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

גילוי תקלות בחישנים וריכבי מנוע סילון על י義 שימור בﻣ purpos

ביצועים המשוクロות בדמד תמרונים

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1. Jet engine component and transducer fault diagnosis using component map replacement
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
3. Engine stations

Drawing refers to the AMT Netherlands B.V. Olympus Design.
The Problem Formulation:

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.

4. Fault detection problem
5. Conventional dynamic engine model

**Background**

**Conventional Dynamic Engine Model**

- \( H, M, \dot{m}_j(t) \)
- \( H, M, \dot{m}_j(t) \)
- \( N(t), \dot{m}_a(t) \)
- \( T_{02}(t) \ldots T_{07}(t) \)
- \( P_{02}(t) \ldots P_{07}(t) \)
- \( \eta_c, \eta_t \)
- \( SM(t), \varphi(t) \)

Initial Condition: \( N_{t=0} \)
Compressor Map:

\[ F_1 \left( m_{2,\text{corr}}, \frac{P_{03}}{P_{02}}, N_{2,\text{corr}} \right) = 0 ; \quad F_2 \left( m_{2,\text{corr}}, \frac{P_{03}}{P_{02}}, \eta_c \right) = 0 \]

6. Compressor map
Turbine Map:

\[ \dot{m}_{4,\text{corr}} = F_3 \left( \frac{P_{04}}{P_{05}}, N_{4,\text{corr}} \right) ; \quad \eta_t = F_4 \left( \frac{P_{04}}{P_{05}}, N_{4,\text{corr}} \right) \]
We assume the validity of a conventional model for the jet engine

Input Values.

\[ VAL_{in} = \text{number of input values} \]

Output Values.

\[ VAL_{out} = \text{number of output value} \]

Conventional Engine Model

Thermodynamic equations

(THERM - thermodynamic equation number)

Complete Conventional Model Conditions:

\[ MAP_{in} + THERM = VAL_{out} \] (1)

Input Engine Component Maps.

\[ MAP_{in} = \text{number of input map Eqs.} \]

8. Complete conventional model conditions
Validity criteria for the **Shortened Inverse Engine Model**

**Input Values**

\[ \text{VAL}_{\text{in}} = \text{number of input values} \]

**Input Engine Component Maps**

\[ \text{MAP}_{\text{in}} = \text{number of input map Eqs.} \]

**Output Values**

\[ \text{VAL}_{\text{out}} = \text{number of output values} \]

**Output Engine Component Maps**

\[ \text{MAP}_{\text{out}} = \text{number of output map Eqs.} \]

(some maps are known (MAP\text{in}) and some are recovered (MAP\text{out})

**Complete Shortened Inverse Model Conditions**:

\[ \text{VAL}_{\text{in}} + \text{VAL}_{\text{out}} = (\text{VAL}_{\text{in}} + \text{VAL}_{\text{out}})_{\text{conv}} \] (2)

\[ \text{MAP}_{\text{in}} + \text{THERM} = \text{VAL}_{\text{out}} \] (3)

9. Complete inverse model conditions
Combined TN/CN Shortened Inverse Engine Model

- **Input**: TN / CN-SHIEM
- **Output**:
  - Parameters for reconstructing the compressor map:
    - $\frac{P_{02}(t)}{P_{03}}$, $m_{a,corr}(t)$, $N_{corr}(t)$, $\eta_c(t)$, ...
  - Parameters for reconstructing the turbine map:
    - $\frac{P_{04}(t)}{P_{05}}$, $m_{4,corr}(t)$, $N_{4,corr}(t)$, $\eta_t(t)$, ...

SixMeasured Quantities

- $x_{1,meas}(t)$
- $x_{2,meas}(t)$
- $x_{3,meas}(t)$
- $x_{4,meas}(t)$
- $x_{5,meas}(t)$
- $x_{6,meas}$

**Parameters for reconstructing the compressor map**

**Parameters for reconstructing the turbine map**

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

10. Combined shortened inverse engine model
11. Methodology

- The SHIEM is applied twice, simultaneously, with same input parameters: once to recover the compressor map and once to recover the turbines map.
- The recovered maps are compared to the engine's original (reference) maps.
- The recovered maps are used to substitute the original maps in the two SHIEMs.
- We apply again the SHIEM, re-evaluate the component map and compare with the reference maps.
- Whenever the differences are large — an additional simulation is applied.
Algorithm for fault detection

Original Compressor, Turbine and Nozzle Maps

TN / CN-SHIEM. Simulation 1a

Claim: Engine and transducers are healthy.

Claim: Compressor is faulty, all transducers are healthy.

Fault compr. map is evaluated.

STOP

Claim: Turbine is faulty, all transducers are healthy.

Fault turbine map is evaluated.

STOP

Claim: Transducer 6 is faulty. Engine is healthy

Go to simulation 1b

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

Claim: Turbine and transducer 6 are faulty.

\[ x_{1-5, meas} \rightarrow TN / CN-SHIEEM. Simulation 1b \]

\[ \Delta x_6^{TN}, \Delta x_6^{CN} \]

Compr. and turb. map evaluations \[ \Delta \text{2 compressor map} \& \Delta \text{2 turbine map} \]

CN-SHIEEM

\[ \Delta x_6^{CN} > \text{Tol}(x_6) \& \Delta \text{2 turb. map} \leq \text{Tol(turb. map)} \]

Yes

Not

TN-SHIEEM

\[ \Delta x_6^{TN} > \text{Tol}(x_6) \& \Delta \text{2 comp. map} \leq \text{Tol(comp. map)} \]

Claim: One of the input transducers is faulty, while transducer 6 is healthy

Original compressor and turbine maps are replaced by the maps evaluated at Simulation 1a

Claim:

Not

Go to simulation 2

STOP

STOP

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

<table>
<thead>
<tr>
<th>Simulation No.</th>
<th>Numbers of input transducers (blue large figures correspond to healthy transducer)</th>
<th>Transducer number compared to simulation</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1,2,3,4,5</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>6,1,2,3,4</td>
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<td>5,6,1,2,3</td>
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<tr>
<td>4</td>
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<td>3</td>
</tr>
<tr>
<td>5</td>
<td>3,4,5,6,1</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2,3,4,5,6</td>
<td>1 (is faulty)</td>
</tr>
</tbody>
</table>

14. Simulations 1 to 6: Algorithm of fault detection for one off six transducers or/and one off two engine components.
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 $\eta_C$
- measurement bias of -5% for the fault transducer $T_{03}$

15. Example of fault diagnosis
Engine maneuver at H=5000ft, M=0.5

\[ \Delta T^{TN}_{03} = 5\%, \quad \Delta T^{CN}_{03} = 8\% > \text{Tolerance}(T_{03}) \]

16. Command and six measured quantities. Simulated and measured \( T_{03} \) comparisons.
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)
18. Compressor map fragment evaluated using data of Simulation 1a.
19. Comparison of the evaluated compressor map fragment with the original map.

\[ \Delta \text{comp. map} = 4\% \quad > \quad \text{Tolerance(comp. map)} \]
20. **Simulation 1a:** Algorithm of fault detection for one off six transducers or/and one off two engine components.
Comparison of Simulated and Measured Compressor Temperature:

\[ \Delta T_{\text{CN}}^{03} = 5\% > \text{Tolerance}(T_{03}) \]

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

Turbine map quantities of Simulation 1b:

$$\Delta m_{4,\text{cor}} = 0.2\%,$$  \(\Delta \eta_t = 0.1\% < \text{Tol(turb. map)} \)
Algorithm for fault detection (continued)

Claim: Turbine and transducer 6 are faulty.

Original compressor and turbine maps are replaced by the maps evaluated at Simulation 1a

STOP

Compr. and turb. map evaluations. → Δ₂ compr. map, Δ₂ turbine map

ΔT₀₃^{TN}, ΔT₀₃^{CN}

ΔT₀₃^{CN} > Tol(T₀₃) & Δ₂ turb. map ≤ Tol(turb. map)

Yes

Not

Δx₆^{TN} > Tol(x₆) & Δ₂ comp. map ≤ Tol(comp. map)

Claim: One input transducer is faulty, while transducer 6 is healthy

Go to simulation 2

Claim: Compressor and transducer T03 are faulty

STOP

Δx₁⁻⁵, meas → TN / CN-SHIEM. Simulation 1b

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.