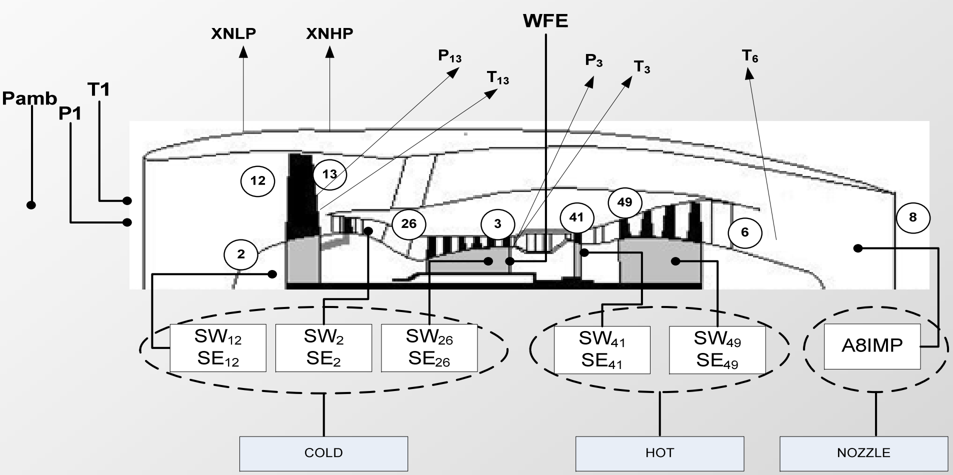


LP-HP-NOZZLE

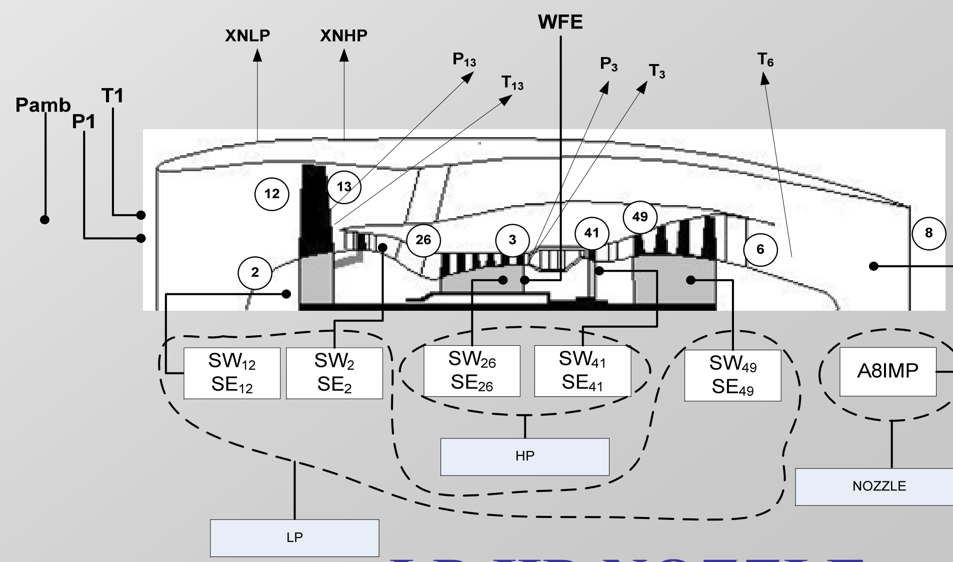
Engine Partitioning

For each partition:

- **FIRST PASS of calculations**
- **Estimation of *health parameters***
- **GPA optimization method is applied as many times as parts of each partition**



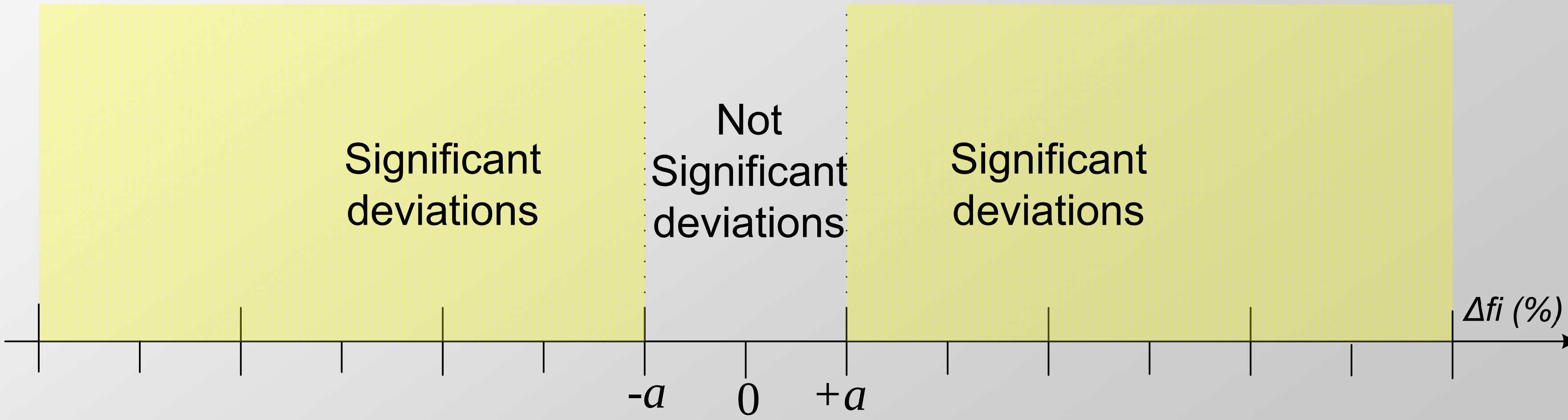
COLD-HOT-NOZZLE



LP-HP-NOZZLE

Statistical Processing – PDF integration

- N measurements sets – N estimations of all *health parameters*
- Estimations in terms of deltas (Percentage Deviations – Δf)
- Definition of threshold α, indicative of fault



Statistical Processing – PDF integration

- **Derivation of sample mean and sample standard deviation**

$$\overline{X} = \overline{\Delta f_j} = \frac{1}{N}\sum_{n=1}^{N} \Delta f_j^{\,n}$$

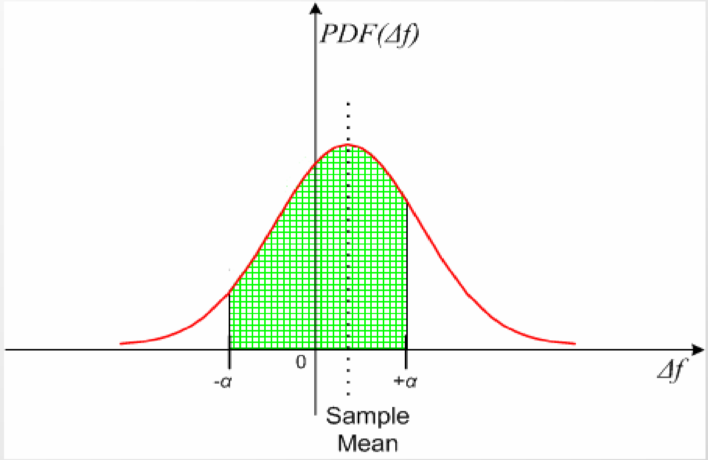
$$s = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}\left(\Delta f_j^{\,n} - \overline{\Delta f_j}\right)^2}$$

- **Integration of normal distribution in the area of [-*α*, +*α*]**
- **This applies for all *health parameters***

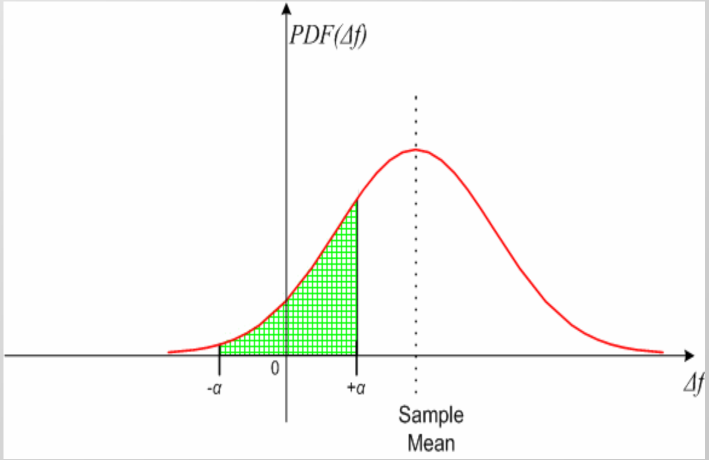
Statistical Processing – PDF integration

$$P(f_j \in \text{"non-faulty"}) = \int_{-a}^{a} normpdf(\Delta f_j)\, d\Delta f_j$$

$$P(f_j \in \text{"faulty"}) = 1 - P(f_j \in \text{"non-faulty"})$$



“non-faulty” health parameter



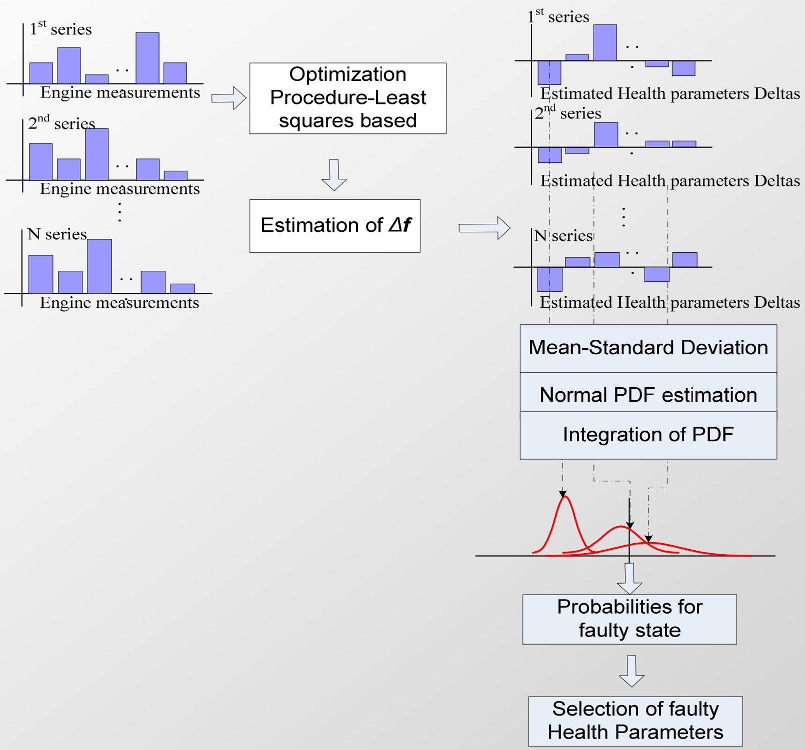
“faulty” health parameter

Fault Isolation Criteria

- **Examination of fault probabilities P ($f_j \in$ *"faulty"*)**

A health parameter f_j is considered to be faulty when,

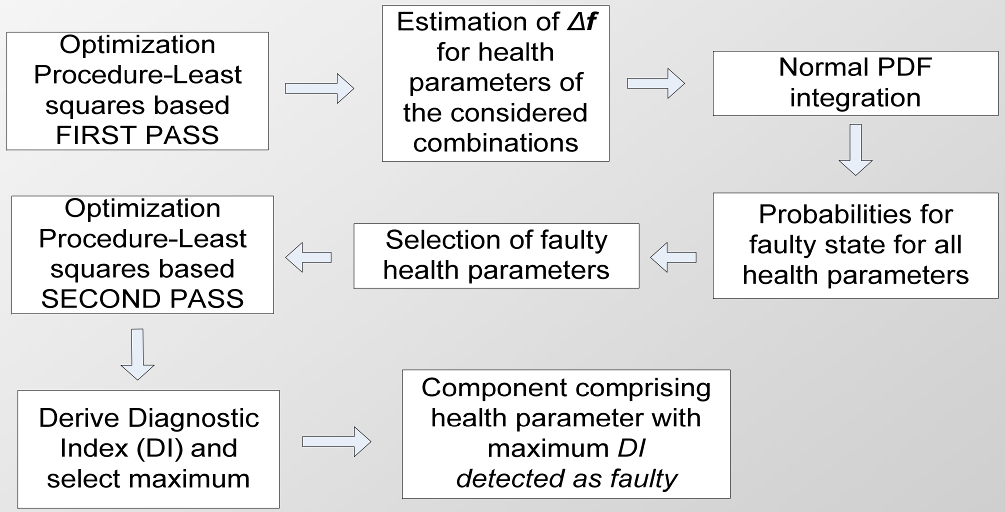
$$P(f_j \in \text{"faulty"}) \geq 50\%$$



Flowchart for selection of *"faulty" health parameters*

Fault Isolation Criteria

- SECOND PASS of calculations
- Estimation of *health parameters* found to be "faulty"
- Again sample mean and sample standard deviation are derived
- DI = $\frac{\overline{X}}{s^2}$
- Faulty engine component the one with maximum DI



Schematic of the whole diagnostic procedure

Fusion mechanism

- **Probabilistic fusion technique (Aggregation of probabilities).**
- **Fusion methodology is applied between FIRST PASS and SECOND PASS.**
- **More precisely to the outputs of PDF integration.**
- ***Linear opinion pool* is utilized (also known as *weighted average*)**

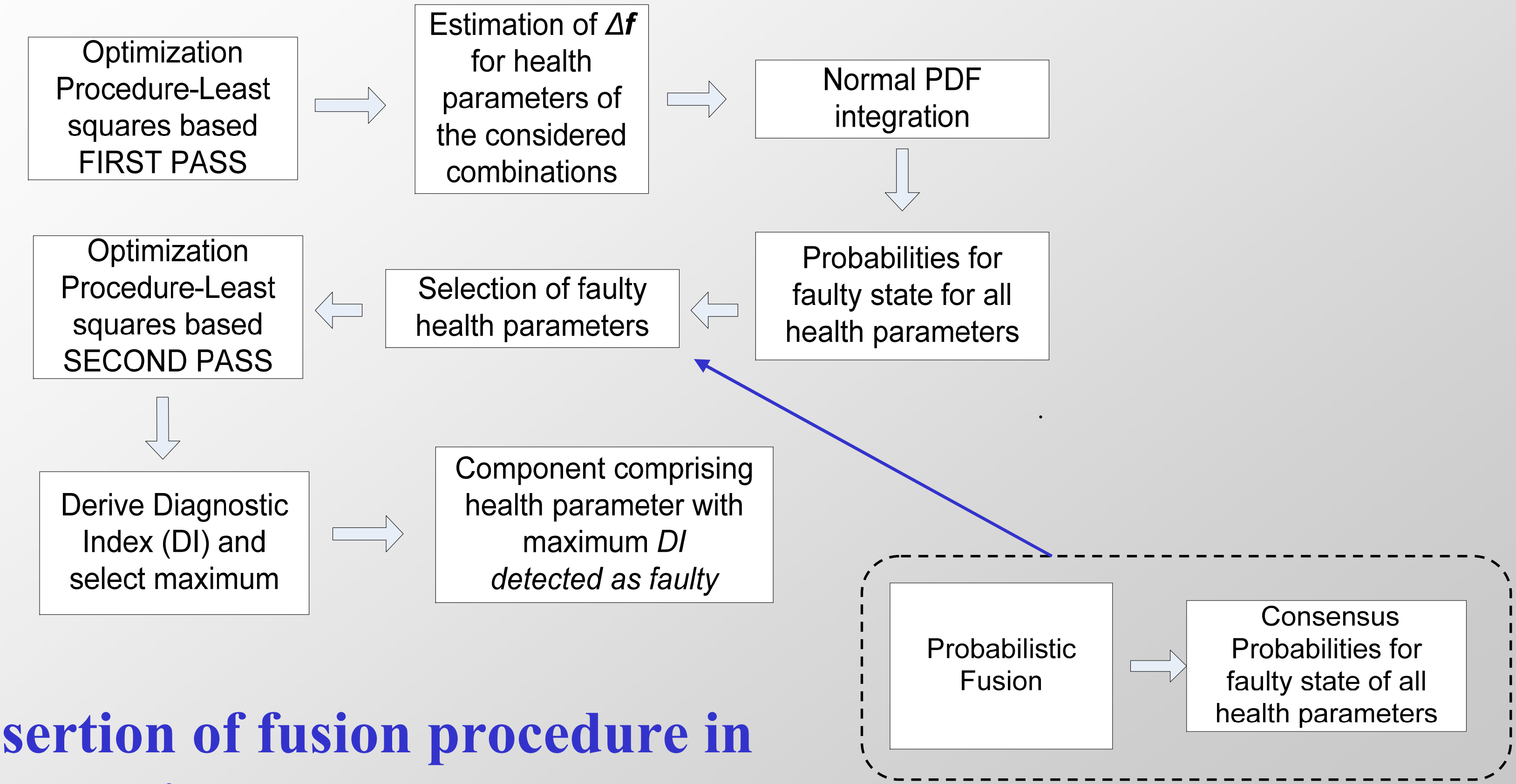
$$X(j) = \frac{\sum_{h=1}^{m} w_{hj} \bullet p_h(f_j)}{\sum_{h=1}^{m} w_{hj}}$$

X (j) **: the probability consensus value**

wij **: the corresponding weights**

$p_h(f_j)$: the probability of health parameter f_j to be "faulty"

Fusion mechanism



Insertion of fusion procedure in diagnostic procedure

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Method implementation

- **15 benchmark component faults on a turbofan engine have been examined.**
- **For each fault N=50 measurements sets have been exploited.**
- **Noisy simulated data from cruise section were utilized.**
- **Noise of realistic magnitude.**

Fault Case	Affected Component	Actual deviated health parameters
a	FAN, LPC	ΔSW2=-0.7%,ΔSE2=-0.4%, ΔSW12=-1%, ΔSE12=-0.5%
b	FAN	ΔSE12= -1%
c	HPC	ΔSW26= -1%, ΔSE26=-0.7%
d	HPC	ΔSE26= -1%
e	HPC	ΔSW26= -1%
f	HPT	ΔSW41=+1%
g	HPT	Δ SW41=-1%, ΔSE41=-1%
h	HPT	ΔSE41=-1%
i	LPT	ΔSE49=-1%
j	LPT	ΔSW49=-1%, ΔSE49=-0.4%
k	LPT	ΔSW49=-1%
l	LPT	ΔSW49=+1%, ΔSE49=-0.6%
m	NOZZLE	ΔA8IMP=+1%
n	NOZZLE	ΔA8IMP=-1%
o	NOZZLE	ΔA8IMP=+2%

The considered fault cases

Operating Point quantities			
P_{amb}	P1	T1	WFE
100 Pa	100 Pa	2 K	2 g/s

Measurements						
XNLP	XNHP	P13	P3	T3	T6	T13
6 rpm	12 rpm	300 Pa	5kPa	2 K	2 K	2 K

Noise level magnitude (3σ)

Individual Diagnostic Methods

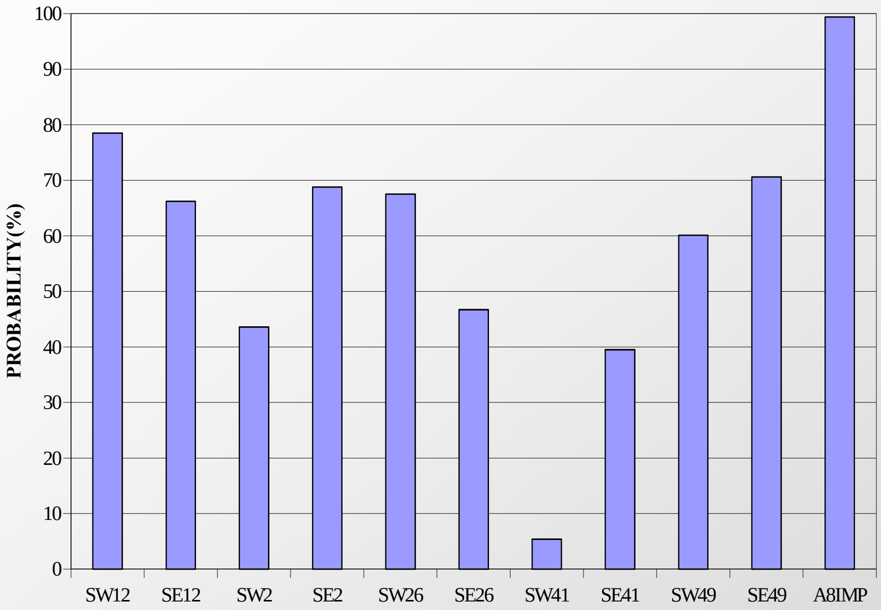
- **Individual GPA diagnostic methods (NLLS, CMBN, PI).**
- **Two modes of Partitioning (CHN and LHN)**

Fault case	Affected Component	NLLS	CMBN	PI	CHN	LHN
a	*FAN, LPC*	*FAN*	*FAN*	*FAN*	*HPT*	*LPC*
b	*FAN*	*FAN*	*FAN*	*FAN*	*FAN*	*FAN*
c	*HPC*	*LPC*	*LPC*	*LPC*	*HPC*	*HPC*
d	*HPC*	*HPC*	*HPC*	*HPC*	*HPC*	*HPC*
e	*HPC*	*HPC*	*HPC*	*HPC*	*HPC*	*LPC*
f	*HPT*	*HPT*	*HPT*	*HPT*	*HPT*	*HPT*
g	*HPT*	*HPT*	*HPT*	*HPT*	*HPT*	*HPT*
h	*HPT*	*HPT*	*HPT*	*LPT*	*HPT*	*HPT*
i	*LPT*	*LPT*	*LPT*	*LPT*	*LPT*	*LPT*
j	*LPT*	*HPT*	*LPC*	*HPT*	*HPT*	*LPT*
k	*LPT*	*HPT*	*LPC*	*HPT*	*LPT*	*LPC*
l	*LPT*	*HPT*	*LPT*	*LPT*	*LPT*	*LPT*
m	*NZLE*	*NZLE*	*LPC*	*NZLE*	*NZLE*	*HPC*
n	*NZLE*	*NZLE*	*NZLE*	*NZLE*	*NZLE*	*LPC*
o	*NZLE*	*NZLE*	*NZLE*	*NZLE*	*NZLE*	*NZLE*

Misdiagnosis with gray shades

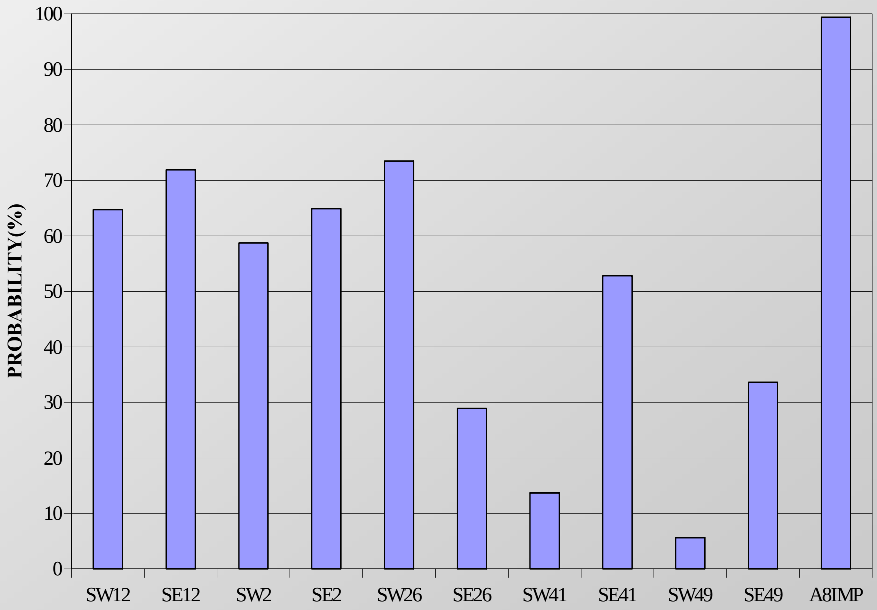
Individual Diagnostic Methods

- **Probabilities after FIRST PASS (CHN and LHN Partitions)**



Fault case "m"

CHN partition

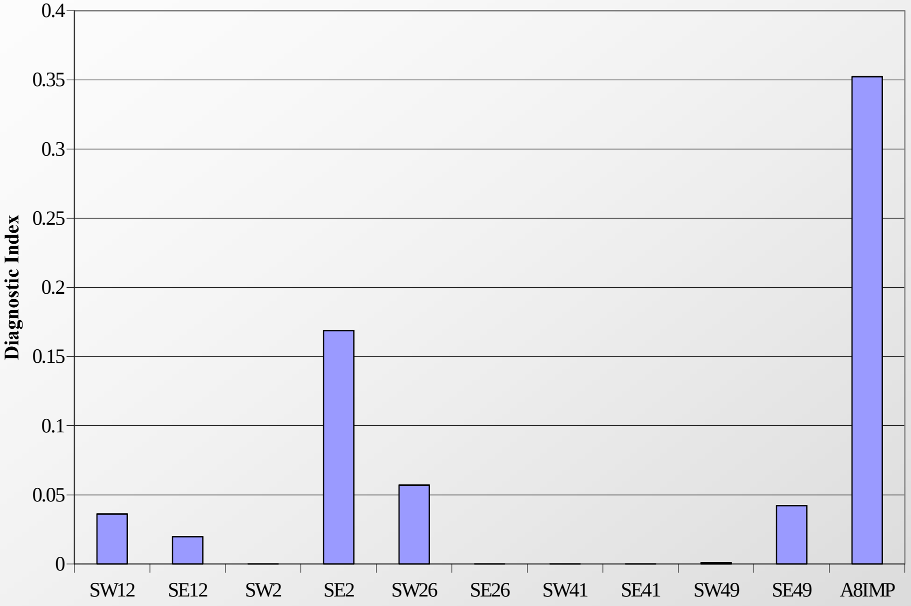


Fault case "m"

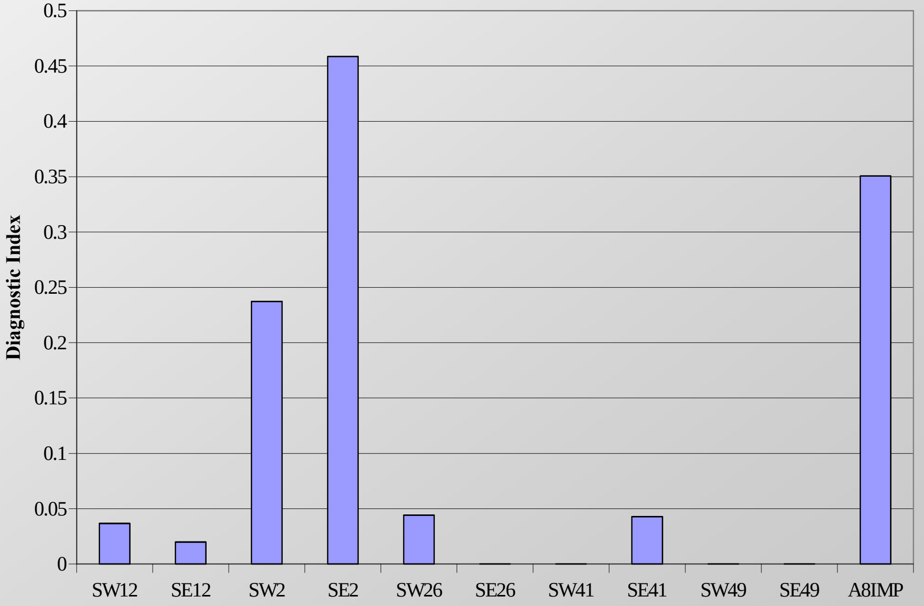
LHN partition

Individual Diagnostic Methods

- **DIs after SECOND PASS (CHN and LHN Partitions)**



Fault case "m"
CHN partition
A8IMP parameter with maximum DI
NOZZLE component



Fault case "m"
LHN partition
SE2 parameter with maximum DI
HPC component

Fusion Procedure

- **Application on the two modes of Partitioning (CHN and LHN).**
- **The probabilities of FIRST PASSes are utilized.**
- **The consensus probabilities drive the selection for SECOND PASS.**

WEIGHT DEFINITION

- ***Weighting application quantifies usage experience, credibility, a priori knowledge etc.***
- ***Has mathematical base (derived from statistics).***
- ***Ease in implementation.***

Two different approaches for weight definition:

- ***"Pessimistic" approach***
- ***"Optimistic" approach***

Fusion Procedure

Two different approaches for weight definition:

- ***"Pessimistic" approach***

The weights (of each diagnostic method) are defined according to its effectiveness.

e.g. If a diagnostic method has an efficiency of 80% then its weight vector is W_i = (0.8, 0.8,…,0.8).

- ***"Optimistic" approach***

The weight of each diagnostic method is defined by comparing its effectiveness to the effectiveness of all other methods.

e.g. If a diagnostic method1 misses 2 examined fault cases and diagnostic method2 misses 4, then method1 has double weight vector W_i than method2

For the purposes of the current work the "optimistic" approach for weight definition was adopted

Fusion Procedure

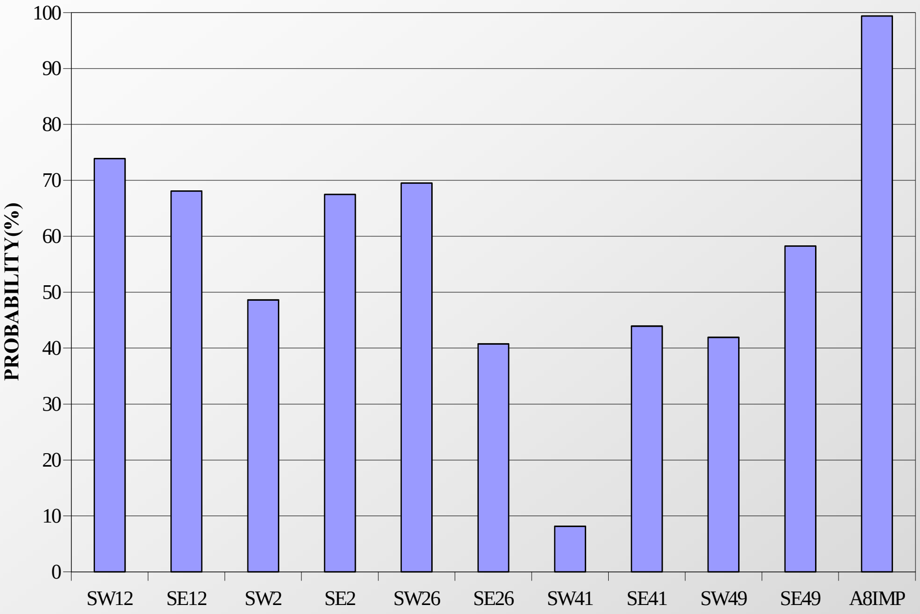
▪Probabilistic Fusion Results

Fault case	Affected Component	CHN	LHN	FUSION
a	FAN, LPC	HPT	LPC	FAN
b	FAN	FAN	FAN	FAN
c	HPC	HPC	HPC	HPC
d	HPC	HPC	HPC	HPC
e	HPC	HPC	LPC	HPC
f	HPT	HPT	HPT	HPT
g	HPT	HPT	HPT	HPT
h	HPT	HPT	HPT	HPT
i	LPT	LPT	LPT	LPT
j	LPT	HPT	LPT	HPT
k	LPT	LPT	LPC	LPT
l	LPT	LPT	LPT	LPT
m	NZLE	NZLE	HPC	NZLE
n	NZLE	NZLE	LPC	NZLE
o	NZLE	NZLE	NZLE	NZLE

Misdiagnosis with gray shades

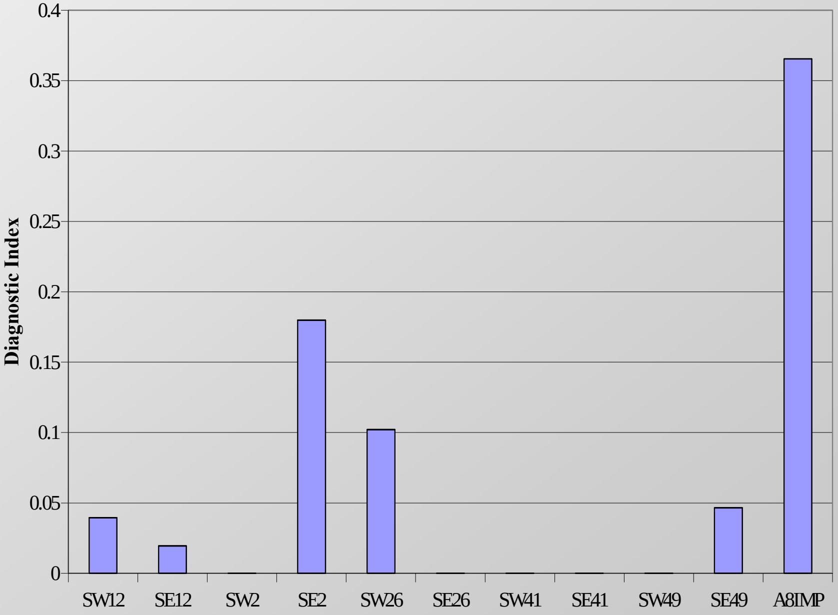
Fusion Procedure

- **Consensus Probabilities after FIRST PASSes and DIs after SECOND PASS**
- **(CHN and LHN Partitions)**



Fault case "m"

Consensus Probabilities



Fault case "m"

A8IMP parameter with maximum DI

NOZZLE component

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Summary - Conclusions

- **A method for the enhancement of effectiveness of previous GPA techniques has been presented. The method handles the obstacle of underdetermined systems with the notion of engine partitioning.**
- **The presented method also introduced a statistical processing methodology (namely PDF integration) for the derivation of fault probabilities concerning the state of *health parameters* of an engine.**
- **Effectiveness of the method has been demonstrated by application to simulated noisy data sets of a turbofan engine.**
- **Secondly, a probabilistic fusion scheme, for further amplification of performance was presented along with application results for effectiveness' demonstration.**
- **Both PDF integration and probabilistic fusion can be embedded to other diagnostic algorithms, a feature of more general usefulness.**