JET ENGINE COMPONENT AND TRANSDUCER FAULT DIAGNOSIS USING COMPONENT MAP REPLACEMENT BY THE MAPS EVALUATED DURING TRANSIENT OPERATION

גילוי תקלות בחישנים ורכיבי מנוע סילון ע"י שימוש במפות ביצועים המשוחזרות בזמן תמרונים

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Objectives

1. Fault detection of engine component and/or transducers
2. Minimization of the transducer numbers
3. Evaluation of faulty engine component maps

Methodology:

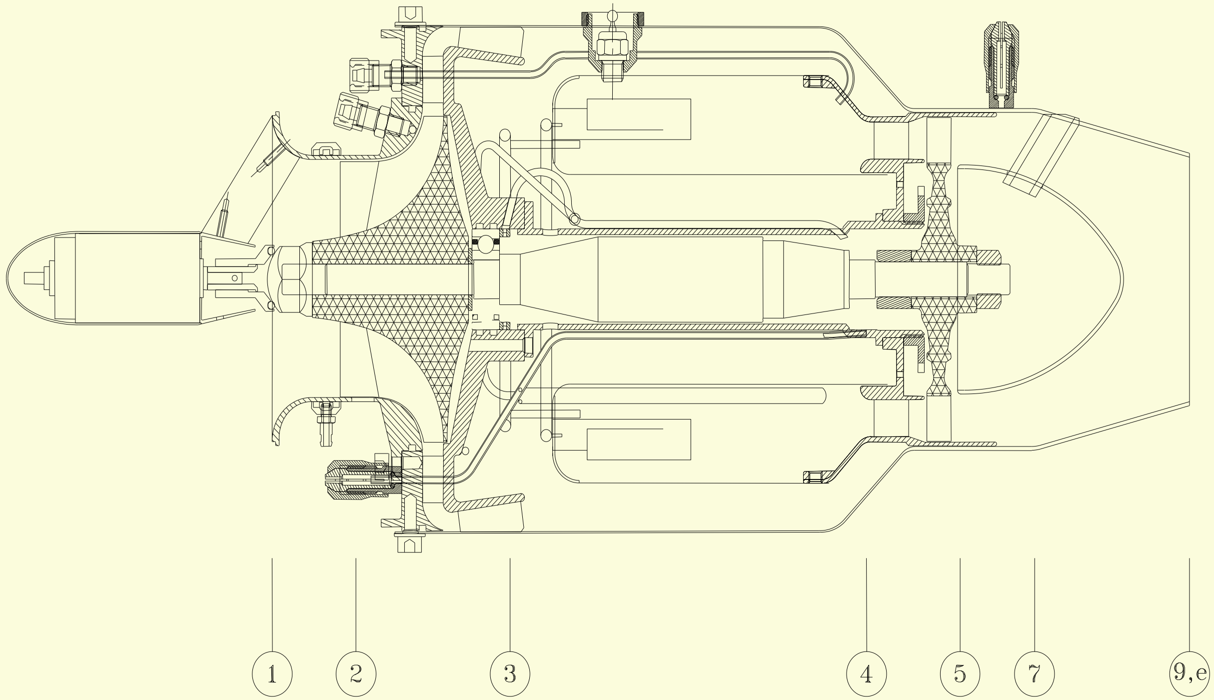
Replacing the original engine component maps by evaluated maps using

Combined Shortened Inverse Engine Model.

Two sub-models were incorporated:

1. without compressor map
2. without turbine map

Single Spool Engine Stations

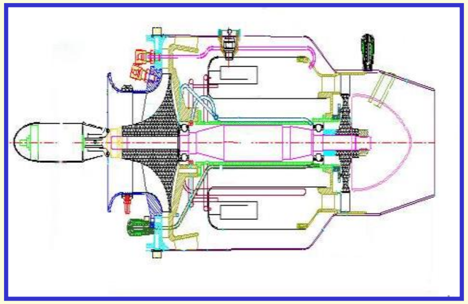


Drawing refers to the AMT Netherlands B.V. Olympus Design.

The Problem Formulation:

$\downarrow H, M$

Command:
$N_{cor,ref}(t)$



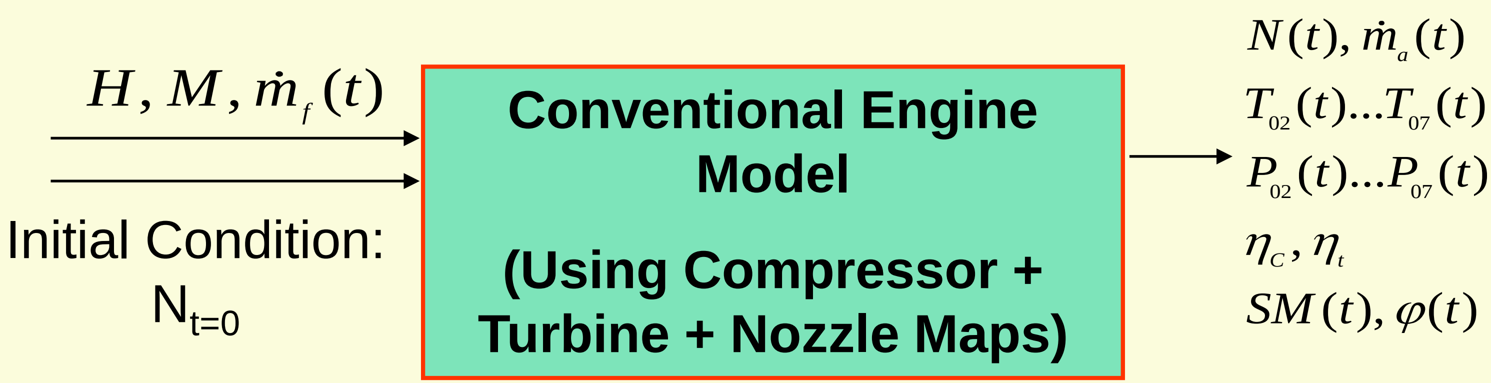
Output:

Typical measured values $H, M, \dot{m}_f, N, T_{03}, T_{05}$

A single transducer and/or single faulty engine component (compressor or turbine) could be present in the engine at a certain time.

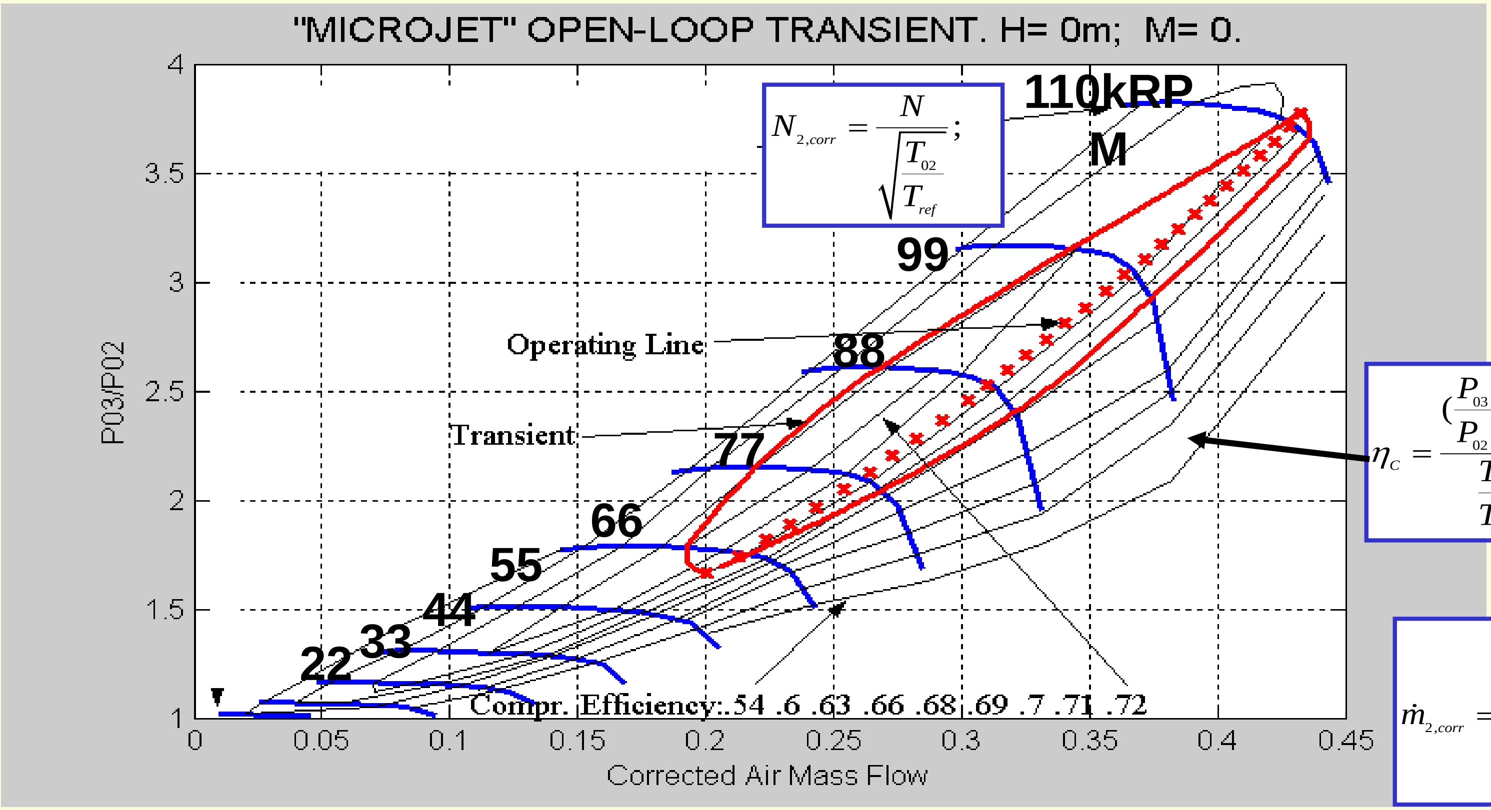
It is required to identify the degraded transducer and/or engine component and to evaluate the degraded engine component map.

Conventional Dynamic Engine Model



Compressor Map:

$$F_1\left(\dot{m}_{2,corr},\ \frac{P_{03}}{P_{02}},\ N_{2,corr}\right)=0\ ; \qquad F_2\left(\dot{m}_{2,corr},\ \frac{P_{03}}{P_{02}},\ \eta_c\right)=0$$



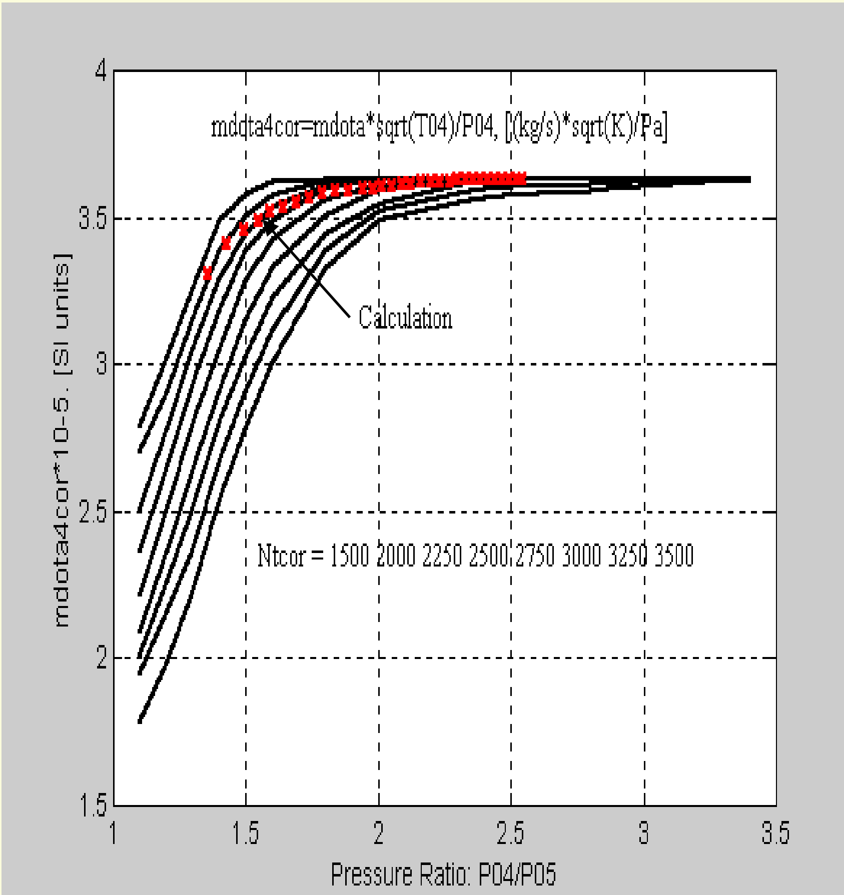
$$N_{2,corr}=\frac{N}{\sqrt{\frac{T_{02}}{T_{ref}}}};$$

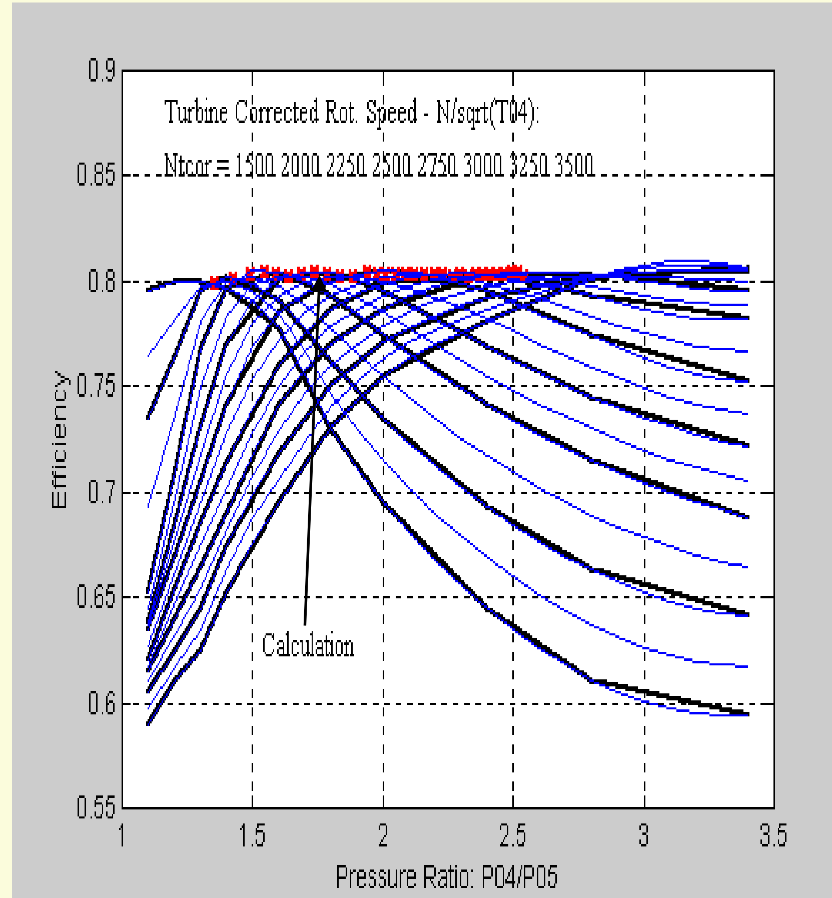
$$\eta_C=\frac{\left(\frac{P_{03}}{P_{02}}\right)^{\frac{\gamma_{a,c}-1}{\gamma_{a,c}}}-1}{\frac{T_{03}}{T_{02}}-1}$$

$$\dot{m}_{2,corr}=\frac{\dot{m}_{a,c}\cdot\sqrt{\frac{T_{02}}{T_{ref}}}}{\frac{P_{02}}{P_{ref}}};$$

Turbine Map:

$$\dot{m}_{4,corr} = F_3\left(\frac{P_{04}}{P_{05}},\ N_{4,corr}\right) ; \qquad \eta_t = F_4\left(\frac{P_{04}}{P_{05}},\ N_{4,corr}\right)$$





We assume the validity of a ***conventional model*** *for the jet engine*

Input Values.

$\mathrm{VAL_{in}}$ = number of input values

Input Engine Component Maps.

$\mathrm{MAP_{in}}$ = number of input map Eqs.

Conventional Engine Model

Thermodynamic equations

(**THERM** - thermodynamic equation number)

Output Values.

$\mathrm{VAL_{out}}$ = number of output value

Complete Conventional Model Conditions :

$$\mathrm{MAP_{in} + THERM = VAL_{out}} \qquad (1)$$

Validity criteria for the Shortened Inverse Engine Model

Input Values

VAL_{in} = number of input values

Input Engine Component Maps

Shortened Inverse Model

Thermodynamic equations

(**THERM** - thermodynamic equation number)

Output Values

VAL_{out} = number of output values

Output Engine Component Maps

MAP_{in} = number of input map Eqs.

MAP_{out} = number of output map Eqs.

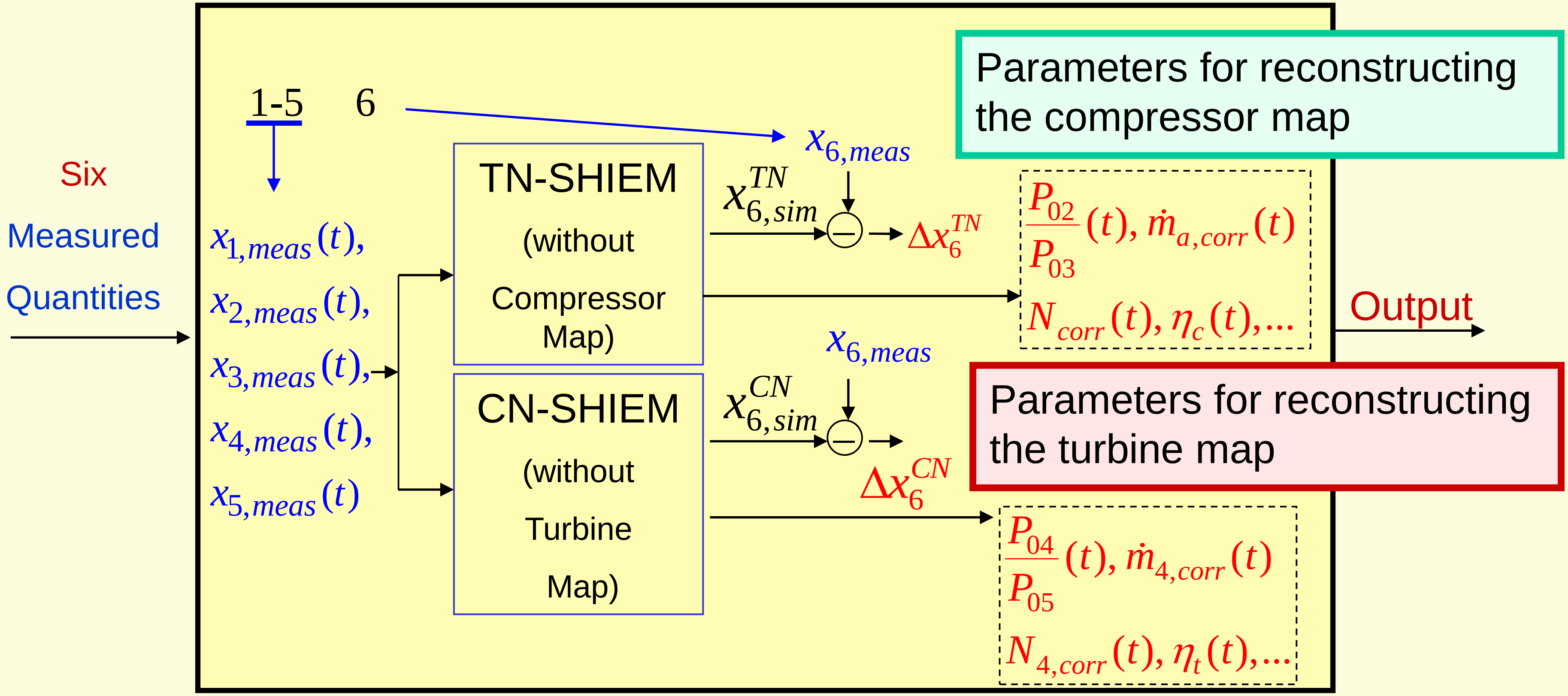
(some maps are known (MAP_{in}) and some are recovered (MAP_{out}))

Complete Shortened Inverse Model Conditions :

$$VAL_{in} + VAL_{out} = (VAL_{in} + VAL_{out})_{conv} \quad (2)$$

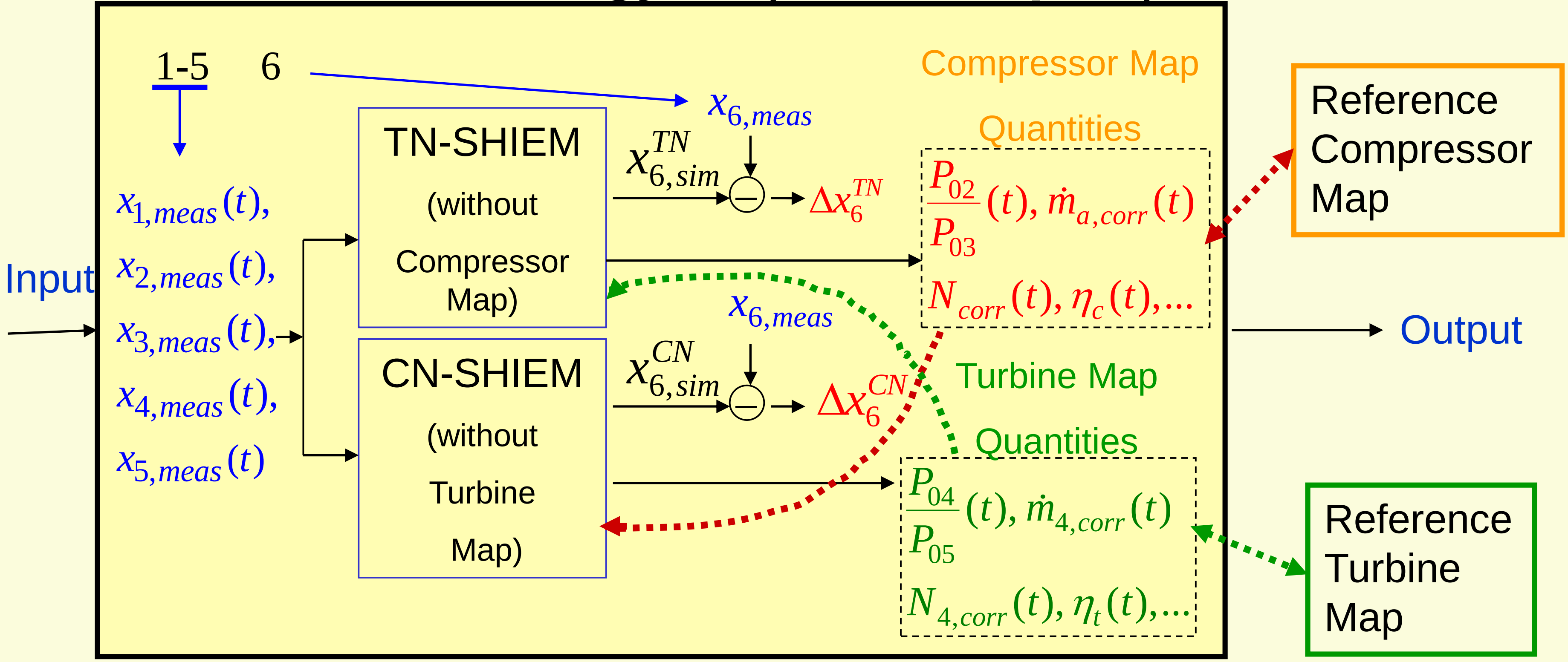
$$MAP_{in} + THERM = VAL_{out} \quad (3)$$

Combined TN/CN Shortened Inverse Engine Model



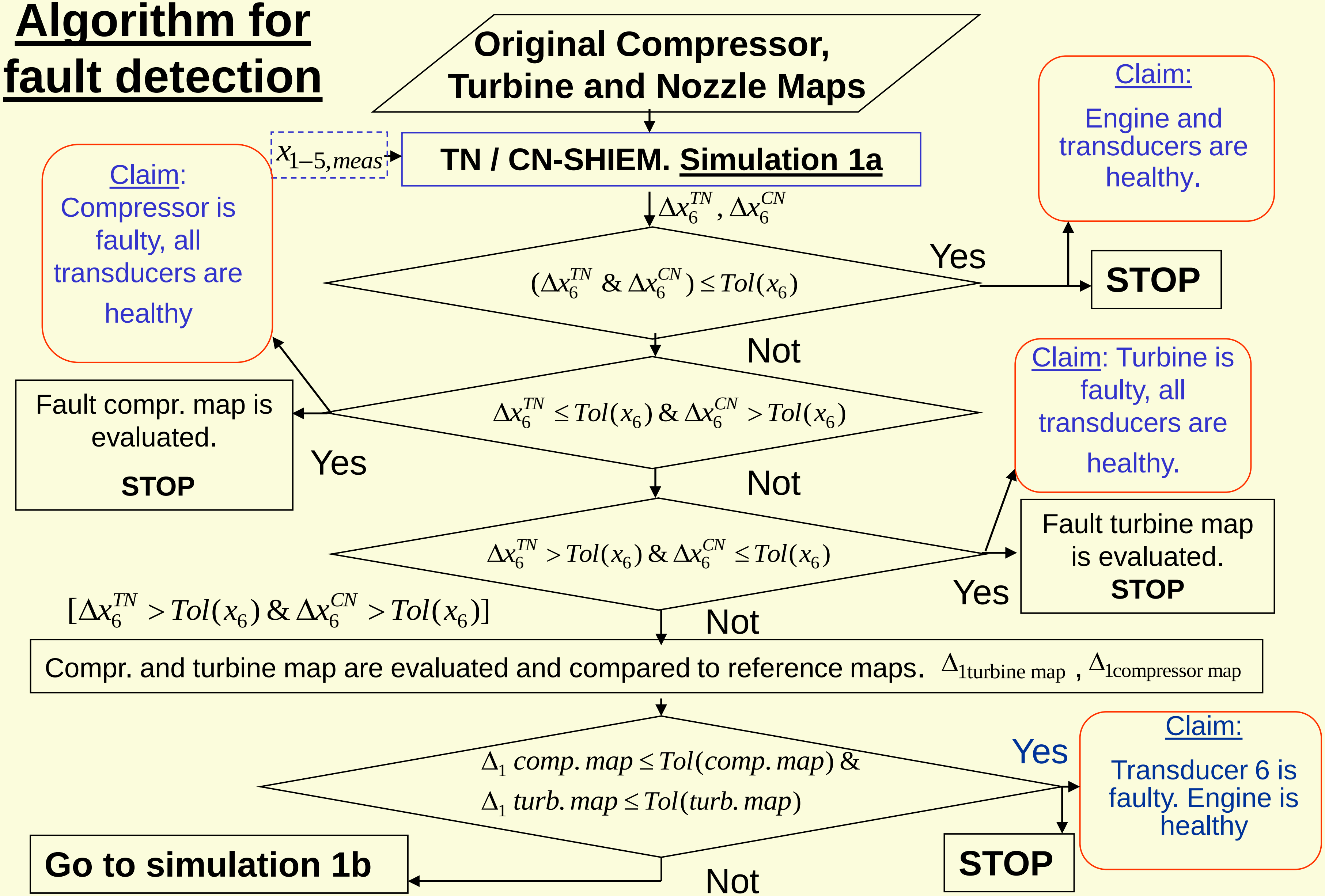
Minimal transducer number is six for engine component / transducer fault diagnosis

Methodology (גרעין של השיטה)



a) The SHIEM is applied twice, simultaneously, with same input parameters: once to recover the compressor map and once to recover the turbines map.
b) The recovered maps are compared to the engine’s original (reference) maps.
c) The recovered maps are used to substitute the original maps in the two SHIEMs.
d) We apply again the SHIEM, re-evaluate the component map and compare with the reference maps.
e) Whenever the differences are large – an additional simulation is applied.

Algorithm for fault detection



12. **Simulation 1a**: Algorithm of fault detection for one off six transducers or/and one off two engine components.

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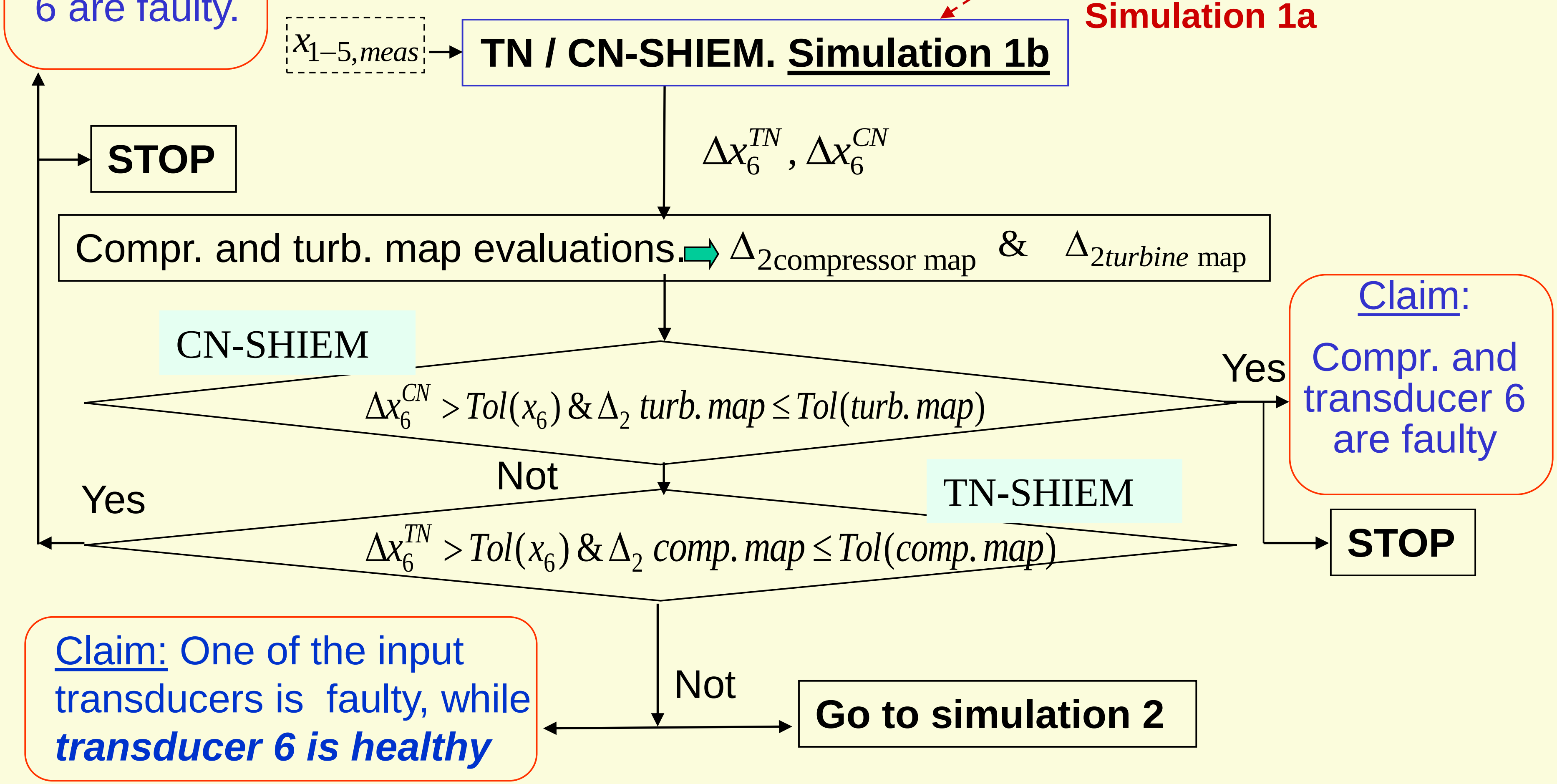
Algorithm for fault detection (continued)



13. **Simulation 1b:** Algorithm of fault detection for one off six transducers or/and one off two engine components.

Algorithm of fault detection for one off six transducers or/and one off two engine components (continued). Simulations 2 to 6

Simulation No.	Numbers of input transducers (blue large figures correspond to healthy transducer)	Transducer number compared to simulation
1	1,2,3,4,5	6
2	*6*,1,2,3,4	5
3	*5,6*,1,2,3	4
4	*4,5,6*,1,2	3
5	*3,4,5,6*,1	2
6	*2,3,4,5,6*	1 (is faulty)

14. **Simulations 1 to 6:** Algorithm of fault detection for one off six transducers or/and one off two engine components.

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An example of a single spool jet engine component and/or transducer fault diagnosis

a) Six measured values: $H, M, \dot{m}_f, N, T_{03}, T_{05}$

b) Original compressor, turbine and nozzle maps are known .

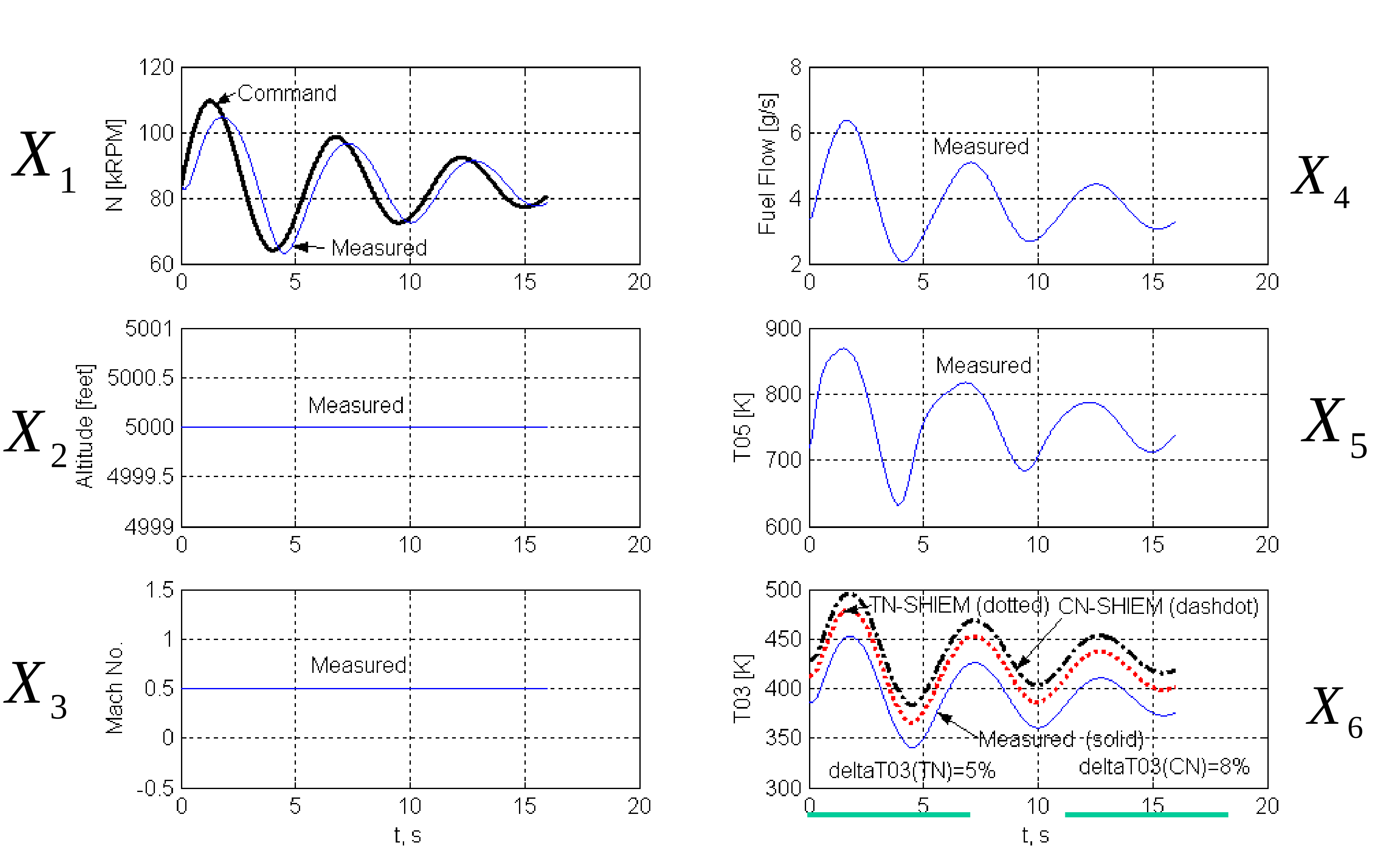
c) A single engine component (compressor or turbine) and/or single transducer faults could be present in the engine at any instance.

d) Relative (allowable) tolerance for all transducers and all engine component maps are 1%

The following faults were inserted in the simulation:

- in the compressor map: 3% degradation of $\dot{m}_{2,\,corr}$ and $\frac{P_{03}}{P_{02}}$,a factor of 0.95 for η_C
- measurement bias of -5% for the fault transducer T_{03}

Engine maneuver at H=5000ft, M=0.5

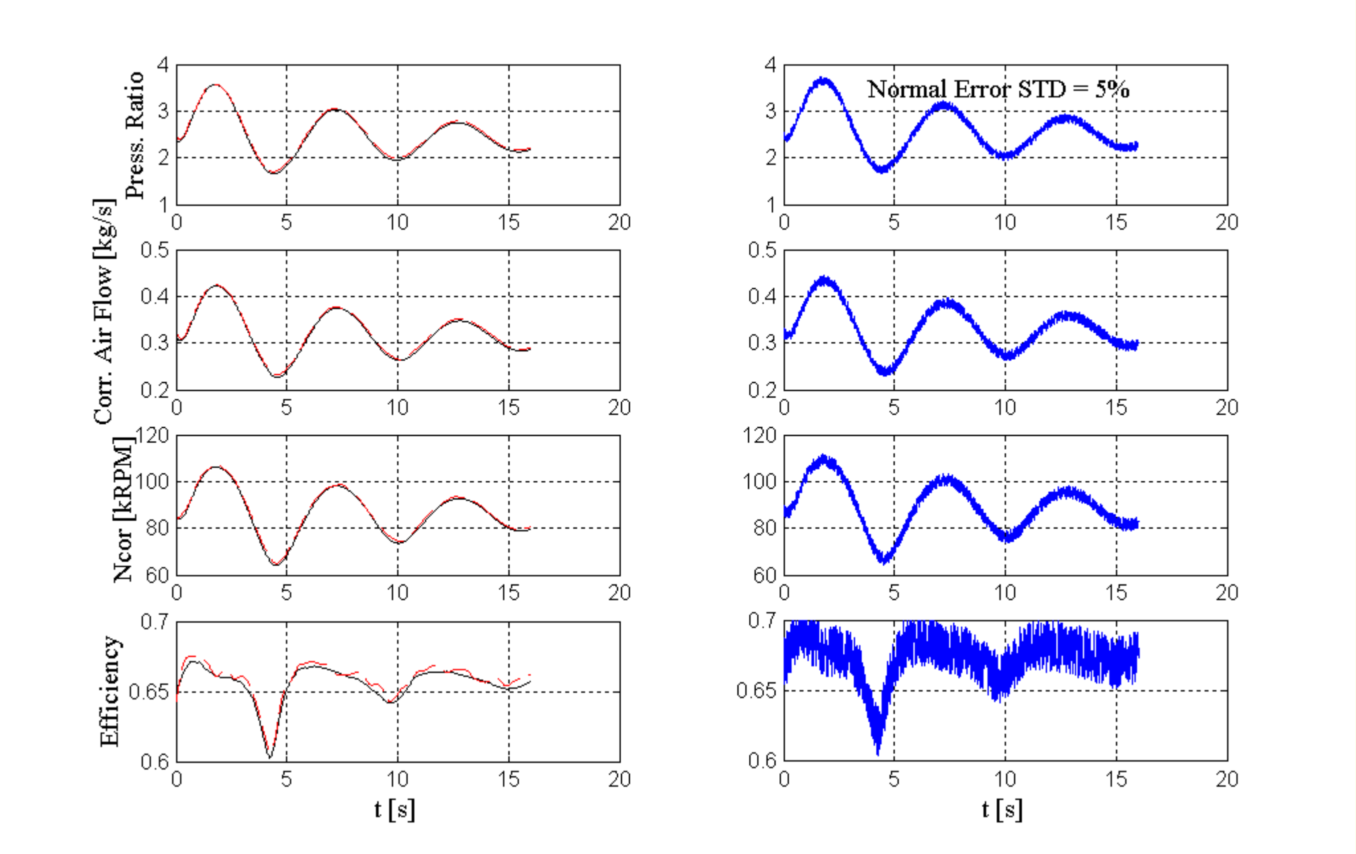


$$\Delta T_{03}^{TN} = 5\%, \quad \Delta T_{03}^{CN} = 8\% \quad > \quad Tolerance(T_{03})$$

16. Command and six measured quantities. Simulated and measured T_{03} comparisons.

Evaluation of Compressor Map

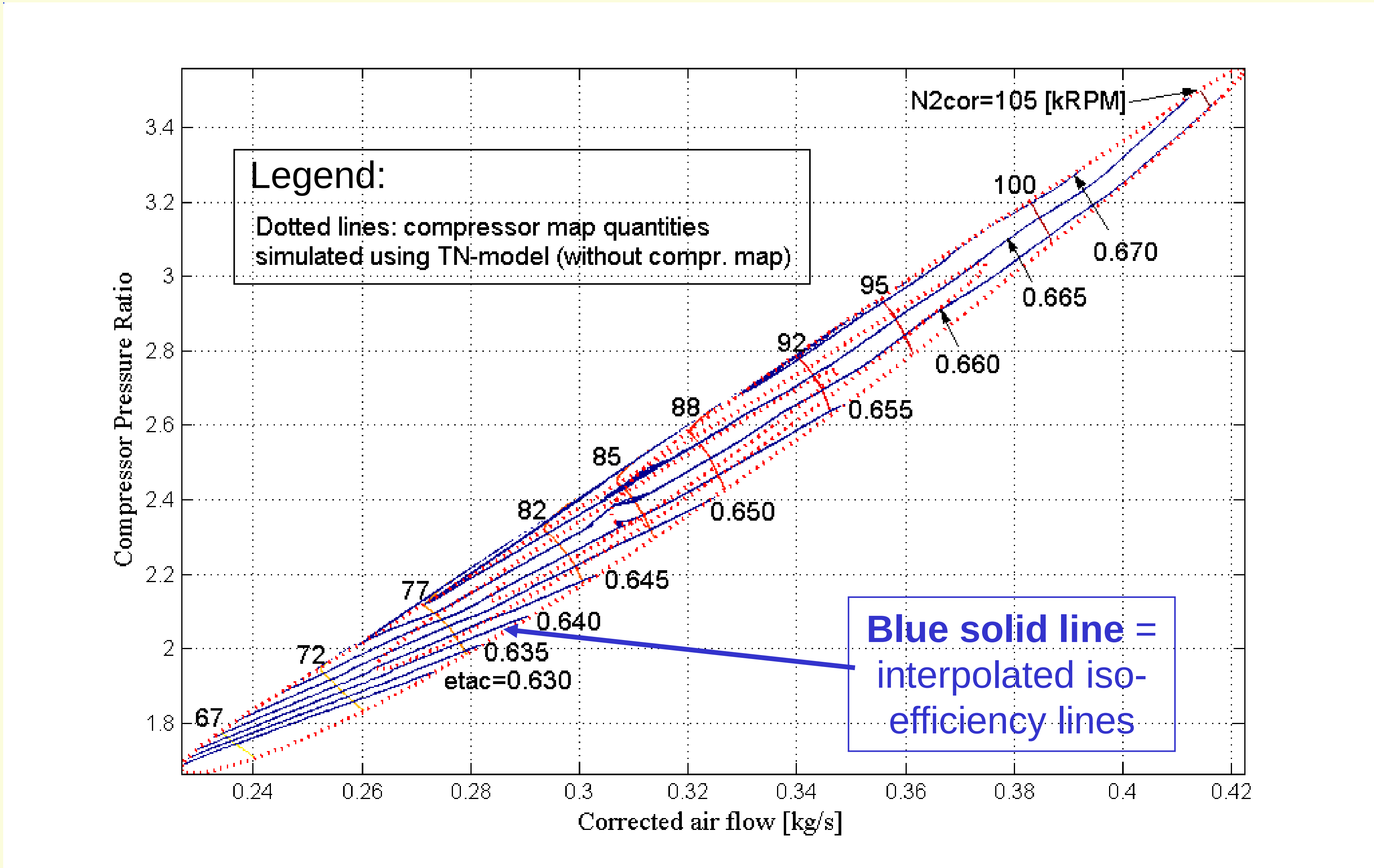
Compressor map quantities of Simulation 1a:



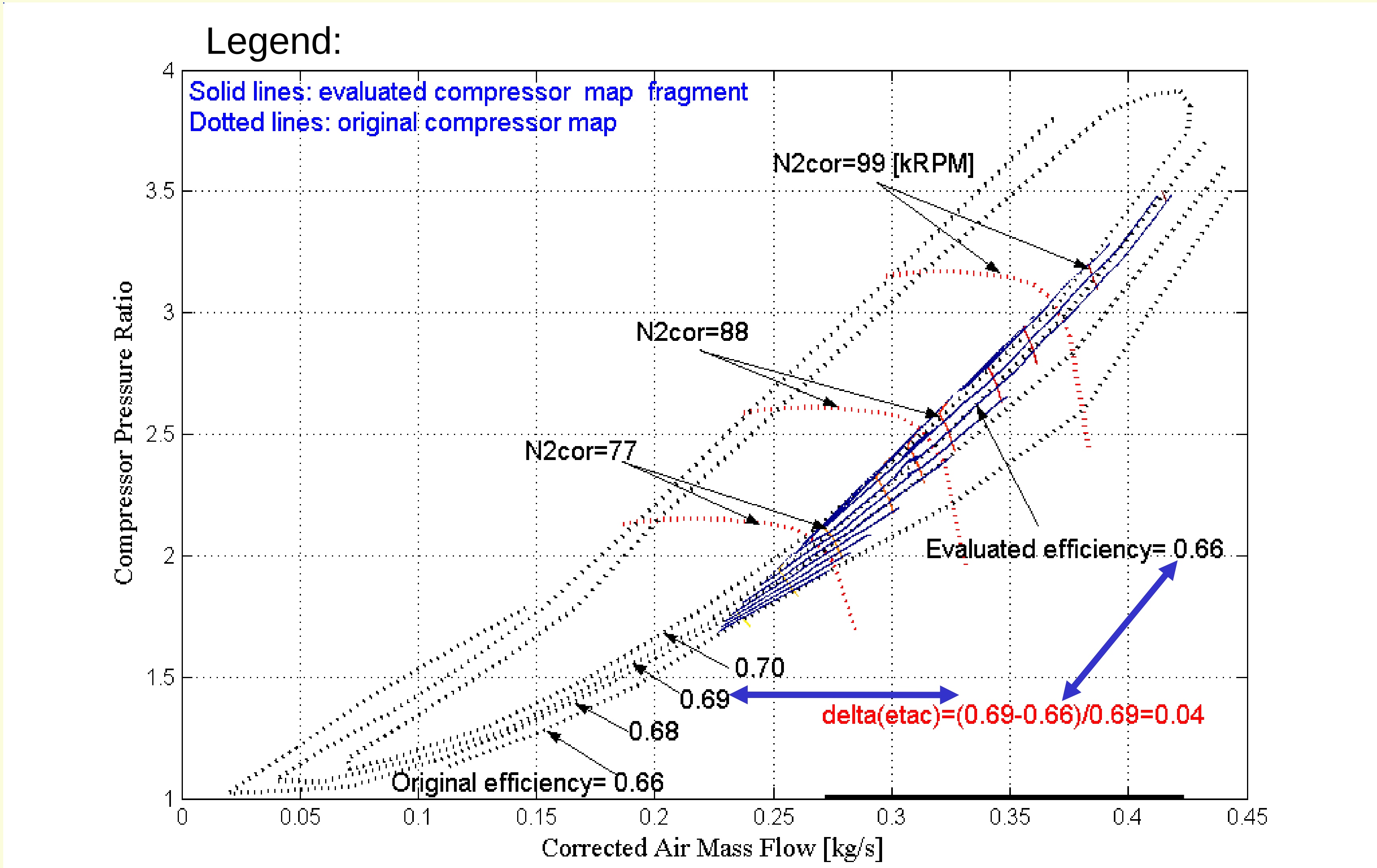
Matlab function FILTFILT performs zero-phase digital filtering by processing the input data in both the forward and reverse directions

17. Noise free (left black solid lines), noised (right) and filtered (left dashed red lines)

Evaluated Compressor map fragment

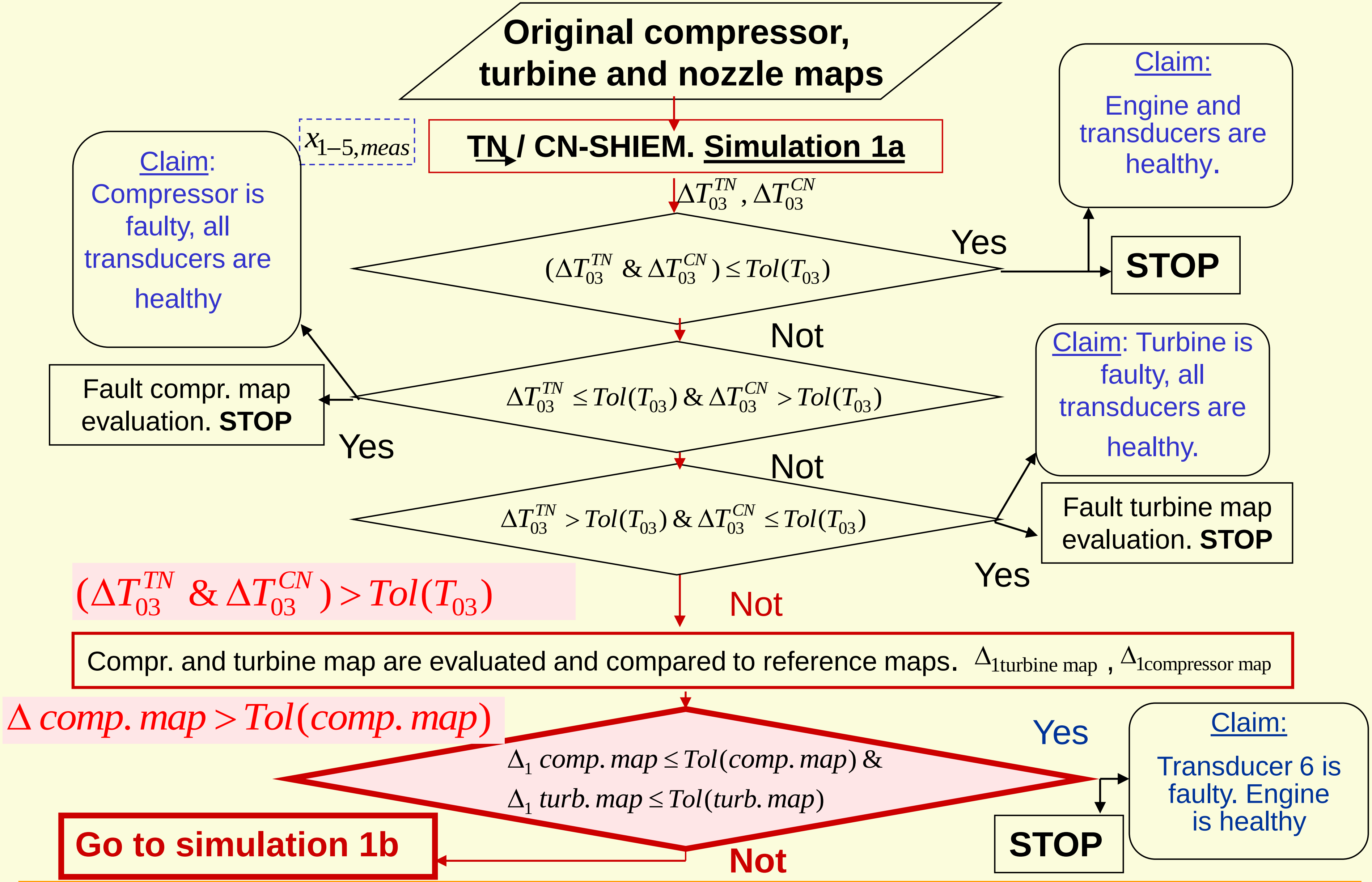


18. Compressor map fragment evaluated using data of Simulation 1a.



$$\Delta\ comp.\ map = 4\% \quad > \quad Tolerance(comp.\ map)$$

19. Comparison of the evaluated compressor map fragment with the original map.



20. **Simulation 1a:** Algorithm of fault detection for one off six transducers or/and one off two engine components.

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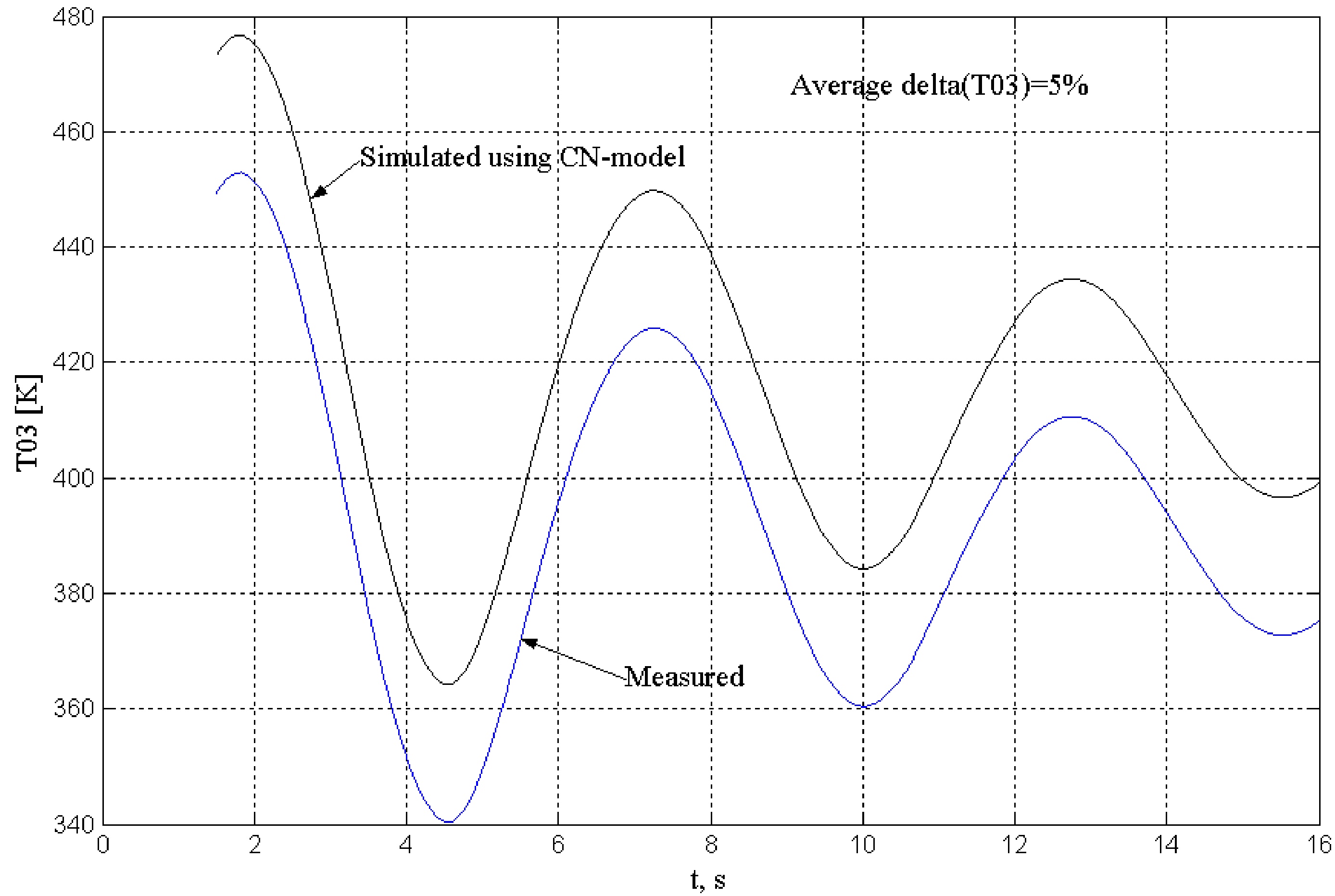
Simulation 1b: Original Compressor Map is Replaced by the Evaluated Map

Comparison of Simulated and Measured Compressor Temperature:

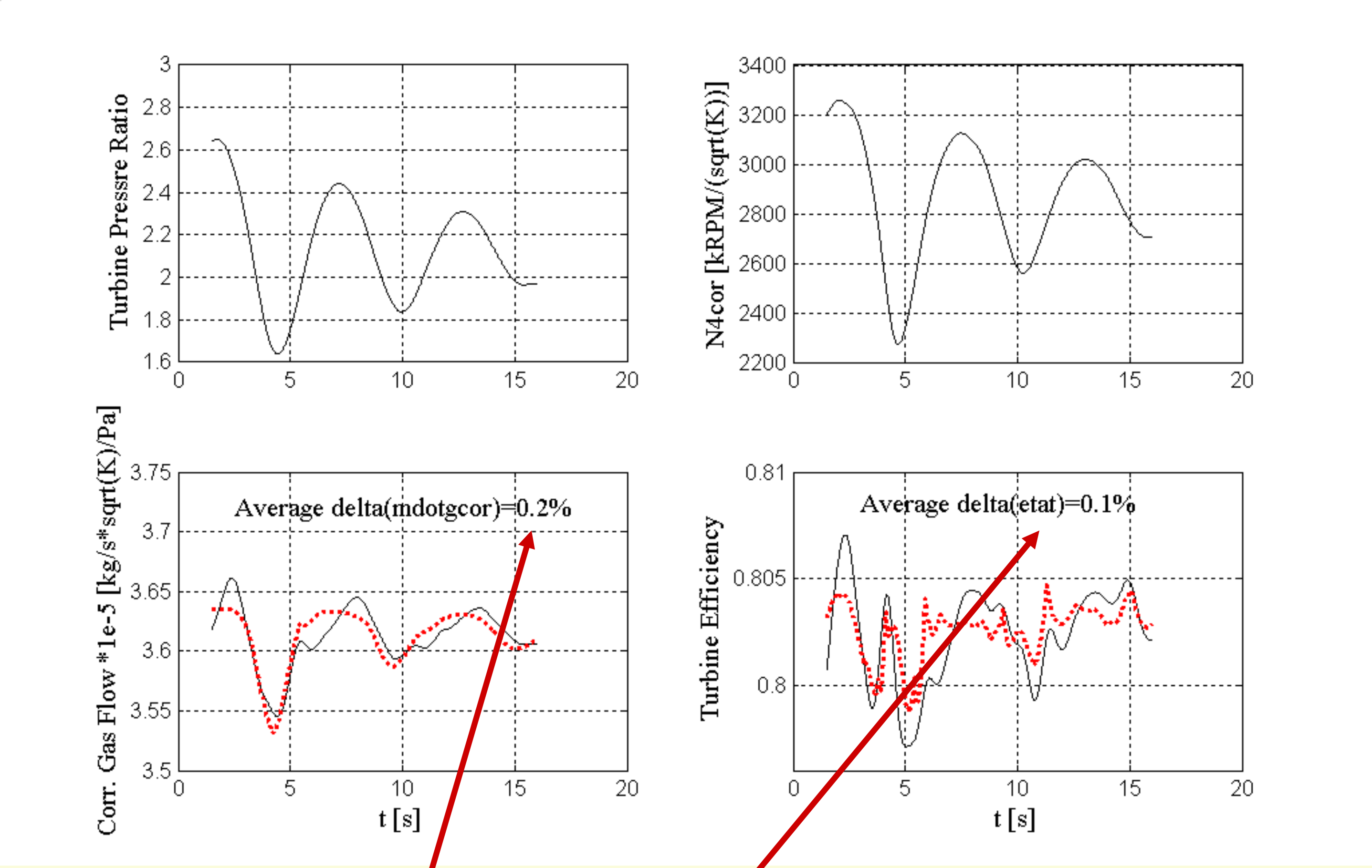


$$\Delta T_{03}^{CN} = 5\% \quad > \quad Tolerance(T_{03})$$

21. Comparison of compressor exit temperatures measured and simulated in Simulation 1b.

Simulation 1b (Continued)

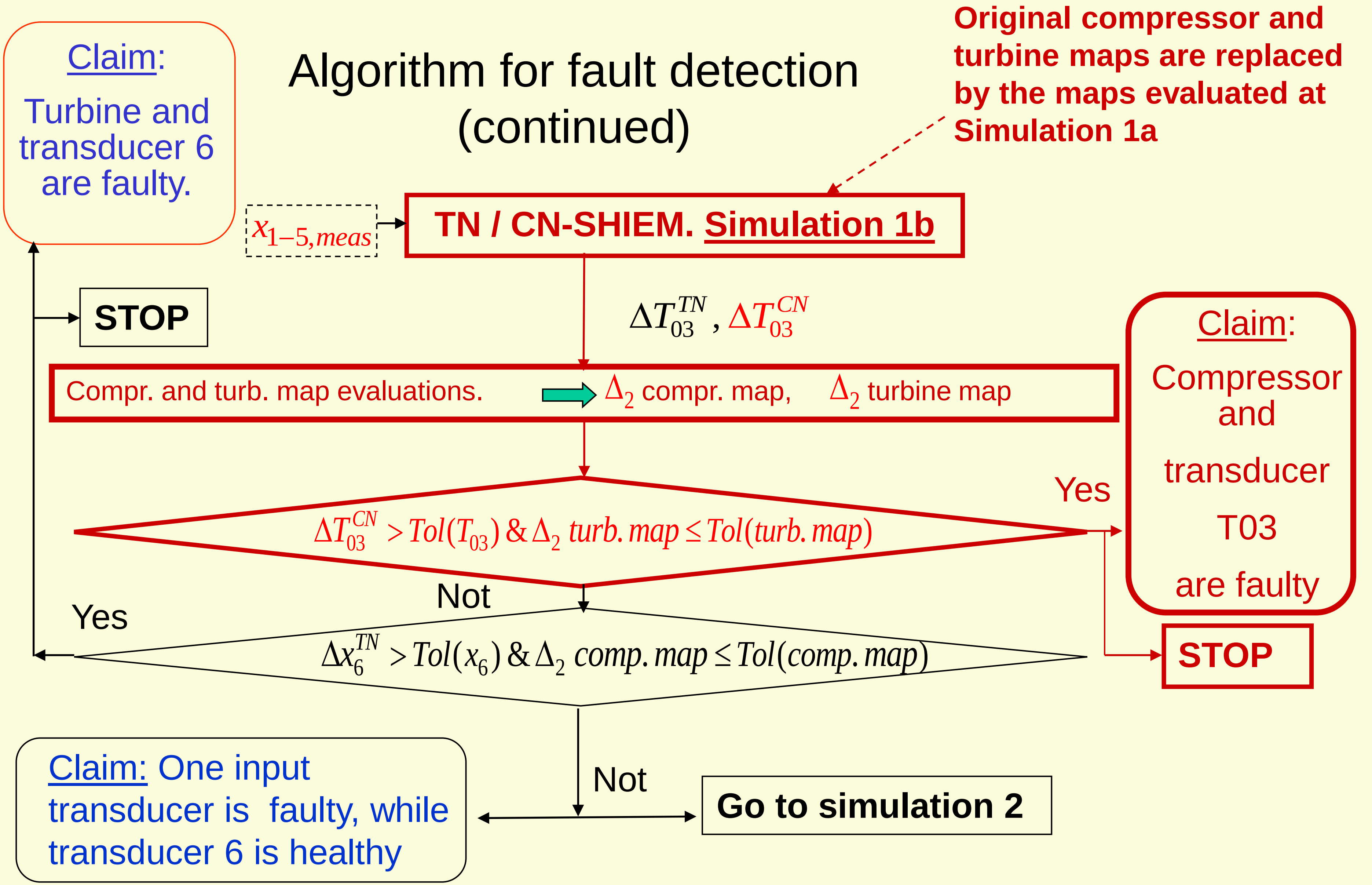
Turbine map quantities of Simulation 1b:



$$\Delta \dot{m}_{4,cor} = 0.2\%, \quad \Delta \eta_t = 0.1\% \quad < \quad Tol(turb.\, map)$$

22. Comparison of turbine map quantities (solid lines) with data calculated using original turbine and recovered Compressor maps (dotted lines).

Algorithm for fault detection (continued)



23. Algorithm of fault detection for one off six transducers or/and one off two engine components. **Simulation 1b**

Final conclusion:

Compressor and transducer T_{03} are faulty.

CONCLUSIONS

1) The method of replacing engine component maps by evaluated ones can be used for engine component map and transducers fault diagnosis using data acquisition during transient operation.

2) The present fault diagnosis method refers to a single fault engine component simultaneously with a single faulty transducer that could be present in the single spool engine. *The minimal required measured quantities is six* for the present fault diagnosis method

3) Only one strategy of fault detection has been described in the present paper. However, alternative algorithms using this method can be developed for different combinations of transducers and engine component maps fault detection.