PERFORMANCE MODEL "ZOOMING" FOR IN-DEPTH COMPONENT FAULT DIAGNOSIS

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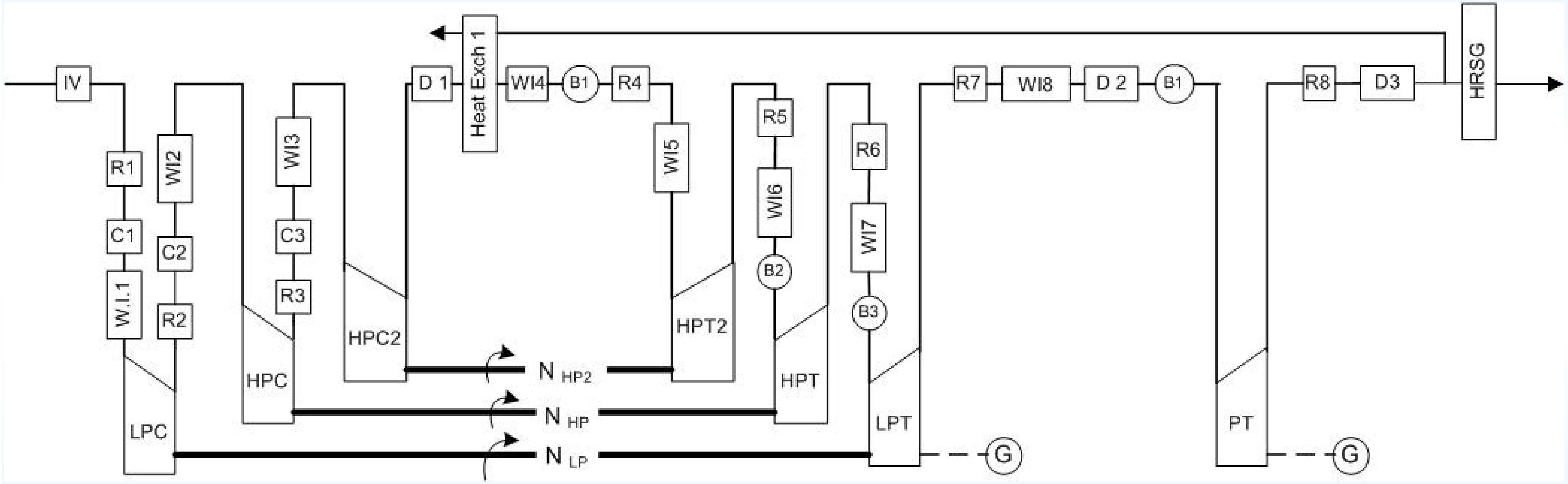
Performance Model "Zooming" for In-depth Component Fault Diagnosis

- A method giving the possibility for a more detailed Gas Path Component fault diagnosis, by exploiting the "zooming" feature of current modelling techniques is presented
- The basic concept of the work is that a 0-D GPA model can be used to point to the faulty component, while a component model of higher fidelity coupled with the engine model can give a more detailed diagnostic information with no additional measurements using empirical knowledge to derive information for typical faults
- For the application of the method a 1-D compressor model is used in conjunction with a GPA engine model, applying a 1-D zooming approach for the compressor

Performance Model "Zooming" for In-depth Component Fault Diagnosis

- **DIAGNOSTIC MODELLING**
  - **Engine Adaptive Model**
  - **Compressor Adaptive Model**
  - **Zooming Feature**
- **COMPRESSOR FAULTS MODELLING**
- **APPLICATION OF THE METHOD**
  - **Fault Simulation**
  - **Engine Level Diagnosis**
  - **Stage Level Diagnosis**
- **SUMMARY & CONCLUSIONS**

Engine Adaptive Model



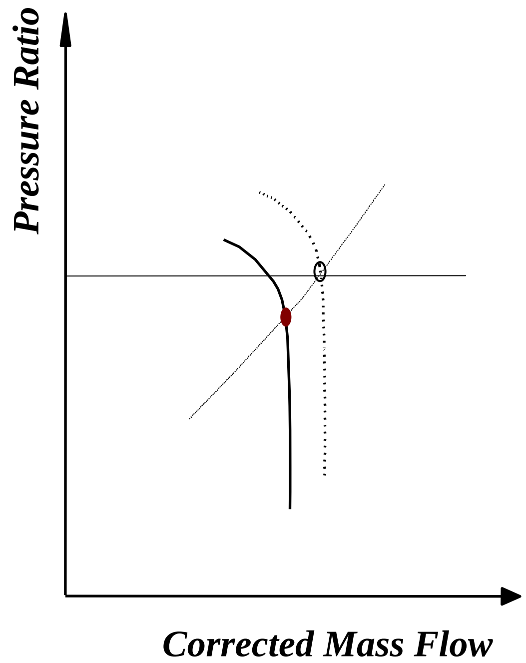
Desire to represent the performance of an individual engine as accurately as possible in all situations

Engine Adaptive Model

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

X_{act} Actual value for parameter

X_{ref} Reference value for parameter



Transformation of component performance maps

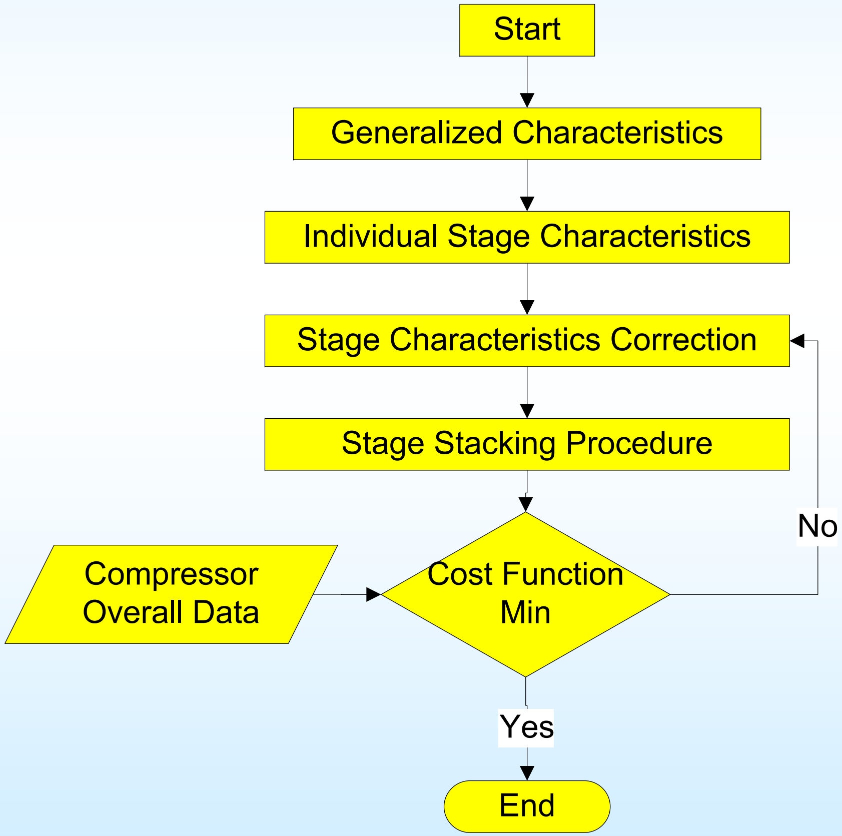
Compressor Adaptive Model

Adaptive Stage Stacking Method

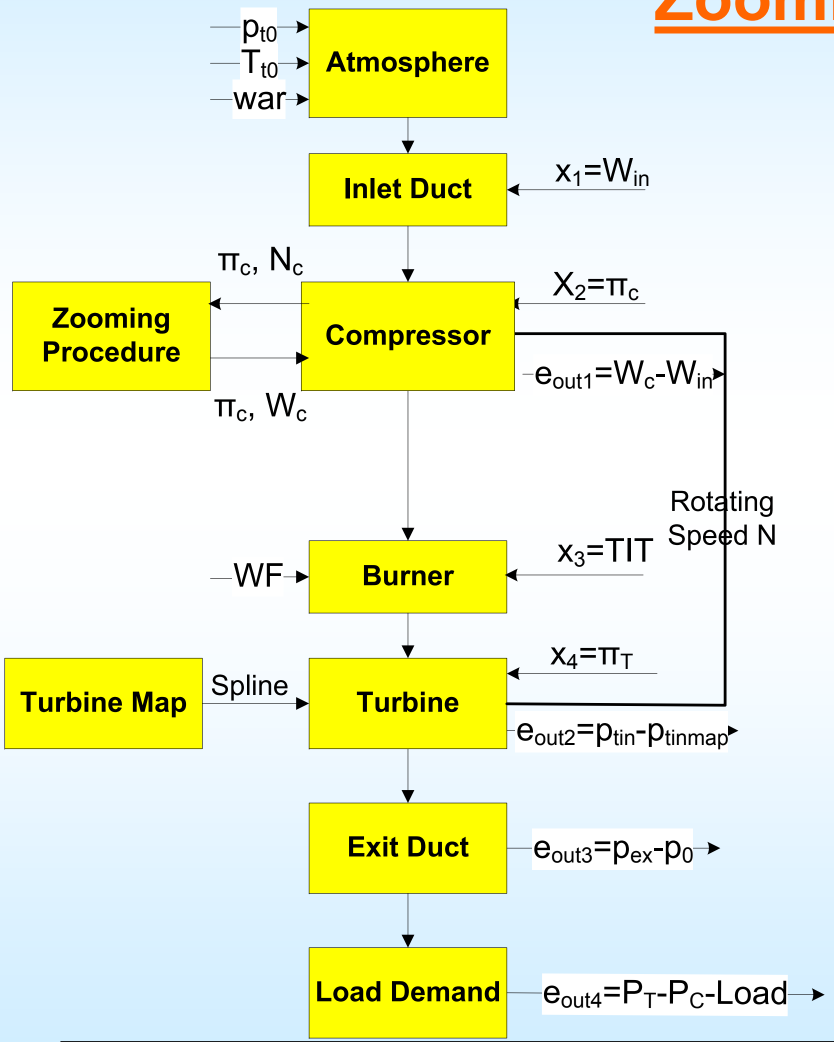
- Establishment of Compressor Stall Limits
- Determination of the Effect of Bleeds and Variable Geometry
- Derivation of Individual Stage Characteristics using MFs

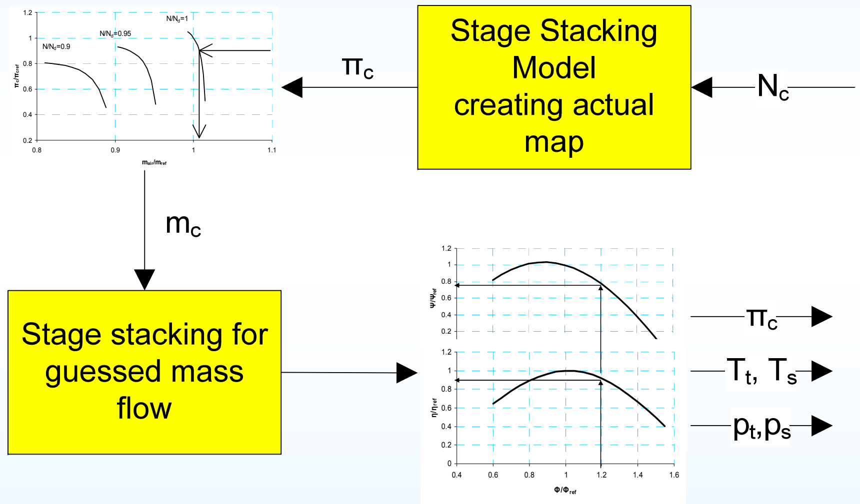
$$f_{\Phi i} = \frac{\Phi_{ref,act}}{\Phi_{ref}} \qquad f_{\eta i} = \frac{\eta_{ref,act}}{\eta_{ref}}$$

$$f_{\Psi i} = \frac{\Psi_{ref,act}}{\Psi_{ref}}$$



Zooming Feature

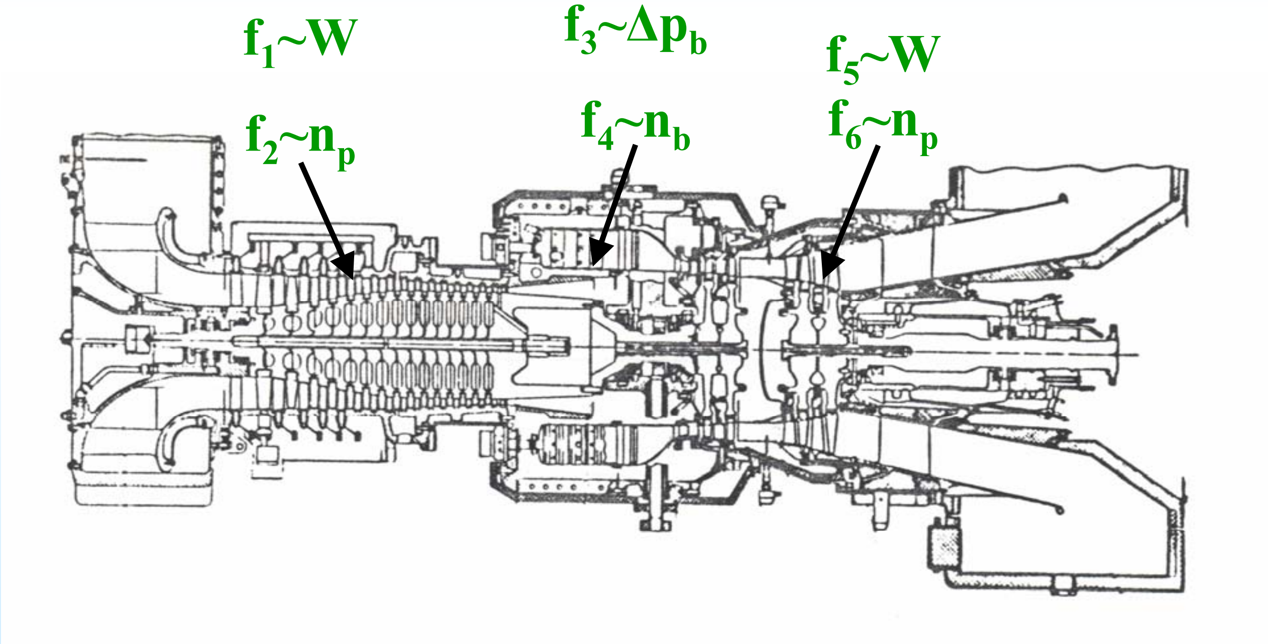




Diagnostic Modelling

Engine Level Diagnosis

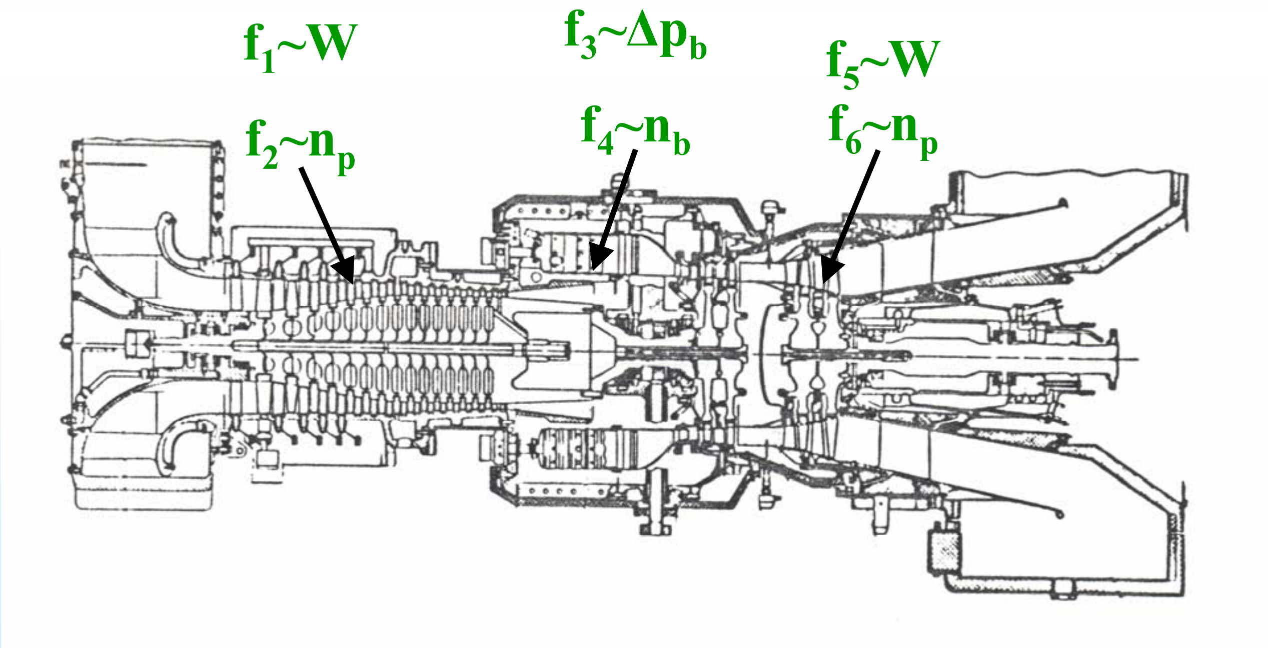
- **Gas Path Analysis, using 0-D modelling and deriving Components Modification Factors**



Diagnostic Modelling

Engine Level Diagnosis – Higher Fidelity

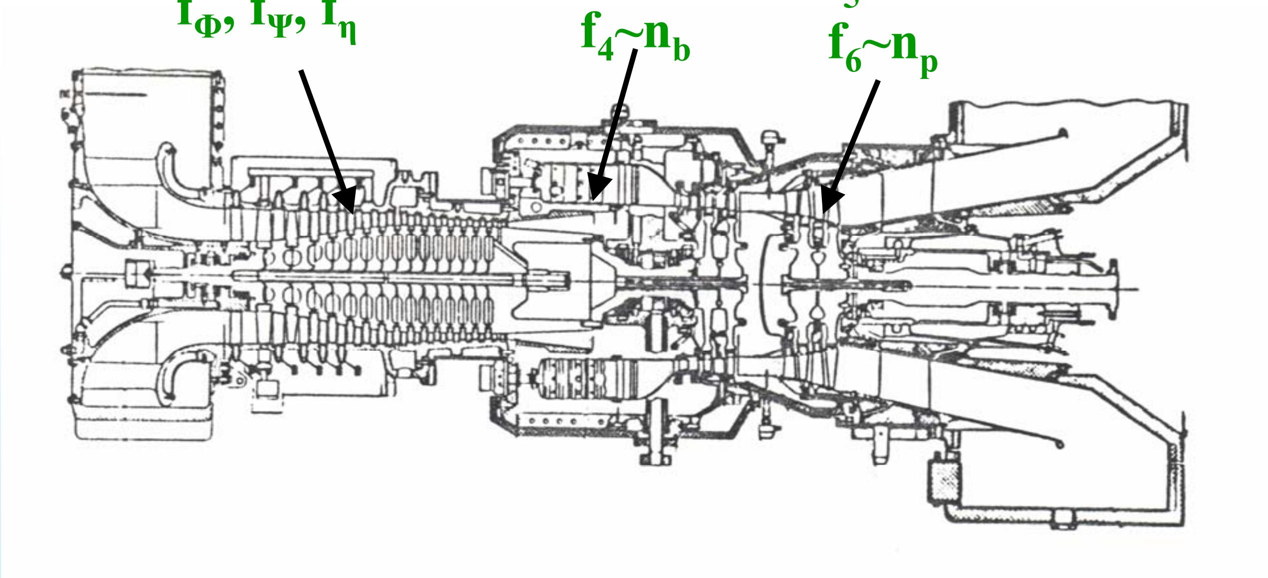
- **Gas Path Analysis, using the zooming feature for the healthy compressor map evaluation and deriving components Modification Factors: Higher Fidelity for the Compressor**



Diagnostic Modelling

Stage Level Diagnosis

- **Gas Path Analysis in combination with Compressor Adaptive Modelling, thus deriving Compressor Stages Modification Factors. In this case appropriate fault modeling is needed in order to reduce the number of unknowns**



Performance Model "Zooming" for In-depth Component Fault Diagnosis

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  - Zooming Feature
- **COMPRESSOR FAULTS MODELLING**
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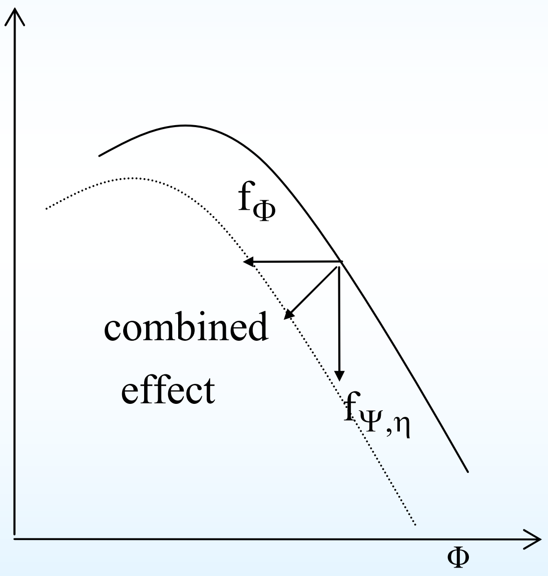
Compressor Faults Modelling

Modification Factors for Faults - Simulation

$$f_{\Phi i} = \left[1 - S \cdot N_i \cdot \left(1 - M_{\Phi}\right)\right]$$

$$f_{\Psi i} = \left[1 - S \cdot N_i \cdot \left(1 - M_{\Psi}\right)\right]$$

$$f_{\eta i} = \left[1 - S \cdot N_i \cdot \left(1 - M_{\eta}\right)\right]$$



$S \in [0,1]$ Fault Severity Factor

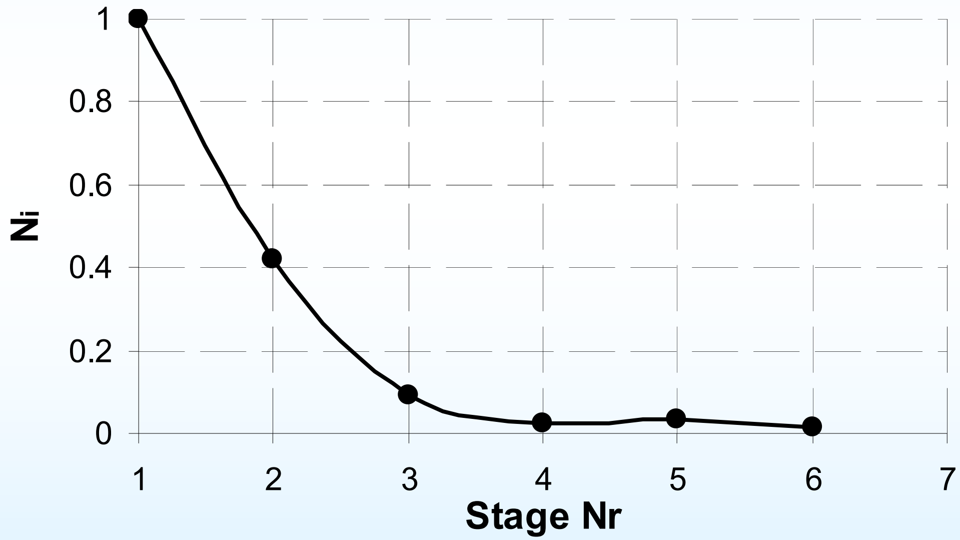
$N_i \in [0,1]$ Distribution Factor

$M_{\Phi,\Psi,\eta}$ Transformation factors: Modification factors for the most affected stage

Compressor Faults Modelling

Compressor Fouling

➢ **Determining the possible distribution of deposits (N_i) via published experimental data.**

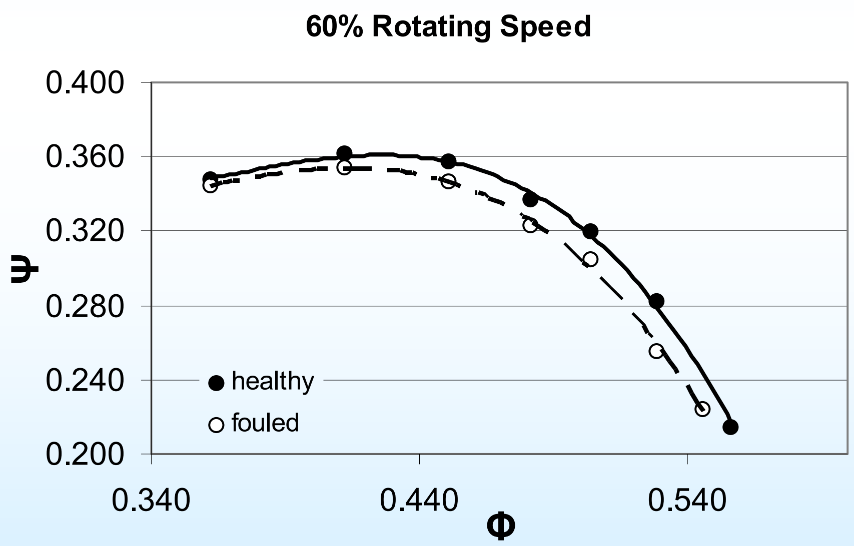


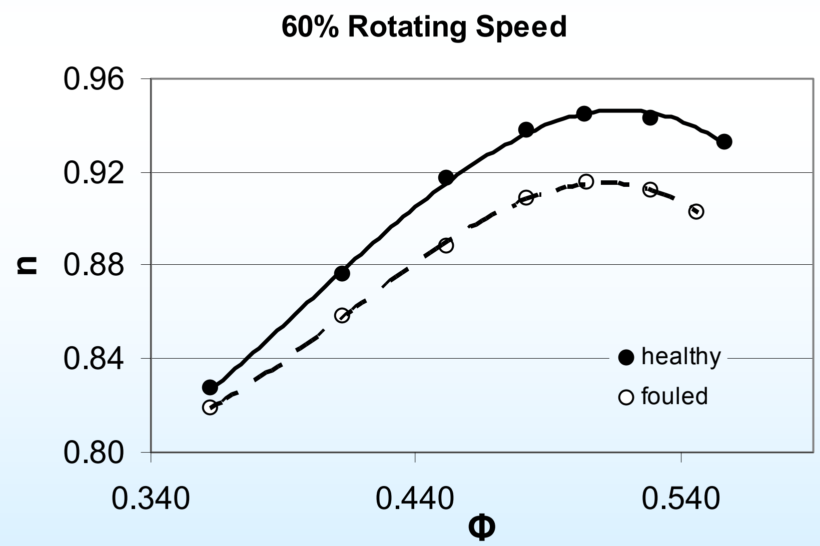
▪ **The distribution is not linear but close to exponential with the first two stages significantly more prone to fouling than the subsequent ones.**

Compressor Faults Modelling

Compressor Fouling

- **Determine the effect of fouling at the performance characteristics of the stage that is most susceptible to fouling (M_{Φ},M_{Ψ}, M_{η}) via published experimental data**



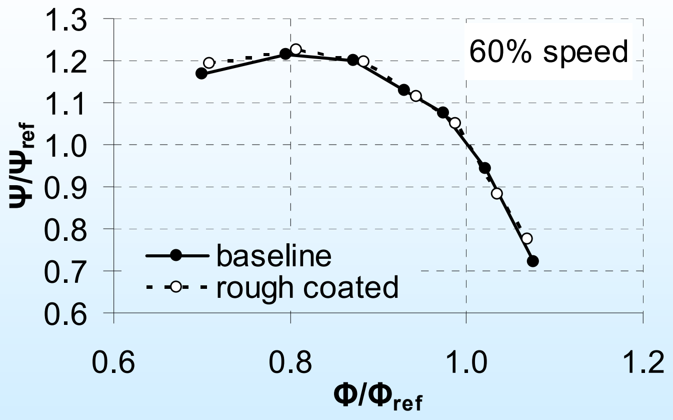


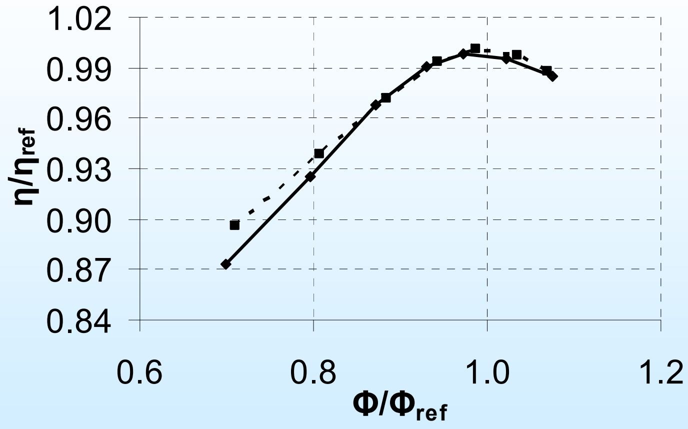
Compressor Faults Modelling

Compressor Fouling

➢ **Determine the effect of fouling at the performance characteristics of the stage that is most susceptible to fouling (M_Φ,M_Ψ, M_η) via published experimental data**

	$\Phi_{ref,fault}/\Phi_{ref}$	$\Psi_{ref,fault}/\Psi_{ref}$	$\eta_{ref,fault}/\eta_{ref}$
M_i	0.986	0.970	0.966





Compressor Faults Modelling

Compressor Tip Clearance Increase

- **Determining the possible distribution of blade erosion (N_i) via published experimental data. A distribution factor as a function of blade height was selected to model tip clearance increase.**

$$N_{i=1,K} = N_K \cdot \frac{h_K}{h_{i=1,K}}$$

- **Determine the effect of tip clearance increase at the performance characteristics of the stage that is most susceptible to erosion (M_Φ,M_Ψ, M_η) via published experimental data.**

	$\Phi_{ref,fault}/\Phi_{ref}$	$\Psi_{ref,fault}/\Phi_{ref}$	$\eta_{ref,fault}/\eta_{ref}$
M_i	0.965	0.931	0.928

Compressor Faults Modelling

Compressor Blade Erosion

- **Determining the possible distribution of blade erosion (N_i) via published experimental data. A distribution factor as a function of blade height was selected to model blade erosion.**

$$N_{i=1,K} = N_K \cdot \frac{h_K}{h_{i=1,K}}$$

- **Determine the effect of blade erosion at the performance characteristics of the stage that is most susceptible to erosion (M_Φ,M_Ψ, M_η) via published experimental data.**

	$\Phi_{ref,fault}/\Phi_{ref}$	$\Psi_{ref,fault}/\Phi_{ref}$	$\eta_{ref,fault}/\eta_{ref}$
M_i	0.971	0.899	0.967

Compressor Faults Modelling

Modification Factors for Faults - Diagnosis

- **Decrease of unknowns as initially we have 3 Modification Factors per stage for the Compressor**

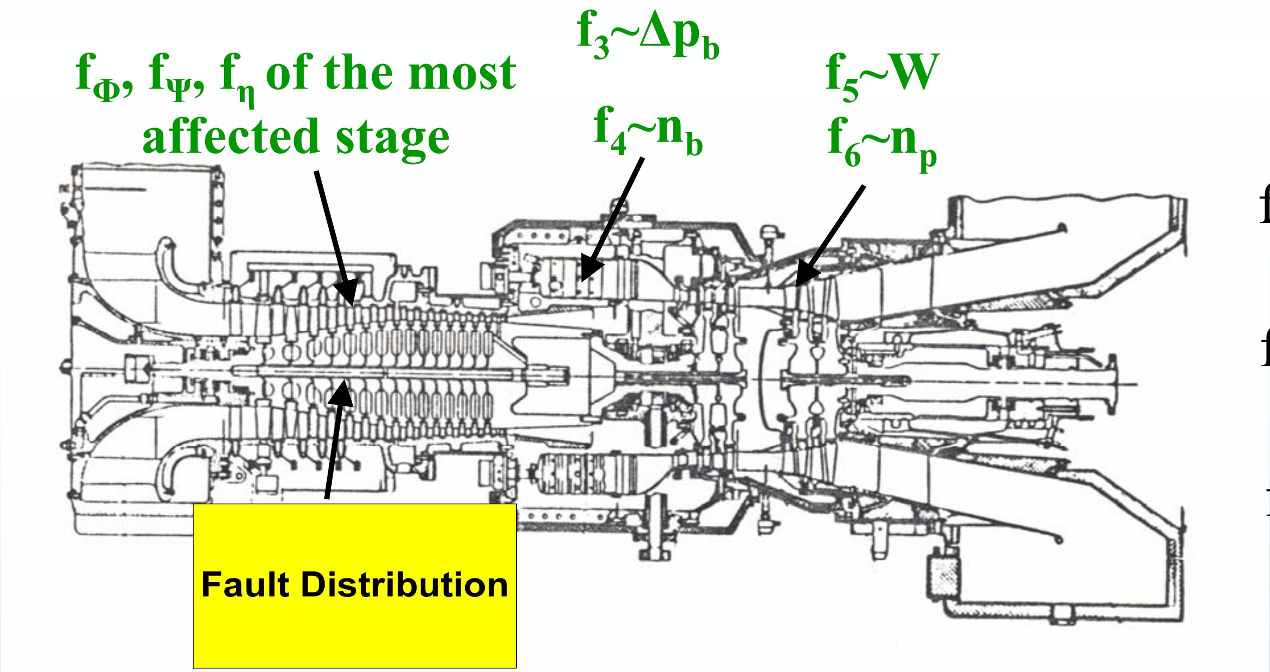
- **The use of Typical Fault Distributions according to research data and operational experience solves this problem**

- **The use of specific fault distributions along the stages reduces the dimensionless modification factors needed for compressor diagnosis to only the ones of the compressor stage with the most severe fault.**

Diagnostic Modelling

Stage Level Diagnosis

- **Gas Path Analysis in combination with Compressor Adaptive Modelling, thus deriving only the Transformation Factors for each tested Fault Distribution**



$$f_{\Phi i} = \left[1 - N_i \cdot \left(1 - M_\Phi\right)\right]$$

$$f_{\Psi i} = \left[1 - N_i \cdot \left(1 - M_\Psi\right)\right]$$

$$f_{\eta i} = \left[1 - N_i \cdot \left(1 - M_\eta\right)\right]$$

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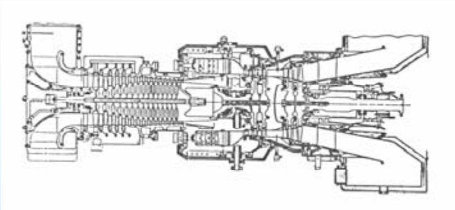
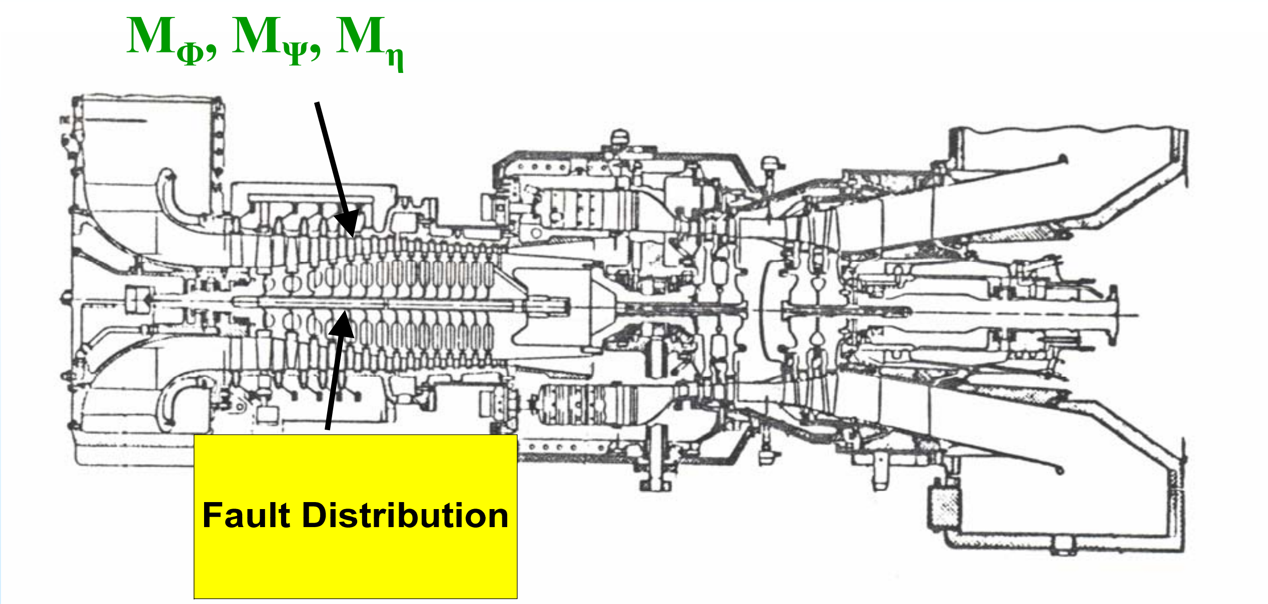


Test Case Engine
Single Shaft Engine (6MW)

Application

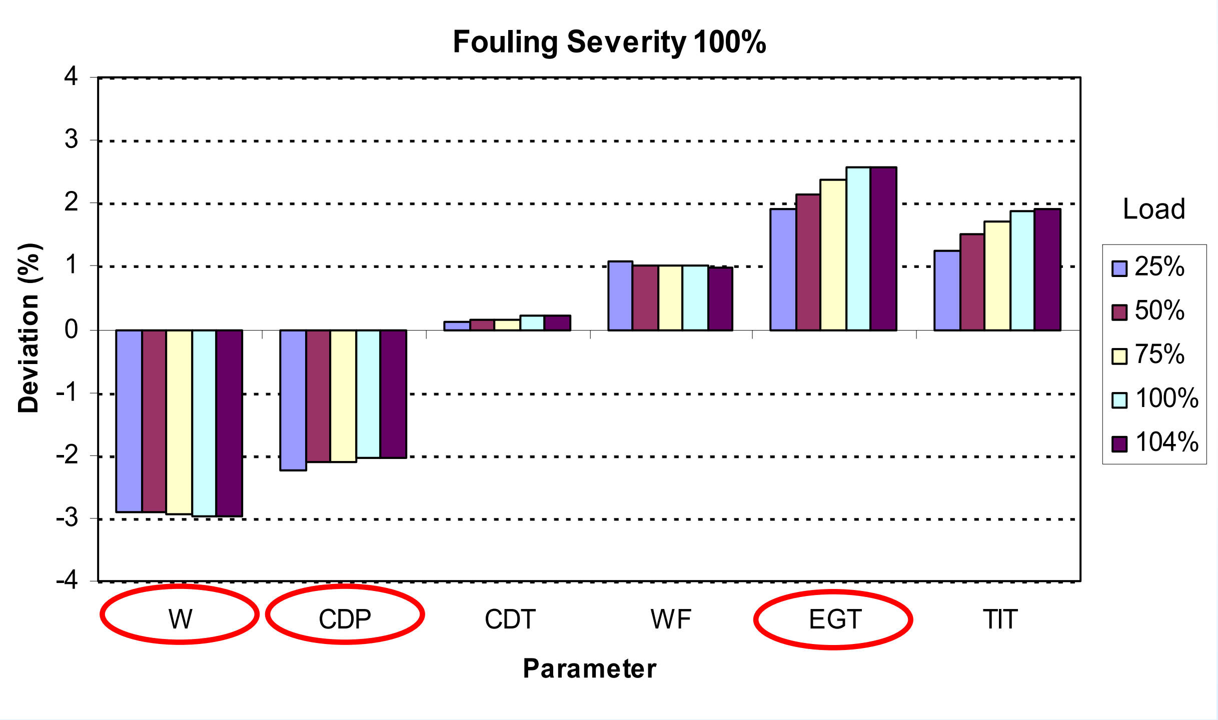
Fault Simulation

➢ **In order to perform fault simulation the transformation factors, the severity factor and the distribution of the faults where applied to the compressor model and the Engine Cycle was calculated for typical power settings**



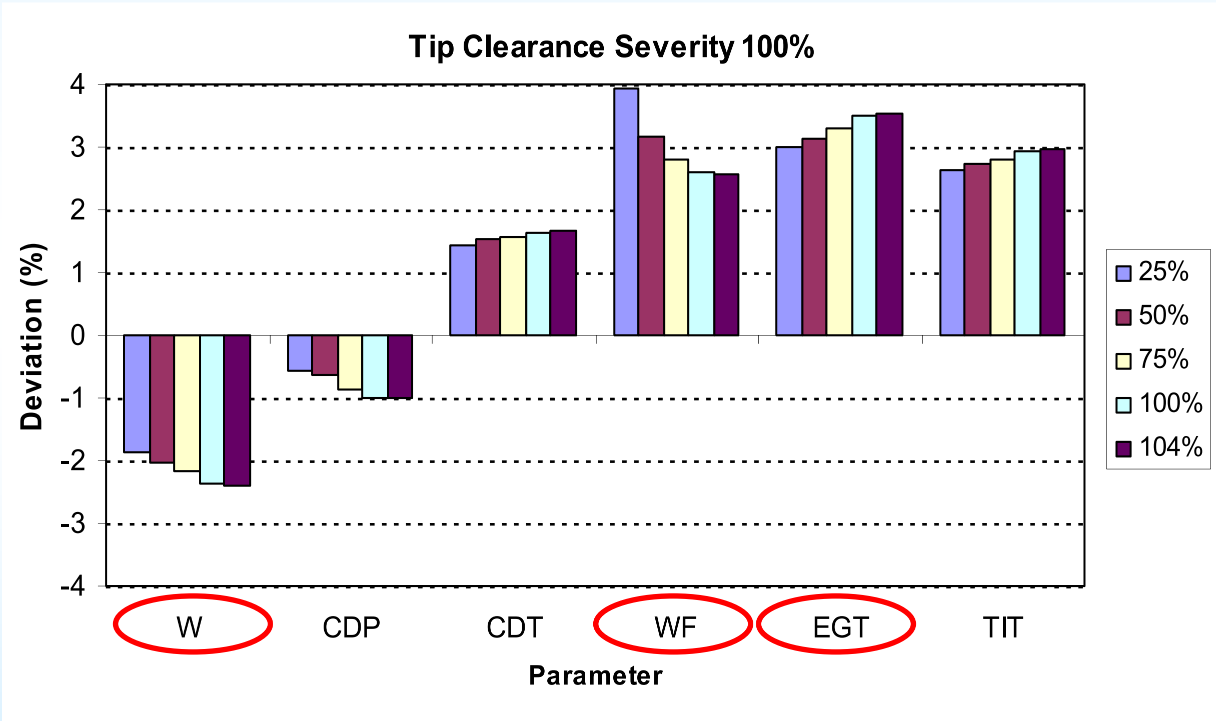
Application

Fault Simulation - Fouling



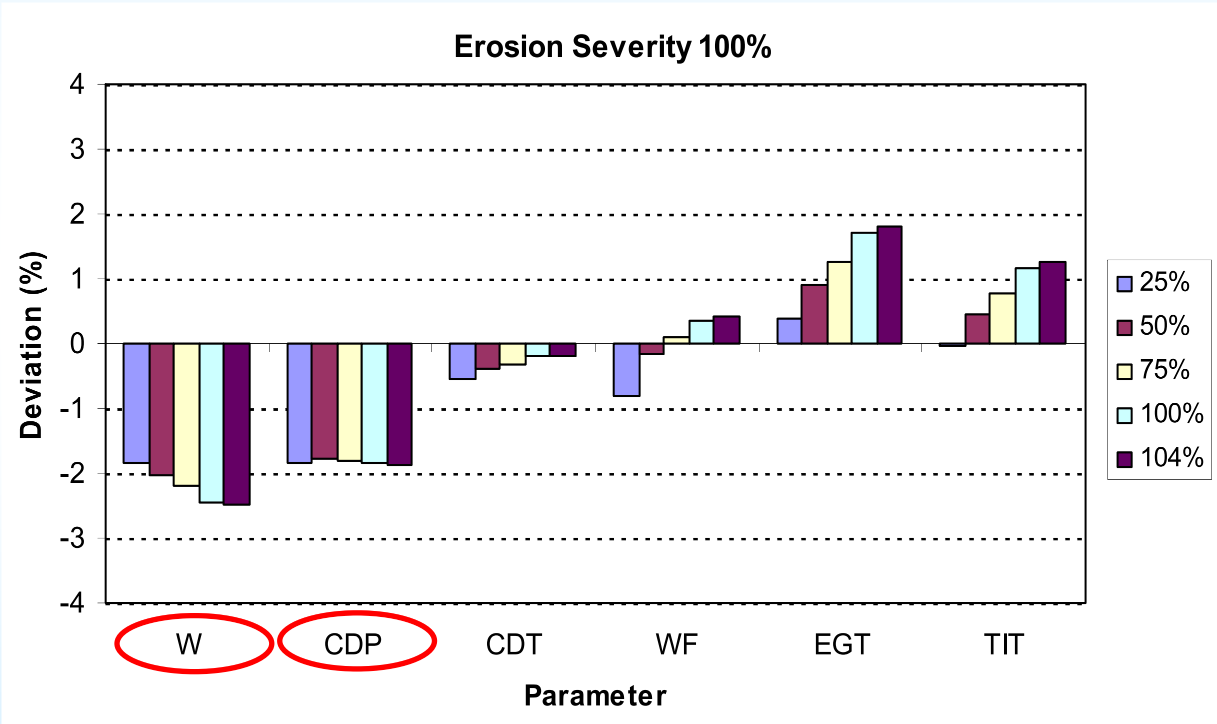
Application

Fault Simulation – Tip Clearance Increase



Application

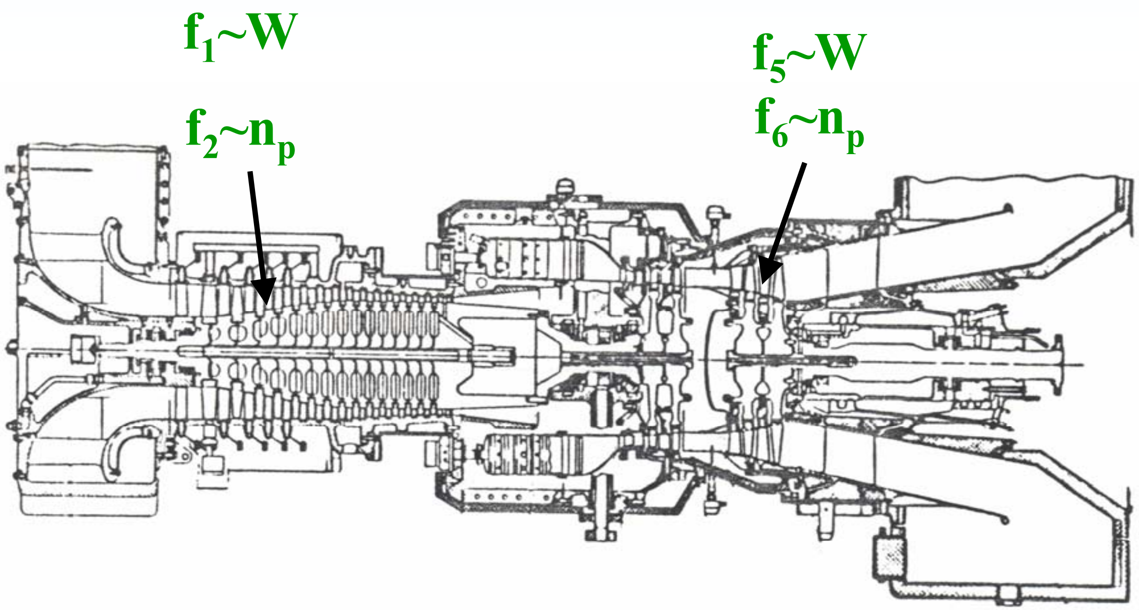
Fault Simulation – Blade Erosion



Application

Engine Level Diagnosis

➢**Gas Path Analysis, using 0-D modelling and deriving components map Modification Factors for the simulated faults**



The basic aim of diagnosis is to answer the questions:

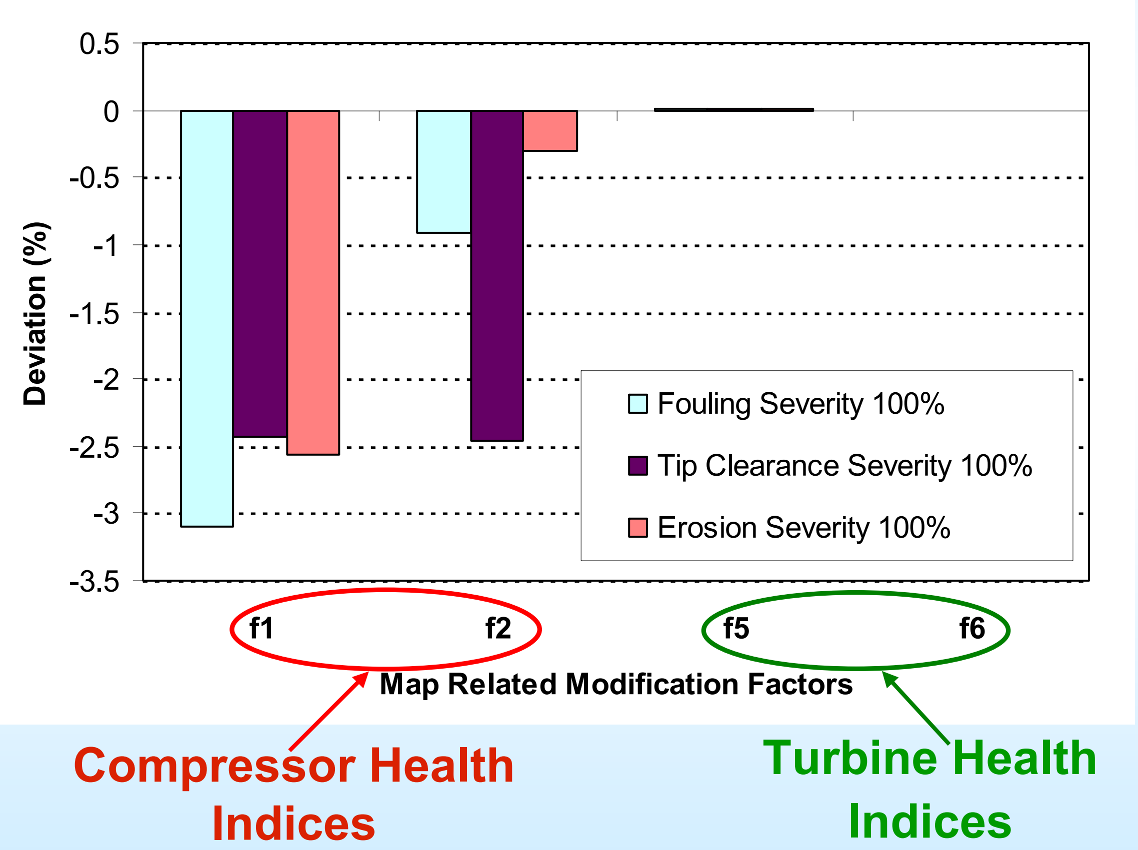
➢**Which is the faulty component?**

➢**What is the severity of the fault?**

➢**What is the type of fault?**

Application

Engine Level Fault Diagnosis

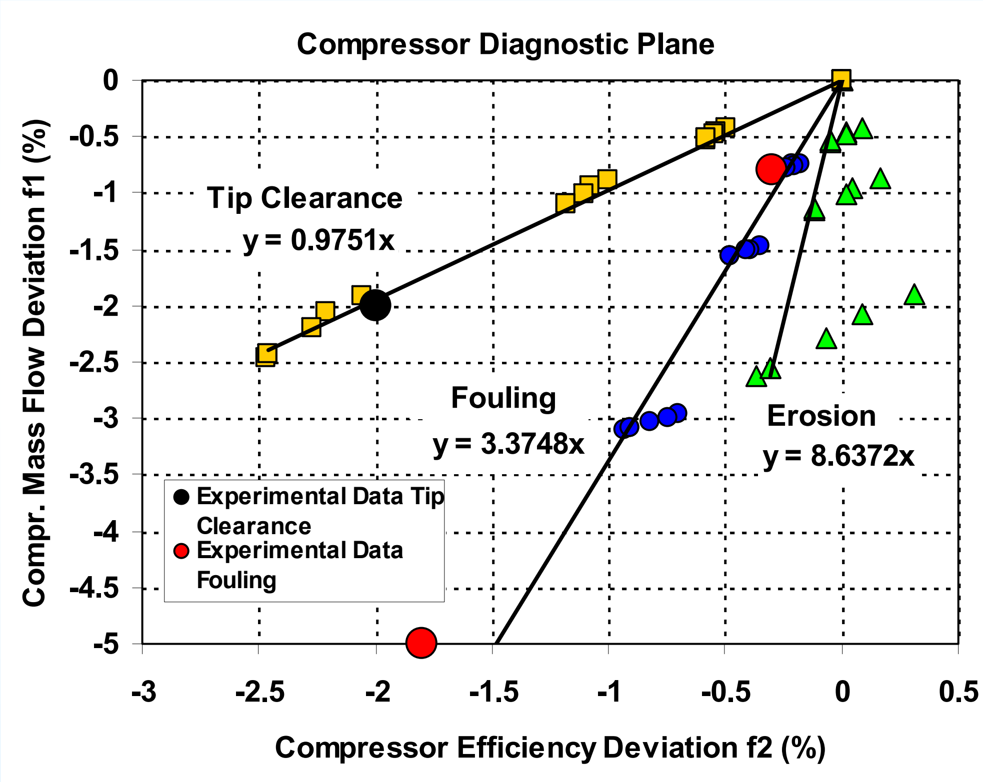


The basic aim of diagnosis is to answer the questions:

- ✓Which is the faulty component?
- ✓What is the severity of the fault?
- ➢What is the type of fault?

Applications

Engine Level Fault Diagnosis



The basic aim of diagnosis is to answer the questions:

- ✓Which is the faulty component?
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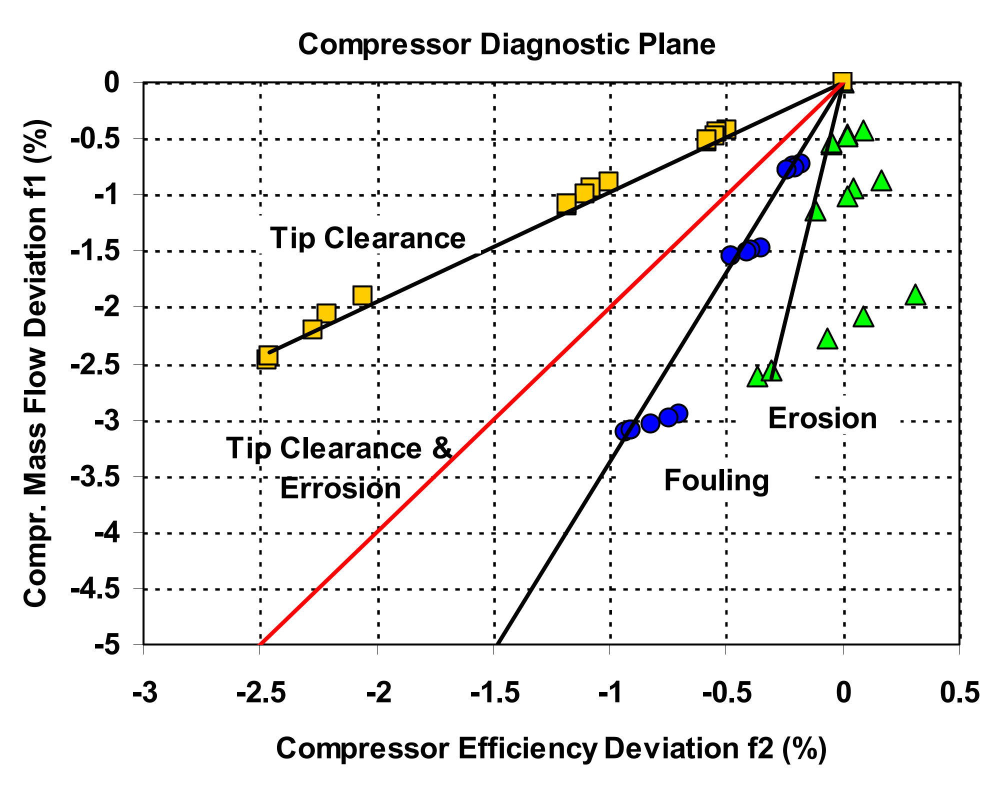
Applications

Engine Level Fault Diagnosis



The basic aim of diagnosis is to answer the questions:

- ✓**Which is the faulty component?**
- ✓**What is the severity of the fault?**
- ✓**What is the type of fault?**
- ➢**Not positive for the case of combined faults**

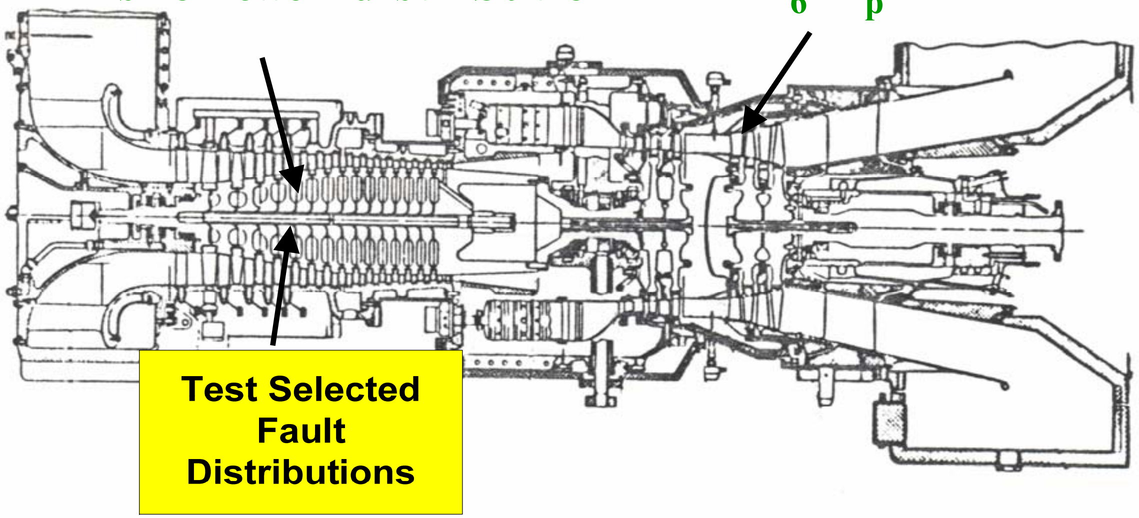
Application

Stage Level Diagnosis

➢Gas Path Analysis in combination with Compressor Adaptive Modelling, thus deriving the Transformation Factors and stages MFs for each tested Fault Distribution

Acquire M_Φ, M_Ψ, M_η and stages MFs for each distribution

$f_5 \sim W$
$f_6 \sim n_p$

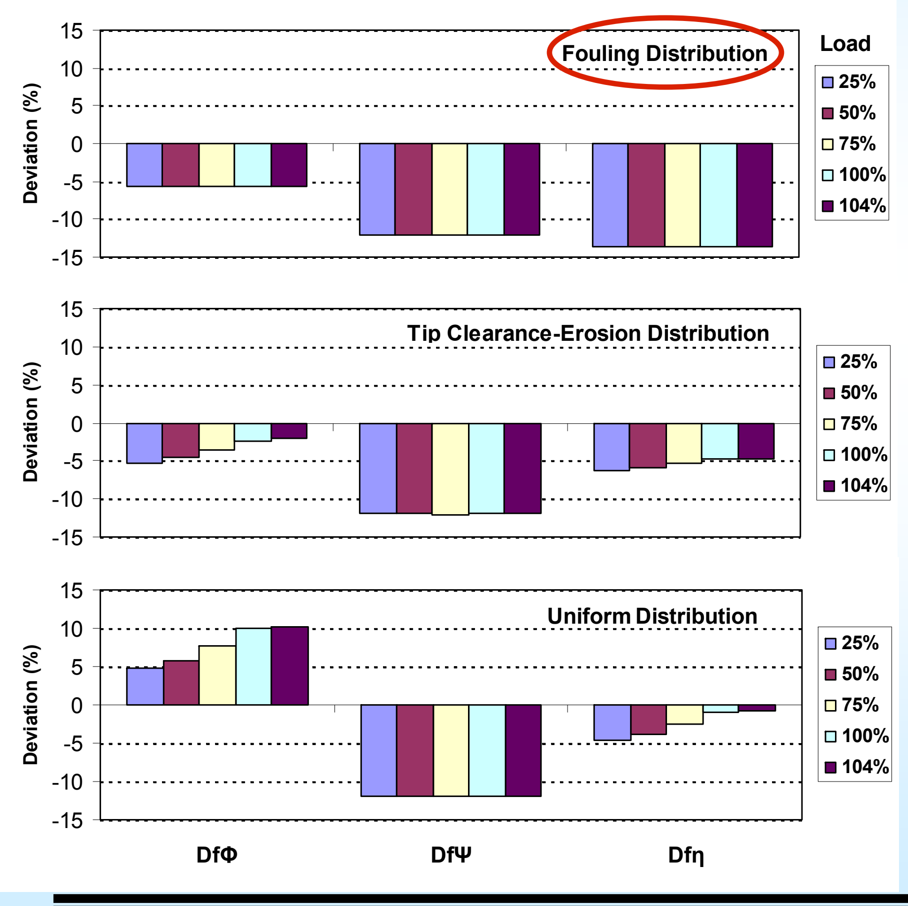


The Distributions tested are:

- ➢Fault Distribution
- ➢Tip Clearance-Erosion Distribution
- ➢A “general” Uniform Distribution

Applications

Stage Level Fault Diagnosis – Fouling



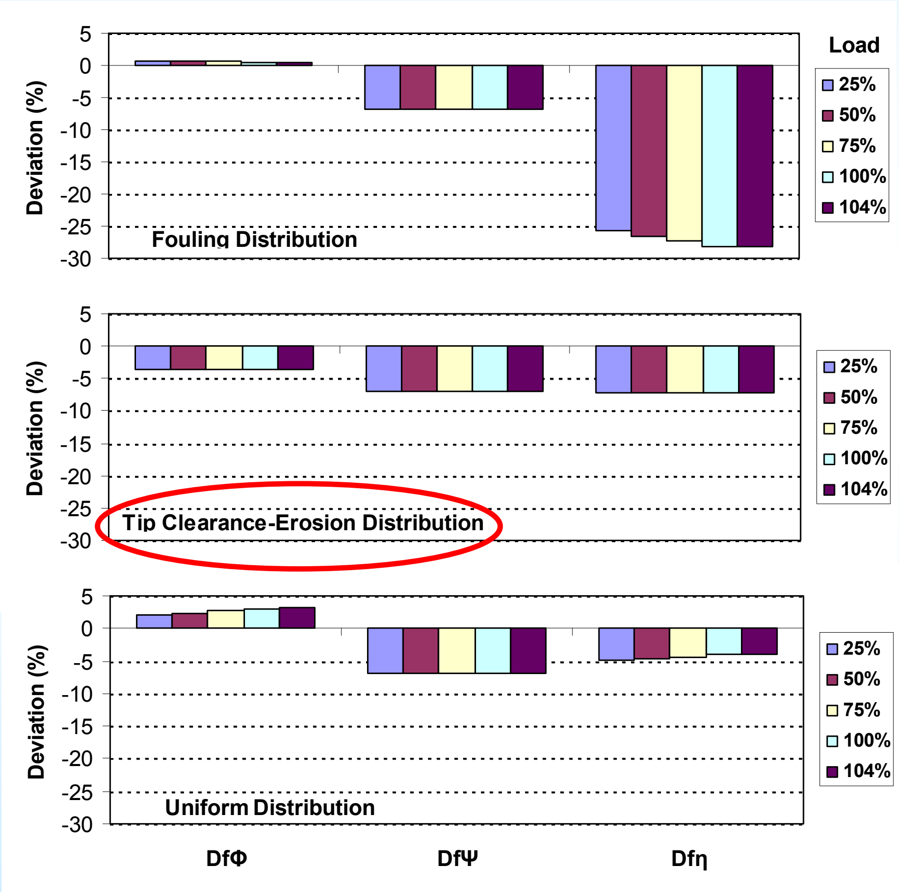
Real Fault: Factors Independent of Power Setting

Wrong Fault: Factors Depending on Power Setting

Wrong Fault: Factors Depending on Power Setting & Non-Physical Solution

Applications

Stage Level Fault Diagnosis – Tip Clearance Increase



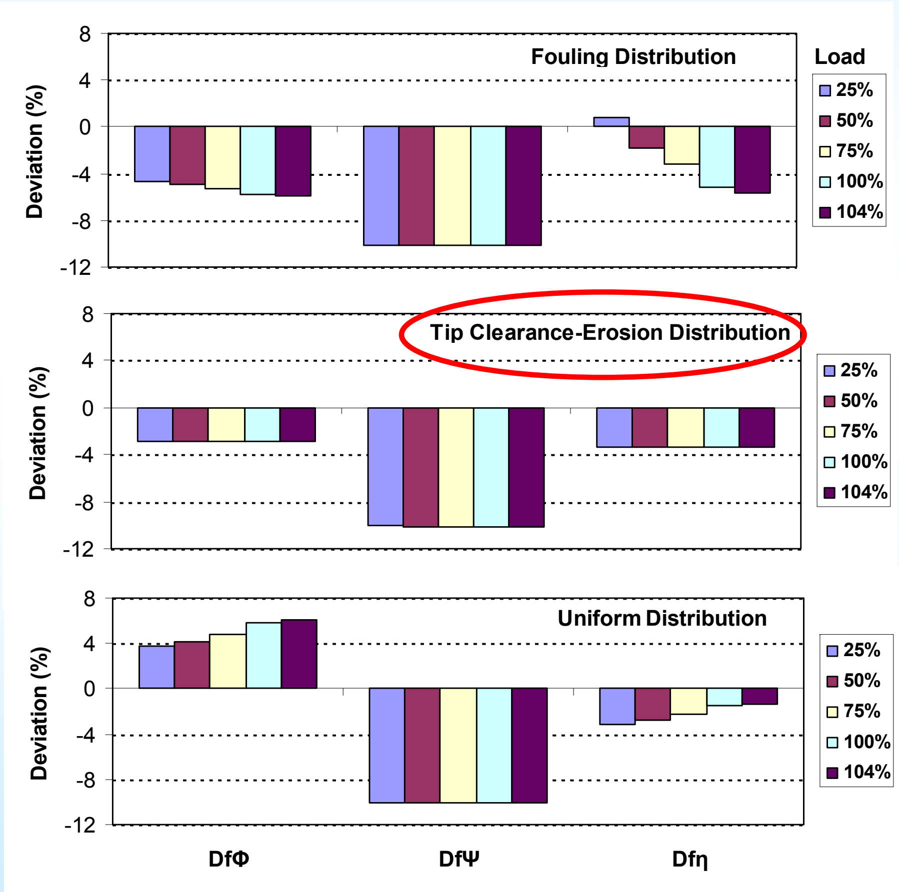
Wrong Fault: Factors Depending on Power Setting & Non-Physical Solution

Real Fault: Factors Independent of Power Setting

Wrong Fault: Factors Depending on Power Setting & Non-Physical Solution

Applications

Stage Level Fault Diagnosis – Erosion



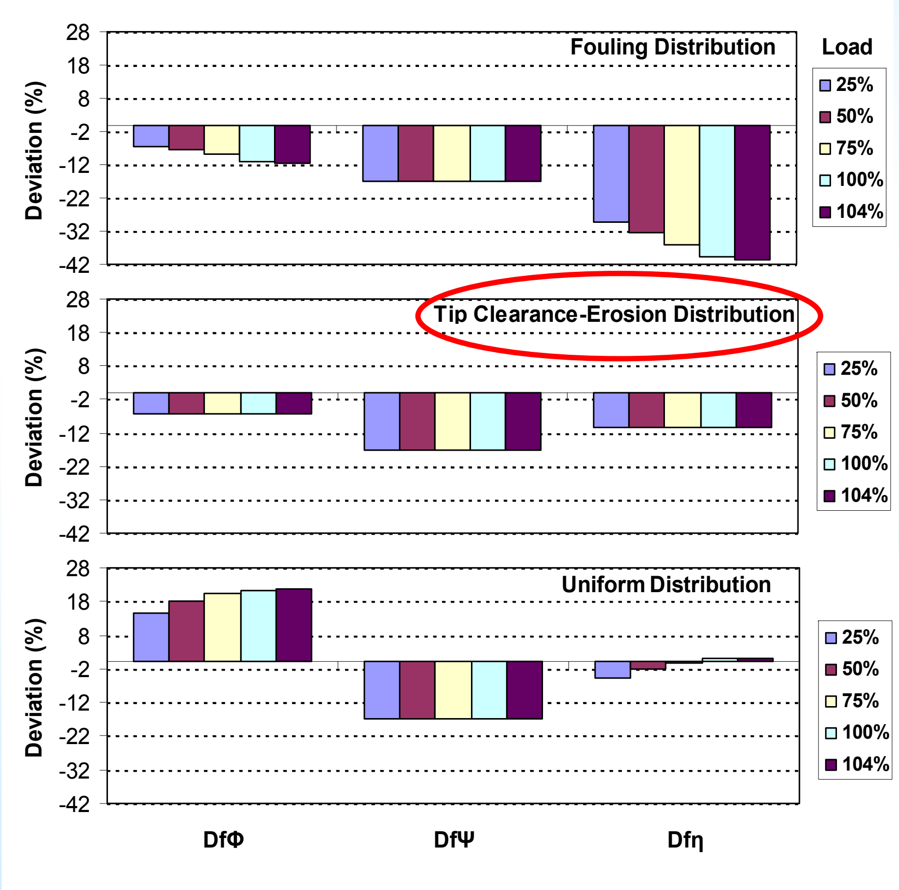
Wrong Fault: Factors Depending on Power Setting

Real Fault: Factors Independent of Power Setting

Wrong Fault: Factors Depending on Power Setting & Non-Physical Solution

Applications

Stage Level Fault Diagnosis – Combined Fault Tip Clearance & Erosion



Wrong Distribution: Factors Depending on Power Setting

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Summary & Conclusions

- A method giving the possibility for a higher fidelity gas path component fault diagnosis has been presented
- The method was materialized by employing a 1-D "zooming" feature in a Gas Path Analysis engine model for the Compressor and was applied to a single shaft engine
- The possibility to derive more detailed information with no additional measurement data is established, by incorporation of empirical knowledge on the type of faults that are usually encountered in practice
- The proposed method was tested against simulated faults, which were modeled by using available experimental data for stage performance degradation and typical fault distributions

Conclusions

- The diagnostic plane's agreement with available experimental data gives confidence for the fault simulation
- Engine Level Diagnosis: The faulty engine component is correctly identified
- Engine Level Diagnosis: The diagnostic plane permits a first identification of the fault type as the trends are different for different faults.
- Stage Level Diagnosis: The results indicate that the fault type can be identified and the distribution of the fault recognized positively, while it has the potential to give positive fault distribution even if combined faults are considered.

Future Work

- Further examination of combined faults diagnosis
- Analysis of the effect of measurement noise on the diagnostic capabilities of the method
- A comparison of the effect of the compressor stages design parameters on the diagnostic plane and on the fault signatures
- Comparison of the proposed method with traditional scaling procedures applied to the compressor (e.g. compressor speed line shape change due to a fault occurrence)