Gas Path Analysis with GSP
for the GEM42 turboshaft engine

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Final thesis

H. Pieters
Wb9652360
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Author

Name : Hanneke Pieters (B.Sc.)
Address : Bagijnhof 37
          2611 AN Delft
          The Netherlands
Telephone : +31 (0)6-38325961
E-mail : h.pieters@student.tudelft.nl
Preface

This report is the result of my master thesis research prepared at Delta Consult. It is part of my mechanical engineering master at the Delft University of Technology, section Energy Technology.

I would like to express my gratitude to Mr. W. Visser and Mr. M. Oostveen of Delta Consult for their help on this study. Moreover, I would like to thank Mr. P. Collé and Mr. J. Van Oord of the Royal Netherlands Navy engine test facility. They provided me with test data and background information on the Rolls-Royce GEM42 engine that is applied in their Westland Lynx helicopters. Finally, Emiel Van Dorp, Tibor Lapikas and Marius De Groot deserve my gratefulness for their great support in reviewing this report.

The results of this study were presented at a mini-symposium titled ‘Rolls-Royce GEM42 engine gas path analysis mini-symposium’ that took place on June 1, 2005 at SKF Engineering and Research Center (ERC), in Nieuwegein, The Netherlands. The mini-symposium was organized for engine operators to offer insight in advanced diagnostic methods and associated operator experiences for the GEM42 engine. The program of this mini-symposium is enclosed in the appendices of this report.

Delft, October 2005
H. Pieters

1 Delta Consult is an SKF group company
Summary

In the past 60 years the gas turbine engine has gained increasing importance as power source. It is applied both for propulsion in aerospace and marine applications as for power generation in land based systems. The increased usage and dependence on gas turbine systems calls for ways to optimize the availability and maintainability while minimizing operating costs.

A software tool for gas turbine performance simulation is the gas turbine simulation program GSP [1]. The aim of a GSP model is to predict the effects of e.g. changed operating conditions and/or component condition deterioration on the engine performance. A GSP model is, like most whole engine performance models, a 0-D model. It represents the engine as a composition of component sub-models for inlet, compressors, turbines, combustion chamber etc. In each sub-model the performance of a component is defined. The performance of turbo machinery components (compressors and turbines) is described by component specific performance maps.

One category of diagnostic methods to assess the condition of a gas turbine engine is Gas Path Analysis (GPA). In GPA, deviations of performance variables measured in the engine gas path are linked to the engine condition. An effective GPA method is adaptive modeling (AM). This method allows engine condition diagnosis on component level. Identification of the engine component(s) that are the root cause(s) of the performance deterioration of a certain engine can optimize the availability and maintainability of the engine.

An AM analysis starts with the model of a healthy reference engine. In an AM analysis the performance variables generated by this reference model are compared with performance variables measured in a deteriorated engine. Initially, the two sets will be different. In an iterative calculation the performance of the (reference) model is adapted until it matches the performance of the deteriorated engine. This is done by changing the performance map of each turbo machinery component. The performance map of the root cause component(s) will require the largest change in order to match the deteriorated performance. For each turbo machinery component, the AM calculation has two degrees of freedom to change the performance map. These degrees of freedom are called condition parameters. The extent to which the condition parameters of a turbo machinery component require adaptation is a measure for the condition deterioration of this component.

In a previous project [11] an adaptive modeling (AM) functionality was developed that can be implemented in a generic component based gas turbine environment, like the Gas turbine Simulation Program GSP. The concept was successfully demonstrated in GSP on CF6 turbo fan engines, tested in the KLM CF6 test facility. In the current project a GSP GPA tool has been developed for the Rolls-Royce GEM42 turbo shaft engine (Westland Lynx helicopter). It was investigated whether similar results could be demonstrated for a fleet of a different type of engine. For this project measurement data was supplied by the GEM42 engine test facility of the Royal Netherlands Navy. Compared to the KLM CF6 test facility, the accuracy of performance variables measured at this test facility is limited.
In order to generate an accurate diagnosis, the GSP GPA tool requires an accurate reference model. This means a reference model that accurately reproduces the values of the performance variables that are measured in the reference engine. In an AM calculation any observed differences between the modeled and the measured performance variables that are beyond user specified tolerance are assigned to engine component condition deterioration(s). Additional differences caused by an inaccurate reference model interfere in the AM calculation and reduce the accuracy of the generated condition diagnosis.

Model inaccuracy and measurement bias are considered to be major phenomena that impede an exact match. To minimize their effect, multi point calibration is applied in the GSP GPA tool. With this method the accuracy of the tool improved over the operating range of 450-780 kW. The GSP GPA tool now is very well able to identify component performance degradation of more than +/- 2%. This makes the tool suitable as diagnostic tool in maintenance practice.

In an AM calculation the number of determined condition parameters has to equal the number of measured independent performance variables. This requirement warrants that the system of model equations to be solved is “square”. In the GEM42 test facility of the Royal Netherlands Navy only 8 independent performance variables are measured. However, in order to determine the condition of all five turbo machinery components, 10 (5x2 condition parameters) would be required. Therefore, a method was developed for the GSP GPA tool that determines values for all condition parameters despite of limited number of measurement data. Numerical experiments were carried out in which subsequently a number of different subsets of 8 condition parameters were applied to analyze a certain artificial measurement set. These artificial measurement sets were values of performance variables corresponding to known component condition deteriorations.

In these numerical experiments persistent observations were done: When condition parameters of the (known) deteriorated components are applied in the AM analysis, the adapted values of the condition parameters show a dominant trend in the results. The developed method is based one this dominant trend. A routine was implemented in the GSP GPA tool that automatically performs multiple analysis cycles with different subsets of 8 condition parameters. Moreover, functionality was integrated to support the user in abstracting the correct trend out of the set of multiple analysis results.

In order to evaluate the developed GSP GPA tool case studies were performed with measurement data of deteriorated engines. The case studies successfully demonstrated the correspondence of analyzed changes in component condition and the information in the available maintenance notes. The method using multiple analysis cycles has proven to be effective and is applicable to other engines.

The GSP GPA tool was extended with a database system and a user interface for maintenance engineers. This provides a useful tool for comparison of analyzed component conditions throughout a fleet of engines. When a large number of analysis data is stored in the database, statistic analyses and data mining become possible options.

Summary
## Contents

Figures ................................................................................................................................. 11
Definitions and nomenclature .............................................................................................. 13

1 Introduction .......................................................................................................................... 20

2 Gas turbine deterioration ...................................................................................................... 22
   2.1 Thermodynamic engine cycle .................................................................................... 22
   2.2 Component performance ......................................................................................... 23
   2.3 Component performance degradation ........................................................................ 26

3 Gas turbine performance simulation ................................................................................... 30
   3.1 Gas turbine cycle models ....................................................................................... 30
   3.2 Gas turbine Simulation Program, GSP .................................................................... 30
      3.2.1 GSP engine models ............................................................................................ 31
      3.2.2 Off-design calculation ....................................................................................... 32
   3.3 Gas path analysis (GPA) ......................................................................................... 33
      3.3.1 Linear and non-linear GPA ................................................................................. 33
      3.3.2 Adaptive modeling (AM) ................................................................................... 34
      3.3.3 Adaptive modeling numerical methods ................................................................. 36

4 Reference engine model .................................................................................................... 39
   4.1 GSP reference model ............................................................................................... 39
      4.1.1 GEM42 turbo shaft engine .................................................................................. 39
      4.1.2 Reference model match ..................................................................................... 39
      4.1.3 Model inaccuracy ............................................................................................... 40
      4.1.4 Measurement uncertainty .................................................................................. 40
   4.2 Model matching methods ............................................................................................ 41
      4.2.1 Design point calibration ...................................................................................... 41
      4.2.2 Off-design model accuracy check ....................................................................... 42
      4.2.3 Multi point calibration ....................................................................................... 44
   4.3 Final reference model accuracy .................................................................................. 45
      4.3.1 Diagnosis accuracy ............................................................................................. 46
      4.3.2 Effectiveness of the GSP GPA tool ..................................................................... 48

5 Diagnostic analysis methodology ....................................................................................... 49
   5.1 Limited measured performance variables ................................................................. 49
   5.2 Dominant trends in analysis results ............................................................................ 50
      5.2.1 Numerical experiments ...................................................................................... 51
      5.2.2 Observations ...................................................................................................... 51
      5.2.3 Explanation ........................................................................................................ 53
   5.3 Averaged analysis results ............................................................................................ 54
5.4 Condition parameter subsets ................................................................. 55
5.5 Implementation in GSP GPA tool ........................................................... 57
  5.5.1 Multiple analysis cycles ................................................................. 57
  5.5.2 Diagnostic validity index ................................................................. 57
  5.5.3 Final session diagnosis ................................................................. 58

6 Results ................................................................................................. 59
  6.1 Case studies ....................................................................................... 59
    6.1.1 Case 1 ....................................................................................... 59
    6.1.2 Case 2 ....................................................................................... 60
    6.1.3 Case 3 ....................................................................................... 61

7 GSP GPA tool for a fleet of GEM42 engines ........................................... 63
  7.1 Database system ................................................................................. 63
    7.1.1 Structure ................................................................................. 63
    7.1.2 Interface ................................................................................. 65
  7.2 User interface ..................................................................................... 66

8 Conclusions .......................................................................................... 72

9 Recommendations .................................................................................. 74

Literature ................................................................................................... 76

Appendix A: M.Sc. assignment (Dutch) ...................................................... 78
Appendix B: GEM42 technical background ............................................... 80
Appendix C: Maintenance procedures Royal Netherlands Navy ................ 82
Appendix D: Selection of condition parameter subsets ......................... 84
Appendix E: Numeric solving method ..................................................... 86
Appendix F: Program mini-symposium ..................................................... 88
Figures

Figure 1, gas turbine cycle expressed in a T,s-diagram .......................................................... 22
Figure 2, basic configuration of a turboshaft gas turbine .......................................................... 23
Figure 3, typical compressor performance map ........................................................................ 25
Figure 4, picture of damaged fan blades (left) and turbine blades (right) [14] ......................... 26
Figure 5, Brayton cycle of deteriorated engine performance at constant fuel flow ................... 27
Figure 6, Brayton cycle of deteriorated engine performance at constant power output ............ 28
Figure 7, GSP engine model in main model window ................................................................. 31
Figure 8, modification of a compressor performance by shifting the lines of Eta and Wc ........ 34
Figure 9, ‘black box’ representation of an adaptive modeling (AM) calculation ....................... 35
Figure 10, summery of the mutual interaction in an equation set of an AM model ..................... 37
Figure 11, internal solving strategy applied by GSP ................................................................. 37
Figure 12, external solving strategy ......................................................................................... 38
Figure 13, schematic representation of GEM42 and the measured performance variables ........ 39
Figure 14, applied design point calibration factors .................................................................... 42
Figure 15, schematic representation of multi point calibration [14] ........................................... 43
Figure 16, effect of off-design match inaccuracy on AM diagnosis ........................................... 43
Figure 17, linear calibration functions, part 1 .......................................................................... 44
Figure 18, linear calibration functions, part 2 .......................................................................... 45
Figure 19, schematic picture of remaining error ....................................................................... 46
Figure 20, input inaccuracy due to noise and interpolation of the calibration factors ............... 47
Figure 21, 8 performance variables vs. 10 condition parameters ............................................ 49
Figure 22, with only 8 measurement values 10 condition parameters can be determined ......... 50
Figure 23, analysis results of 8 different cycles with known ..................................................... 52
Figure 24, three different subsets with respect to included root cause parameters .................. 53
Figure 25, averaged values of cycle analyses in numerical experiments ................................... 54
Figure 26, the eight applied predefined condition parameter subsets ....................................... 55
Figure 27, diagnostic validity index: extreme values add to the index ...................................... 58
Figure 28, case 1: August 2000 and February 2002 ................................................................. 60
Figure 29, case 1 indicating differences between analysis results ............................................. 60
Figure 30, case 2: February 2002 and March 2002 ................................................................. 61
Figure 31, case 2 indicating differences between analysis results ............................................. 61
Figure 32, case 3: March 2002 and September 2003 .............................................................. 62
Figure 33, case 3 indicating differences between analysis results ............................................. 62
Figure 34, diagnostic section of the data base structure ........................................................... 64
Figure 35, schematic picture Master-Detail database structure .............................................. 64
Figure 36, window: user interface of the GSP GPA tool for fleet condition history .................. 65
Figure 37, window: wizard portal of GEM42 GPA tool .......................................................... 66
Figure 38, window: loading new test data to data base ........................................................... 67
Figure 39, window: selection of operating point for analysis .................................................. 68
Figure 40, window: generation of final session diagnosis ........................................... 69
Figure 41, window: generation of final session diagnosis ........................................... 70
Figure 42, cross section of GEM42 engine ................................................................. 80
Figure 43, chart used to determine P.P.I. value corresponding to certain T4.49 and Torque .. 83
Figure 44, predefined subsets for analysis ................................................................. 84
Figure 45, non-linear relation between (system) error and state variable ...................... 87
Definitions and nomenclature

Glossary

In this report a number of key terms are introduced that will be new to the majority of the readers. Other terms are common knowledge, but due to frequent usage in literature and practice they have different meanings to different people. For proper understanding of this report a clear definition of a number of terms is important. The table below therefore gives a brief definition of these key terms. The order of the terms is the order of introduction in the report. The majority of the terms will be explained in more detail in the report. If this is the case, the specific paragraph(s) are indicated in the table.

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo machinery component</td>
<td>A turbo machinery component is a piece of equipment that exchanges energy between a continuous flow and a rotating shaft via blades mounted on that shaft. (<a href="#">15</a>). The turbo machinery components present in a gas turbine are compressor(s) and turbine(s).</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Efficiency in this report refers to the isentropic efficiency of a process. It is defined as the ratio between the ideally (reversibly) required energy and the actually (irreversibly) required energy to achieve a certain thermodynamic change. (Isentropic) efficiency is a measure for the losses in the process.</td>
</tr>
<tr>
<td>Performance/performance variables</td>
<td>For a gas turbine, performance refers to the thermodynamic behavior of the entire engine system or the sub-systems. Primary performance variables include values indicating power output or thrust. More detailed performance variables include pressures, temperatures, flow rates, velocities, efficiencies and many more. Performance may be expressed in single variable values (0-dimensional) up to time dependent processes in a 3D space (4 dimensional). In this report the performance of the aerodynamic processes inside the turbo machinery components is represented 0-dimensional.</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
| Compressor performance | In a compressor a continuous mass flow is compressed. In 0-D the performance of this compression is described by a set of four performance variables:  
- rotational speed  
- pressure ratio  
- mass flow  
- efficiency  
The performance of the process expresses with what rotational speed a certain pressure ratio is achieved in a certain mass flow. Dependent of the design of the component and the (off-design) operating point, the performance of a process involves certain losses. This is expressed in the value for efficiency of the specific performance.  
The 0-D performance of a compressor can be expressed in a component performance map. |
| Turbine performance | In a turbine a continuous mass flow is expanded. The performance of this process can be described with the same set of parameters as stated for the compressor.  
The performance of the expansion process expresses with what pressure drop (pressure ratio) in a certain mass flow a certain power is obtained. Power is related to the rotational speed. Again, dependent of the component design and the (off-design) operating point, the performance of a process involves certain losses that are expressed in the efficiency of this specific performance.  
The 0-D performance of a turbine can be expressed in a component performance map. |
| GSP engine model | The aim of a GSP model is to predict effects of e.g. changed operating conditions on the engine performance.  
A GSP model consists of a number of sub-models corresponding to a particular engine component configuration. In each sub-model the performance of a component is defined. The performance of each turbo machinery component is described by a component specific performance map. |
<table>
<thead>
<tr>
<th>Definition</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Gas Path Analysis (GPA)</strong></td>
<td>Gas Path Analysis is a category of methods to assess the condition of a gas turbine. In GPA, deviations of performance variables measured in the engine gas path are translated to engine condition information.</td>
</tr>
<tr>
<td><strong>Adaptive modeling (AM)</strong></td>
<td>AM is a modeling approach where models can adapt to measured data by adjusting model characteristics. AM can be used as a non-linear GPA method for gas turbines. By modifying the internal model properties such as component performance maps, the overall engine performance in the model is changed towards the (deteriorated) measured data. The required change of the performance maps of certain component(s) is a measure for condition deterioration of the component(s).</td>
</tr>
</tbody>
</table>
| **Condition parameter**                                                  | Component performance is usually affected by changes in component condition due to deterioration phenomena such as corrosion or erosion. In GSP changes in component condition relative to the healthy reference, are expressed using two condition parameters:  
  - *Eta*, expresses the change in process efficiency at equal values of the other three performance variables (pressure ratio, mass flow and rotational speed).  
  - *Wc*, expresses the change in mass flow that flows through the turbo machinery component at equal values of the other three performance variables (pressure ratio, rotational speed and efficiency). |
| **Map modifier**                                                         | A map modifier is a parameter whose value represents some (usually linear) deviation from performance values obtained from a component performance map. In GSP, the value of a map modifier is expressed in percents relative to the reference performance map. |
| **Model calibration**                                                    | For the accuracy of the AM diagnosis it is important that the applied reference model accurately reproduces the measured reference performance. However, several phenomena impede an exact match of the modeled and the measured performance. Some of these phenomena, such as model inaccuracy and measurement |

**Definitions and nomenclature**
bias, have constant characteristics. The effect of these constant characteristics is reduced by model calibration. The model calibration factors are the quotient of measured and modeled performance variable values.

**Multi point calibration**  
Paragraph 4.2.3

The *multi point calibration* method improves the off-design accuracy of the reference model over a certain operating range. For each performance variable a continuous calibration function is defined. The calibration function is a polynomial fitting the available reference calibration factors at different power settings.

**Multiple analysis cycle**  
Chapter 5

*Multiple analysis cycles* is a method that can generate values for all condition parameters even with limited availability of measurement. The method uses the dominant trend that root cause condition parameters show in an AM analysis. The GSP GPA tool automatically performs multiple (several) analysis cycles with in each analysis cycle a different predefined subset of eight condition parameters. Finally, the tool applies the dominant trend to identify the components that are the root cause for the overall engine performance deterioration.
### Symbols

<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Formula</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( W_{xc} )</td>
<td>Corrected mass flow 'x'</td>
<td>[ W_{xc} = \frac{w_X \cdot T_X}{T_{ISA}} ]</td>
<td>kg/s</td>
</tr>
<tr>
<td>PR</td>
<td>Pressure ratio</td>
<td>[ PR = \frac{p_2}{p_1} ]</td>
<td>-</td>
</tr>
<tr>
<td>( N_l )</td>
<td>Low pressure spool speed</td>
<td></td>
<td>[rpm]</td>
</tr>
<tr>
<td>( N_h )</td>
<td>High pressure spool speed</td>
<td></td>
<td>[rpm]</td>
</tr>
<tr>
<td>( N_{hcx} )</td>
<td>Corrected high pressure spool speed</td>
<td>[ N_{hcx} = \frac{N_h}{T_X / T_{ISA}} ]</td>
<td>[rpm]</td>
</tr>
<tr>
<td>Eta</td>
<td>Efficiency</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>( Eta_{compressor} )</td>
<td></td>
<td>[ Eta_{compressor} = \frac{\Delta T_{isentropic}}{\Delta T} ]</td>
<td>-</td>
</tr>
<tr>
<td>( Eta_{turbine} )</td>
<td></td>
<td>[ Eta_{turbine} = \frac{\Delta T}{\Delta T_{isentropic}} ]</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>[ P = \dot{W} \cdot c_p \cdot \Delta T ]</td>
<td>kW</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Error tolerance</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>( T_{xs} )</td>
<td>Total temperature at point x</td>
<td></td>
<td>K</td>
</tr>
<tr>
<td>( T_{xs} )</td>
<td>Static temperature at point x</td>
<td></td>
<td>K</td>
</tr>
<tr>
<td>( p_{xs} )</td>
<td>Total pressure at point x</td>
<td></td>
<td>bar</td>
</tr>
<tr>
<td>( p_{xs} )</td>
<td>Static pressure at point x</td>
<td></td>
<td>bar</td>
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</table>

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>EGT</td>
<td>Exhaust gas temperature</td>
</tr>
<tr>
<td>HPC</td>
<td>High pressure compressor</td>
</tr>
<tr>
<td>HPT</td>
<td>High pressure turbine</td>
</tr>
<tr>
<td>LPC</td>
<td>Low pressure compressor</td>
</tr>
<tr>
<td>LPT</td>
<td>Low pressure turbine</td>
</tr>
<tr>
<td>PT</td>
<td>Power turbine</td>
</tr>
<tr>
<td>CC</td>
<td>Combustion Chamber</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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**Definitions and nomenclature**
<table>
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<tr>
<th><strong>Abbreviation</strong></th>
<th><strong>Description</strong></th>
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</thead>
<tbody>
<tr>
<td>Tt23</td>
<td>Total LPC outlet temperature</td>
</tr>
<tr>
<td>Pt23</td>
<td>Total LPC outlet pressure</td>
</tr>
<tr>
<td>Tt3</td>
<td>Total HPC outlet temperature</td>
</tr>
<tr>
<td>Pt3</td>
<td>Total HPC outlet pressure</td>
</tr>
<tr>
<td>Fuel</td>
<td>Fuel flow</td>
</tr>
<tr>
<td>Tt4.49</td>
<td>Total PT inlet temperature</td>
</tr>
<tr>
<td>Ts49</td>
<td>Static PT outlet temperature</td>
</tr>
<tr>
<td>Nh</td>
<td>High pressure spool speed</td>
</tr>
<tr>
<td>Nl</td>
<td>Low pressure spool speed</td>
</tr>
<tr>
<td>Ns</td>
<td>Free power turbine spool speed</td>
</tr>
<tr>
<td>Tq</td>
<td>Torque</td>
</tr>
</tbody>
</table>

**Measured ambient conditions**

<table>
<thead>
<tr>
<th><strong>Abbreviation</strong></th>
<th><strong>Description</strong></th>
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<tbody>
<tr>
<td>AIT</td>
<td>Air inlet temperature (Static/Total LPC inlet temperature)</td>
</tr>
<tr>
<td>Pamb</td>
<td>Ambient pressure (Static/Total LPC inlet pressure)</td>
</tr>
<tr>
<td>Densío</td>
<td>Intake air humidity</td>
</tr>
</tbody>
</table>

**Subscripts**

<table>
<thead>
<tr>
<th><strong>Subscripts</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>det</td>
<td>Deteriorated</td>
</tr>
<tr>
<td>c</td>
<td>Corrected</td>
</tr>
<tr>
<td>ref</td>
<td>Reference</td>
</tr>
</tbody>
</table>

Definitions and nomenclature
1 Introduction

In the past 60 years the gas turbine engine has gained increasing importance as a power source. It is used both for propulsion in aerospace and marine applications as for power generation in land based systems. Its favorable characteristics such as high efficiency and a high power to weight ratio have been a driving force for further development of this relatively young type prime mover.

The increased usage and dependence on gas turbine systems calls for ways to optimize the availability and maintainability while minimize operating costs. In the last decades more and more advanced diagnostic methods have been developed to assess gas turbine performance. Such methods can direct appropriate maintenance actions in case of performance deterioration.

Several categories of diagnostic methods are available to assess the condition of a gas turbine engine and its different components in a qualitative or quantitative way. Such categories are e.g. visual inspection, vibration analysis and gas path analysis. In Gas Path Analysis (GPA), the deviation of performance variables, measured in the engine gas path, is linked to the engine condition.

A gas turbine is a complex piece of equipment with many interacting parts. Therefore, software tools are required to predict effects of changed input variables, like ambient conditions or power setting, on the engine performance. The Gas turbine Simulation Program GSP\(^2\) is such a gas turbine modeling environment. The component based structure of GSP makes it very flexible and suitable for handling a wide variety of gas turbine performance problems and engine configurations [1].

An effective GPA method is adaptive modeling (AM). Adaptive models have an inherent capability to generate a condition diagnosis on engine component level. In a previous project an adaptive modeling functionality was developed that can be implemented in a generic component based gas turbine environment, like GSP and turn any GSP engine model into an adaptive model [11].

The concept was successfully demonstrated in GSP with the CF6-50 turbofan engine. Test data applied in this case was supplied by the KLM engine test facility in Amsterdam [11]. A follow-up project [14] focused on improving the accuracy and user-friendliness of the diagnostics tool. In this project also KLM engine test facility cases were used, now moreover including the CF6-80 engine. A diagnostic tool, specifically configured for the KLM CF6 test facility, was developed.

The current project's objective is to apply the GSP GPA functionality on a different type of engine than used in the previous studies and investigate whether similar results can be demonstrated. Moreover, the developed GSP GPA tool should be applicable for analysis of a

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\(^2\) GSP has been developed in at NLR (National Aerospace Laboratory, The Netherlands) and Delft University of Technology

M.Sc. thesis H. Pieters
fleet of engines. The Rolls-Royce GEM42 turbo shaft engine of the Westland Lynx helicopter was selected for this purpose.

Test data used in this case was supplied by the GEM42 engine test facility of the Royal Netherlands Navy. Compared to the KLM CF6 test facility, the accuracy of performance variables measured on this test facility is limited.

In the development of the GSP GPA tool for the GEM42 four main tasks were identified:

- Analysis of the effect of model accuracy and measurement uncertainty on the accuracy of the final analysis results and finding a method to minimize this effect.

- Assessment of the feasibility of the use of the GSP GPA tool with limited availability of measured performance variables and finding methods to compensate for these limitations.

- Extension of the tool with a database system to accumulate (analyzed) engine test data and make it suitable for diagnostics on a fleet of engines.

- Implementation of the additional functionalities developed for the three preceding tasks in a user friendly user-interface for maintenance engineers.

Chapter 2 starts with a short introduction on the thermodynamic cycle in a gas turbine and explains why overall engine performance (degradation) can be observed in gas path measurement data.

In chapter 3, gas turbine performance simulation is discussed. It gives a brief description of the gas turbine simulation program GSP and explains the principles of the GPA method used in this project, adaptive modeling (AM).

Chapter 4 describes the calibration method that was applied to optimize the accuracy of the GSP GPA tool. Chapter 5 explains the multiple analysis cycle methodology that was developed in order to achieve an engine condition diagnosis on turbo component level.

In chapter 6 the accuracy of the tool is evaluated with three case studies in which existing test data was analyzed. The analysis results were compared with the overhaul notes. Chapters 7 presents the GSP GPA tool developed for the GEM42 showing a selection of the developed user interfaces.

Finally, the conclusions and recommendations with respect to future work are discussed in chapter 8 and 9.
2 Gas turbine deterioration

This chapter gives a short introduction of the thermodynamic cycle in a gas turbine. It moreover explains why overall engine performance (degradation) can be observed in changed values of performance variables measured in the engine gas path.

2.1 Thermodynamic engine cycle

The thermodynamic cycle of a gas turbine engine is known as the Brayton cycle. In this cycle air is subsequently compressed, heated and expanded, resulting in a net (useful) power output, see the $T,s$-diagram in Figure 1.

![T,s-diagram](image)

Figure 1, gas turbine cycle expressed in a $T,s$-diagram

The black trajectory (stations 2 - 3 - 4 - gg - 5) indicates operation of a healthy reference engine. Ambient air enters the engine at station 2. The air pressure is increased in the compressor up to station 3. The pressurized air enters the combustion chamber where it is heated. At station 4 the hot pressurized air enters the turbine section where it expands to ambient pressure and leaves the system at station 5.

In order to realize the described Brayton cycle a gas turbine engine has the following basic configuration (see Figure 2). The core part of the engine is called gas generator and consists of at least one compressor-turbine combination and a combustion chamber. The compressor

---

3 Depending on the performance and design requirements the gas generator consists of a single or a multi spool configuration.

M.Sc. thesis H. Pieters
is driven by the expansion power in the turbine. Depending on the engine's operating point there is power equilibrium between the compressor and turbine in the gas generator. The power absorbed by (or abstracted from) a mass flow is proportional to the temperature difference in this mass flow. In Figure 1, the ΔT over the compressor (station 2 to 3) is equal to the ΔT over the turbine (station 4 to gg), implying power equilibrium.

The expansion power is transferred from the turbine to the compressor through the shaft on which both are mounted. The remaining expansion power (station gg to 5) is available as net engine power output. Depending on the application of the gas turbine, the gas generator is completed with either a nozzle to produce thrust or a free power turbine to produce shaft power (like indicated in Figure 2).

The ratio of available net power output and the fuel flow (both proportional to ΔT) added in the combustion chamber is defined as the overall efficiency of the engine cycle, see Figure 1.

![Figure 2, basic configuration of a turboshaft gas turbine](image)

The performance of a gas turbine refers to the thermodynamic behavior of the entire engine system or sub-systems. Primary performance is expressed in variables indicating the power output or thrust generated by the engine. More detailed performance variables include pressures, temperatures, flow rates, velocities, efficiencies and many more.

The performance of the engine cycle is related to the performance of each turbo machinery component in the engine. The two main factors affecting the performance of gas turbines are component efficiencies and turbine working temperatures. The higher they can be made the better the all round performance of the engine. The achievable component efficiency is mainly dependent of its (aerodynamic) design. The achievable working temperatures are mainly dependent of the availability of materials that can resist extreme temperatures.

### 2.2 Component performance

In the design of a gas turbine, first of all the required overall engine performance (design load) is defined. From this overall performance, requirements are derived for the design performance of the individual (turbo machinery) components. In a 0-D approach component performance is expressed in single values of performance variables.

M.Sc. thesis H. Pieters
For a compressor the 0-D performance requirement may be expressed as: The rotational speed (N) that achieves a certain pressure ratio (PR) in a certain mass flow (W) and with certain efficiency. The achieved efficiency is strongly related to its aerodynamic design.

Each compressor is designed for optimal performance at nominal design load. This implies that the aerodynamic design of the compressor blades is optimized to accommodate a smooth flow profile at design load. Apart from blade design also surface roughness and tip clearance are minimized for design load in order to minimize aerodynamic losses.

The component design is moreover affected by the required off-design performance. If e.g. the engine is designed for application in a military fighter aircraft, load changes will regularly occur. In that case also performance at off-design operation should be optimized. In case however of e.g. an industrial gas turbine, running continuously on nominal design load, off-design performance is of less importance.

The performance of turbo machinery components throughout their operating range can be expressed in a component performance map. Figure 3 shows a typical compressor performance map. In this characteristic, the following non-dimensional performance variables can be distinguished:

- Pressure ratio (PR):
  \[ \pi = \frac{p_{02}}{p_{01}} \]

- Corrected mass flow:
  \[ w_{xc} = \frac{w_x \cdot \sqrt{T_x}}{p_x} \]

- Corrected rotational speed
  \[ Nh_{cx} = \frac{Nh}{p_{ISA}} \]

- Isentropic efficiency:
  \[ \eta_{ISA, compressor} = \frac{\pi^{\gamma - 1} - 1}{\theta - 1}, \text{ with } \theta = \frac{T_{02}}{T_{01}} \]

The performance in component maps is expressed in dimensionless parameters, in order to make it independent of the component inlet conditions. The performance parameters \( w_{xc} = \frac{w_x \cdot \sqrt{T_x}}{p_x} \) and \( Nh_{cx} = \frac{Nh}{\sqrt{T_x}} \) are usually also termed as non-dimensional mass flow and rotational speeds, respectively, although they are not truly dimensionless. However, this is allowed when the performance map is applied for a specific component with fixed size [8].

M.Sc. thesis H. Pieters
In the map a *Surge line* is indicated. Beyond this line, the phenomenon surging occurs. Surging is associated with a sudden drop in pressure delivery, and with violent aerodynamic pulsation which is transmitted throughout the whole engine [8]. Surge may cause serious damage to the machine. Operation close to this line should therefore be strictly prevented. This performance information throughout the operating range is usually obtained with rig experiments. Often the experimental data are complemented with analytical CFD analysis results, to for example simulate surge.

In Figure 3 the design operating point is indicated with a small square, typically located in an area with the highest efficiency. At off-design operation different flow profiles will occur. The deviating flow velocities and angles of attack in the turbo machinery components affect the occurring aerodynamic losses. This is due to increased viscous friction, turbulence etc. Other off-design effects may also increase, such as changes in pressure loss, heat loss, combustion loss etc.

At changing operating load, a (component) operating point shifts along the so called 'engine operating line' (see Figure 3). The dot indicates a possible off-design operating point, typically located in an area with lower efficiency.

The compressor performance map in Figure 3 includes an engine operating line. This is the line along which the compressor operating point will move when (gradually) changing the engine power setting. The values of all performance variables of the compressor decrease when reducing the engine performance. Due to the less optimal performance at off-design operation, also the compressor efficiency will decrease, as indicated in the figure.

---

4 In a rig experiment the performance of a single engine component is tested outside the engine
The performance of a turbine can be described in a similar way as the compressor. The correlation between the performance variables are expressed in a turbine performance map.

2.3 Component performance degradation

In the previous paragraph it was explained that due to a less optimal flow profile at off-design operation a lower overall efficiency is achieved compared to design operation. This performance reduction is a reversible process; when shifting back to design load, a healthy component will regain the initial design performance and design efficiency. When however, the condition of an engine component deteriorates with respect to its design condition, permanent performance degradation is the result.

Engine performance degradation is a result of performance degradation of one or more engine components. During operation a gas turbine is exposed to extreme conditions that affect the physical condition of its components. Possible damage or deterioration mechanisms are: corrosion, erosion and foreign object damage, resulting in increased surface roughness, increased tip clearance, changed blade shapes or even missing blades, see Figure 4.

Additional losses due to such component damage obviously affect the component’s performance. Stall problems or even back flow introducing (partial) flow blockage, may occur in compressors at operating points where the healthy component would have performed without any problems. In such case the actual component performance is no longer in accordance with the performance described in the map.

![Figure 4, picture of damaged fan blades (left) and turbine blades (right) [14]](image)

When the condition of one (or more) engine component(s) deteriorates this affects the power equilibrium between the turbo machinery components. Thus, at equal operating conditions, the engine will obtain a different power equilibrium.

To illustrate the changes in overall performance the operation of a gas turbine engine with a deteriorated gas generator turbine is considered. In the following example, initially the operating conditions remain constant; the power added to the system in the combustion chamber is assumed to be the same. How will the “sudden” deterioration of the turbine performance affect the overall engine performance and how will the power equilibrium change?

M.Sc. thesis H. Pieters
• Extra losses due to turbine deterioration result in a decreased power transfer from the turbine to the compressor. This results in a reduction of the spool speed.

• With the reduced power transferred to the compressor, the pressure ratio that can be achieved in the compressor will be smaller. This results in a lower pressure at the compressor outlet.

• The turbine inlet pressure will also be lower. This implies that a lower pressure ratio will remain for expansion in the free power turbine. This implies a lower net power output. A lower net power output at equal fuel flow means a lower overall engine efficiency and a higher SFC.

• Finally, a new steady operating point will be obtained at which the components in the gas generator have new power equilibrium.

This changed performance is visualized by the deteriorated cycle in Figure 5 ('det'). The cycle shows a reduced pressure ratio and lower overall engine efficiency. The deteriorated cycle shows that although at equal operating conditions deviating values of the performance variables will be measured. The deviating values are therefore an indication for deteriorated engine condition.

In practice, the operating conditions (fuel flow input) generally will not be kept constant. The pilot requires a certain power output in order to carry out his/her orders and will therefore try to keep the engine's power output constant.

M.Sc. thesis H. Pieters

Figure 5, Brayton cycle of deteriorated engine performance at constant fuel flow
In the second example therefore, in stead of the operating conditions, the power output will be kept constant. What will happen to the values of the performance variables in case of a "sudden" deterioration of the turbine performance?

- Extra losses due to turbine deterioration result in a decreased power transfer from the turbine to the compressor. This results in a reduced spool speed.

- With the reduced power transferred to the compressor, the pressure ratio that can be achieved in the compressor will be smaller. This results in a lower pressure at the compressor outlet.

- The turbine inlet pressure will also be lower. Both the pressure ratio in the turbine as and the power turbine will be lower.

- However, the fuel flow increased; more power input is required to overcome the losses and keep the power output constant. This results in a much higher turbine inlet temperature and a higher power turbine outlet temperature.

- The increased fuel flow input at equal power output means a lower overall engine efficiency and a higher SFC.

The changed cycle is indicated in Figure 6.

Figure 6, Brayton cycle of deteriorated engine performance at constant power output
The increased temperature values in the expansion process are very characteristic. In case of constant power output and deterioration of any component, always higher temperatures will be measured in the turbines, due to the increased fuel flow. For this reason in most on-board performance monitoring systems the EGT (exhaust gas temperature) value plays an important role. It gradually rises during the engine deterioration process, but for safe operation should never cross certain a limit value.

It is important to note is that at the new operating point both for the compressor and turbine a reduced efficiency is observed. From the figures it can however not be derived which component is the cause of the overall performance deterioration. This is due to the new equilibrium that is obtained within the engine. The operating point of the (healthy!) compressor shifted to a less optimal performance due to changed equilibrium. Due to the effect all (turbo machinery) components have on each other advanced methods are required to predict the true root cause for performance degradation. This will be explained in more detail in the following chapters.
3 Gas turbine performance simulation

Software programs are required to simulate changes in input variables, like ambient conditions or power setting and predict the effects on the engine performance. This chapter gives a short introduction on gas turbine performance simulation. A brief description is given on the gas turbine simulation program GSP that is used in the current project. Finally, the principles of the GPA method adaptive modeling (AM) is explained.

3.1 Gas turbine cycle models

Most whole engine performance models are 0-D models, representing the engine as a composition of component sub-models for inlet, compressors, turbines, combustion chamber etc. In the sub-models, off-design component performance is expressed in thermodynamic relations and/or component performance maps.

The 0-D approach is efficient from a calculation point of view; gas properties are determined only at the component inlet and outlet. For engine system performance calculations this approach provides sufficient detail. However, for special purposes, like e.g. the (re)design of a component, sub-models can sometimes consist of a (extensive) 2-D or 3-D CFD simulation. This allows investigation of spatial phenomena inside the component such as the effect of changes in temperature profiles and pressure profiles on the engine performance. However, in such simulations also more extensive computational capacity is required.

A performance model expresses the simulated engine performance in values of performance variables. Temperatures and pressures throughout the engine as well as net power output, rotational spool speed(s) and fuel flow can be calculated. Also overall engine performance indicators such as specific fuel consumption (SFC) and engine efficiency can be calculated. See for more information on off-design calculation paragraph 3.2.2.

3.2 Gas turbine Simulation Program, GSP

One software tool for gas turbine performance simulation is the gas turbine simulation program GSP. This program was developed by the NLR (National Aerospace Laboratory, The Netherlands) and Delft University of Technology. The component based structure of GSP makes it very flexible and suitable for handling a wide variety of gas turbine performance problems and engine configurations [1]. The next paragraph will briefly explain how an engine specific performance simulation model of any gas turbine configuration can be built in GSP.

M.Sc. thesis H. Pieters
3.2.1 GSP engine models

A GSP model consists of a user specified arrangement of gas turbine component icons (inlet, compressor(s), combustor, turbine(s), duct, exhaust) in the main model window. This arrangement corresponds to a particular engine configuration (see Figure 7). The main model window moreover, contains the control component icons representing the engine control system (e.g. rotor speed control, fuel control). To simulate an engine operating point, ambient (flight) conditions must be specified in the ‘Amb. Cond’ tab sheet (upper left corner). Each component-icon forms an interface to the corresponding component sub-model.

![Figure 7, GSP engine model in main model window](image)

The performance of each component is represented in a component sub-model. For the development of a model of an existing gas turbine typically limited performance data is available. Vital details about e.g. the (design) performance of the turbo machinery components expressed in detailed component maps are in general confidential information of the OEM\(^5\).

An engine model in GSP is therefore matched to measured performance data by user-specification of design performance variables. The specified values of design rotational speed, design Mach number, design efficiency and (in case of e.g. a compressor or an inlet) design pressure ratio for each component together define the design performance of this component.

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\(^5\) Original Equipment Manufacturer (OEM).

M.Sc. thesis H. Pieters
For off-design performance simulation, GSP applies scaled component maps selected from public domain libraries. Public domain libraries are open data bases containing large numbers of component performance maps. Generally, they describe the performance of turbo machinery components that were developed many years ago. The performance information in the maps is therefore no longer of large value for present-day component development. For this reason OEMs may place these maps at public disposal.

The selection of a map for application in a specific sub-model is based on component similarities. Type, size and number of stages are important characteristics to match in order to approximate the modeled component performance as close as possible. Also the period in which a component was developed should be taken into account in the map selection to account for similar aerodynamic design characteristics and material properties. Each map is scaled to the model design point to match the modeled component performance as close as possible.

3.2.2 Off-design calculation

After the design point specification, off-design calculations can be performed. The core of the (dynamic) simulation model consists of a set of non-linear system equations corresponding to the conservation laws of energy and mass. The number of equations in the set depends on the number of components in the modeled engine.

Like in most gas turbine simulation programs, GSP calculates the new steady-state operating point by solving the set of system equations. Satisfying the equation set warrants a physically sound solution like e.g. that the mass flow air going through the compressor is equal to the mass flow air through the subsequent turbine. And, power equilibrium between the compressor and the turbine on the same shaft.

In order to satisfy the set of system equations (all equal to zero), an equal number of engine performance variables (states) $S$ has to be determined, such as fuel mass flow, compressor and turbine pressure ratios, corrected mass flow and rotor speed(s). Equation 1 shows the implicit form of a set of $n$ error equations.

$$
\begin{align*}
&f_i(S_i, P, U) + \cdots + f_i(S_n, P, U) = 0 \\
&\vdots \\
&f_i(S_i, P, U) + \cdots + f_n(S_n, P, U) = 0
\end{align*}
$$

The equations in the set are a function of:

- $S_i$: $n$ independent state variables
- $P$: a vector consisting of gas path performance variables
- $U$: a vector containing power control settings and ambient conditions

\(^6\) Also transient performance calculations are possible; in that case a solution is a derivative to the operating line.

M.Sc. thesis H. Pieters
The simulated performance is dependent of the operating conditions imposed on the model. Moreover, the performance map used in each sub-model plays an important role. Like in the real engine, the performance of the components affects to a large extent the power equilibrium that is obtained between the compressors and turbines in the gas generator.

In order to solve the system an iterative calculation is performed using the Newton-Raphson method. See for more information on this solving method Appendix E: Numeric solving method.

### 3.3 Gas path analysis (GPA)

As explained in paragraph 2.3, engine performance degradation can be measured. The observation of different values of performance variable at equal operating conditions is an indication of deteriorated engine condition.

Gas path analysis (GPA) is a diagnostic method in which deviations of performance variables measured in the engine gas path are translated to engine condition information. Since the components in the engine all affect each other, a change in a single gas path variable can be related to multiple engine components. This is illustrated with the example in paragraph 2.3. This complicates the linear linking of changes performance to single deteriorated component(s), the so called root cause component(s).

When few parameters are measured, a GPA result can only express a condition diagnosis on engine level. This is for example the case for the overall performance index PPI (see Appendix C: Maintenance Policy Royal Netherlands Navy) where only the turbine exhaust gas temperature (EGT) and rotational spool speed N are involved.

If however, a minimum number of performance variables are measured, advanced GPA methods can predict the root cause(s) of engine deterioration on component level. Such a high quality diagnosis allows a significant reduction of maintenance time and a corresponding cost reduction. Due to the dependency on the availability of gas turbine systems and the increasing computational power, diagnostic methods like GPA have become more and more advanced and important.

#### 3.3.1 Linear and non-linear GPA

The GPA accuracy is, apart from the accuracy and availability of the measured test data and the accuracy of the applied performance model, determined by the accuracy of the used GPA algorithm. A large number of publications show development of different GPA approaches which mainly can be divided in two groups: linear GPA (LGPA) and non-linear GPA (NLGPA) [2]. Both methods can quantify the condition of each component in condition parameters.

Linear GPA (LGPA) methods are based on the assumption that the relation between deterioration and measured performance deviations can be expressed in a set of linear equations. Because in reality the correlation of these parameters is based on complex non-linear phenomena and aerodynamic relations, the range in which LGPA methods are valid is
small. Only analysis of performance data measured close to the reference operating point are possible. Thus, the component condition deviations should be small.

Non-linear GPA (NLGPA) methods are not limited by this restriction. A non-linear GPA method takes interference between deterioration and non-linear engine characteristics into account in the non-linear thermodynamic model. This allows gas path analysis over a wider range and improves the model accuracy with respect to LGPA. Disadvantages of non-linear GPA are however, that it is more complex and requires larger calculation capacity.

See also Appendix E: Numeric Solving Methods.

Through the past 15 years several different non-linear GPA techniques have been developed including *adaptive modeling* (AM), *neural networks* (NN) and *genetic algorithms* (GA) described in a large number of publications.

The M.Sc. thesis [11] evaluated the state of the art in GPA methods and determined, supported by case studies, that AM is a very effective method for implementation in GSP.

Based on these results an adaptive modeling (AM) functionality was developed that can be implemented in a generic component based modeling environment. This was demonstrated successfully in GSP in a previous project.

### 3.3.2 Adaptive modeling (AM)

A way to simulate engine component deterioration is to specify the associated effects on component performance degradation in the model. One method to represent component deterioration is using 'map modifiers' that change the performance simulated in a sub-model. This way the effect of component deterioration on the overall performance can be integrated in the model.

![Diagram](image.png)

**Figure 8, modification of a compressor performance by shifting the lines of \( \eta \) and \( \dot{\gamma} \)**

M.Sc. thesis H. Pieters
Figure 8 shows how the performance in a compressor sub-model can be modified with ‘map modifiers’. By variation of the (dimensionless) map parameters efficiency ($\eta$) and corrected mass flow ($\bar{m}$), the effect of any component condition deterioration can be simulated. The other two parameters (PR and Nc) remain unchanged during the map modification. Therefore, $\eta$ and $\bar{m}$ are called component condition parameters.

Adaptive modeling is based on the same method of map modification. Figure 9 shows a ‘black box’ representation of an adaptive modeling (AM) calculation. Engine performance data measured in and around the gas path of a deteriorated engine are used as AM model input. The measured operating variables determine the initial baseline model performance. This is the off-design performance that would be observed in a healthy reference engine. These baseline performance values are compared with the measured values in the gas path; any differences in values initiate the AM calculation.

In an AM calculation the component performance(s) in the sub-models is adapted in an iterative procedure by changing the component performance maps with the map modifiers. This way the overall engine performance is adapted. The calculation is continued until the engine model output is equal to the measured performance variables. Then the iterative calculation is stopped. At that moment the engine (reference) baseline model has changed into a model that simulates the performance of the deteriorated engine.

The output of an AM calculation called the analysis result. The analysis result consists of diagnostic information of each condition parameter expressed in a map modifier value [%]. The value of the map modifier is an indication for the rate of deterioration of the component. The significant values assign the components that are the main cause for engine performance deterioration.
3.3.3 Adaptive modeling numerical methods

Numerically, an adaptive model can be represented by adding a number of equations to the basic model equation set. This number of added equations is equal to the number of performance variables to adapt to. The added equations form extra constrains for the model solution: in AM mode the model should, apart from fulfilling the conservation laws, also generate performance variables that are equal to the measured performance variables. Equation 2 shows the general form of the equations that are added to the model in AM mode.

\[ f_{ni} = P_{i,\text{model}} - P_{i,\text{measured}} \leq \varepsilon_m \]  

Equation 2

\( P \) represents any performance variable to which the model has to be adapted by AM. \( P_{i,\text{model}} \) and \( P_{i,\text{measured}} \) are the adapted and measured values of parameter \( P_i \), respectively. \( \varepsilon \), represents the AM tolerance, the allowed remaining difference between both value sets.

In order for the extended equation set to find a single solution (in other words, to keep the equation set “square”) a number of extra variables equal to the number of added measurements is required. These additional variables are the ‘map modifiers’. Equation 3 shows the extended set of model equations that form the core of an AM model. \( f_1 \) to \( f_n \) are the basic error equations with \( s_1 \) to \( s_n \) corresponding states. \( f_{m1} \) to \( f_{mm} \) are the additional equations generated by the AM-module and \( s_{c1} \) to \( s_{cm} \) are the map modifiers, which represent the unknown component condition deterioration, the system needs to be solved for. Vector \( (\varepsilon) \) consists of the conservation equation tolerance \( \varepsilon \), and the AM tolerances \( \varepsilon_{m1} \) to \( \varepsilon_{mm} \). This tolerance can be specified by the user.

\[
\begin{align*}
    f_1(s_1) + \cdots + f_1(s_n) + f_1(s_{c1}) + \cdots + f_1(s_{cm}) &= \varepsilon \\
    \vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \\
    f_n(s_1) + \cdots + f_n(s_n) + f_n(s_{c1}) + \cdots + f_n(s_{cm}) &= \varepsilon \\
    f_{m1}(s_1) + \cdots + f_{m1}(s_n) + f_{m1}(s_{c1}) + \cdots + f_{m1}(s_{cm}) &= \varepsilon_{m1} \\
    \vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \hspace{2cm} \vdots \\
    f_{mm}(s_1) + \cdots + f_{mm}(s_n) + f_{mm}(s_{c1}) + \cdots + f_{mm}(s_{cm}) &= \varepsilon_{mm}
\end{align*}
\]

Equation 3, extended equation set of an AM model

The basic error equation set and the additional equation set affect each other, as summarized in Figure 10. When the performance of one (or more) component sub-models is modified

M.Sc. thesis H. Pieters
with the map modifiers, this affects the power equilibrium in the engine, represented by the basic error equation set (upper left, Equation 3). This effect is integrated in the equations in the upper right part of the equation.

The changed power equilibrium causes the model performance variable to adapt, which affects the additional AM equations (lower left Equation 3). The changed map modifiers moreover affect the additional equations (lower right Equation 3).

![Table](https://example.com/table.png)

**Figure 10**, summery of the mutual interaction in an equation set of an AM model

GSP applies an internal solving strategy to solve the AM calculation (see Figure 11). This implies that the effect both sets have on each other is integrated in a single calculation loop. This provides numerical stability and makes the calculation fast. Moreover, integration of the (adapted) condition parameters in the model allows direct performance analysis on the deteriorated engine.

![Diagram](https://example.com/diagram.png)

**Figure 11**, internal solving strategy applied by GSP

As an alternative on this solving strategy AM functionalities can also apply an external solving strategy (see Figure 12). This strategy is however more time consuming compared to the internal one.

The external solving strategy applies two separate loops; one to solve the basic model equation set and one to solve the additional equation set. The two loops are processed successively until a stable adapted model is achieved. This is a slower strategy, because many more iteration steps are required.

M.Sc. thesis H. Pieters
To solve the model equation set, a Newton-Raphson based solver is used. See for a more detailed description of this method Appendix E: Numeric solving methods. Moreover, an extensive explanation of AM numerical method can be found in [11] and [14].
4 Reference engine model

In GPA, performance degradation measured in an engine is linked to engine condition deterioration. For this purpose an accurate reference model is required that simulates the engine performance corresponding to a healthy engine. In the current chapter, development of the GEM42 reference model is described. Moreover, applied calibration methods to optimize the reference model match are explained.

4.1 GSP reference model

4.1.1 GEM42 turbo shaft engine

For the current project the Rolls-Royce GEM42 engine was selected. This engine was designed especially for helicopter application. It consists of a two-shaft gas generator and a free power turbine, as shown in Figure 13. This large number of turbo components makes it an interesting case for application of GPA, because the root cause for performance degradation can be more diverse. See for more technical background Appendix B: GEM42 Technical Background.

4.1.2 Reference model match

In Figure 13 the performance variables and operating variables measured in the engine are indicated. Nh, the high pressure spool speed, is the control variable. The GSP reference model was matched to test data of an engine classified by the Royal Netherlands Navy as "healthy".

M.Sc. thesis H. Pieters
By adjusting the design performance of the component sub-models, the overall model performance is matched as close as possible to the performance measured in the reference engine.

The accuracy of this match has a large effect on the accuracy of the final condition diagnosis generated by the GSP GPA tool. In an AM calculation any observed differences between the modeled and the measured performance variables that are beyond user specified tolerance are assigned to engine component condition deterioration(s). Additional differences caused by an inaccurate reference model match interfere in the AM calculation and reduce the accuracy of the generated condition diagnosis.

However, several phenomena impede an exact match between the model and the engine performance data. Remaining differences are due to:

- **Model inaccuracy**
  - Secondary effects due to model simplifications
  - Use of inaccurate (scaled public domain) performance maps

- **Measurement uncertainty**
  - Measurement noise
  - Measurement bias
  - Malfunctioning sensors

### 4.1.3 Model inaccuracy

A model is an abstract construction or idea that is a simplified view on a process or phenomenon in reality [13]. The simplified 0-D representation of the engine in GSP implies that certain secondary spatial effects such as the occurrence of parameter profiles (e.g. of temperature profiles and pressure profiles) are not taken into account.

For the general purpose of whole engine performance calculation this 0-D representation is a reasonable model simplification. In case of application as reference model however, the measured values, to compare to, are actually affected by the presence of parameter profiles at engine stations. This may result in a significant difference between measured and model performance values.

Another source for model inaccuracy is the use in GSP models of public domain component maps, scaled to the model design point (see paragraph 3.2). The performance represented in these maps deviates from the actual component performance. This can introduce a significant inaccuracy in the off-design performance simulation.

### 4.1.4 Measurement uncertainty

Measurement uncertainty is an important source of error in diagnostic accuracy. It can be divided in noise (scatter) which effect is non-repeatable and bias which causes a more or less constant off-set between the actual and the measured values.
Unfortunately, no sensor is free of noise or bias. The accuracy of the measurements depends of the quality of the used instrumentation. This can be related to the sensor type, the sensor brand and moreover to the number of sensors that measure a single variable. Furthermore, measurement uncertainty can be caused by e.g. sensor fouling or incorrect sensor placement. The intensity of noise and bias moreover may be affected by the engine performance.

Another source of measurement inaccuracy is the presence of malfunctioning sensors transferring very deviant values or no value at all (dead signal). Sensor failure causes inconsistent data sets and when applied in an AM calculation often leads to an extreme and unrealistic AM solution or to no solution at all. Therefore, malfunctioning sensors often can be clearly identified.

### 4.2 Model matching methods

As explained, several phenomena cause the fact that if only the performance of the sub-models is adjusted a certain difference will remain between the modeled and the measured performance. This does not imply however, that no accurate diagnosis can be achieved.

In an AM calculation the measured performance is regarded relative to the reference model performance. As long as the same reference model is used and measurements are done with the same measurement equipment, the difference due to model inaccuracy and bias is (approximately) constant. With the difference known, its effect can be reduced with the application of model calibration.

The calibration factors in this matching method are defined as the quotient of the measured value of a performance variable and its corresponding model value. This is expressed in Equation 4.

\[
\text{Calibration factor}_i = \frac{X_{i,\text{measured}}}{X_{i,\text{mod} \, \text{el}}} = C_{OPi} \
\Rightarrow X_{i,\text{measured}} = X_{i,\text{mod} \, \text{el}} \cdot C_{OPi}
\]

Equation 4

Multiplication of the model value with the calibration factor results in an exact match with the measured reference values.

#### 4.2.1 Design point calibration

First of all a design point calibration is applied. In a design point calibration only the inaccuracy caused by measurement bias and model simplifications is considered. This is because in a design point calculation no component performance maps are involved.

As it is assumed that the difference due to model inaccuracy and bias is constant, it does not matter which performance variables are matched exactly and which are selected for calibration. In the matching procedure of the GEM42 reference model it was decided to exactly match the majority of the performance variables and leave a larger deviation to only a
few. An alternative approach could have been leaving a small difference for all performance variables and apply small calculation factors on each variable. Both approaches are equally fine.

Figure 14 shows the calibration factors that were applied in the GEM42 reference model to reduce the deviation of modeled and measured performance. Six of the total eight performance variables were matched (almost) exactly. The calibration factors required for the remaining two (Pt23 and Pt3) are relatively large.

![Design point calibration factors](image)

**Figure 14, applied design point calibration factors**

### 4.2.2 Off-design model accuracy check

The applied design point calibration realized a model match at design operation. At off-design however, the effect of model inaccuracy and measurement uncertainty remains. Deviations between modeled and measured performance may change as a function of the power setting. This is due to the effect of the applied performance maps in the model at off-design simulation. Moreover, as indicated before, sensors may generate different values of bias at different operating points.

Figure 15 illustrates how these differences may result in significant deviations between model and measured performance at off-design operation.

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It is important to know the effect the deviation illustrated in Figure 15 has on the accuracy of the AM analysis. If the effect is significant, further model calibration is required. In order to quantify this effect, AM analysis was carried out with two off-design performance sets measured on the reference engine.

Figure 16 shows the analysis results obtained with these two measurement sets. One set was measured at a power setting lower than design (dark, \( \text{Nhc} 42408 \) rpm) and one was taken at a power setting higher than design (light, \( \text{Nhc} 43325 \) rpm). The effect of the deviation between reference model performance and measured performance at off-design operation is significant. It calls for further optimization of the reference model match.
4.2.3 Multi point calibration

For the improvement of the off-design accuracy of the reference model, the multi point calibration method is the most efficient and flexible method [14]. Instead of calibrating the model on only a single operating point (the design point), a calibration function is defined for each performance variable over a certain operating range. Basically, the calibration functions are discrete and only valid at specific power setting values. Therefore, polynomials fitting the available exact calibration factors are defined. This way the calibration functions can be transformed into a continuous function of the power setting.

In the multi point calibration applied on the GEM42 reference model linear interpolation functions were defined between the five available exact calibration factors. The calibration factors are a function of the value Nhc (Corrected rotational shaft speed) as indicated in Equation 5. This way, apart from the power setting, also the effects of ambient temperature on the required calibration factors is encountered for in the calibration.

\[
C_{f_x}(Nhc_x) = C_{f_x}(Nhc_{x,low}) + \left(C_{f_x}(Nhc_{x,high}) - C_{f_x}(Nhc_{x,low})\right) \frac{n_{x} - n_{x,low}}{n_{x,high} - n_{x,low}} \\
\]  

Equation 5

Figure 17 and Figure 18 show the linear interpolation functions of all 8 performance variables over the calibrated operating range.
As indicated in the figure the multi point calibration was applied at four off-design operating points over a range of 4772-43325 [rpm]. The operating point at 42955 [rpm] is the design point.

Expressed in units of power the model was calibrated over a power range of 450-780 kW. This range was selected based on the availability of reference measurement data in this range. Moreover, test data for which the tool is useful generally do not exceed the power of 780 kW in the engine performance test, due to their deteriorated performance.

4.3 Final reference model accuracy

Implementation of the multi point calibration reduced the effect of model inaccuracy and bias on the GSP GPA tool accuracy. However, the effect of a certain residual error remains. This residual error is due to the presence of scatter in the measurement data. Moreover, it is probable that the calibration factors that are obtained through linear interpolation incorporate a certain scatter as well. The linear interpolation functions provide approximated values of the calibration factors, no exact values.

Due to these two causes a small difference remains between the modeled and the measured performance. The schematic picture in Figure 19 indicates the error that remains despite of the applied model calibration. Its effect on the accuracy of the diagnostic result of the GSP GPA tool can not be neglected.

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7 See also Appendix C: Maintenance procedure Royal Netherlands Navy

M.Sc. thesis H. Pieters
If test data can always be recorded at power settings equal to the reference settings, multi point calibration is a very effective method to improve the diagnostic accuracy. In that case measurements can be taken when the engine operates at almost\(^8\) equal operating points (the little squares in the figure above). At these operating points the applied calibration factors are accurate and can strongly reduce the effects of model inaccuracy and measurement uncertainty. This is for example the case in the KLM CF6 test facility in Amsterdam where measurement data are always recorded at 22%, 39%, 65%, 94% and 100% of max. take-off power.

This is however different in the case of the GEM42 engine test facility of the Royal Netherlands Navy. In this test facility it is not possible to adjust the engine on specific predefined power settings. This means that during an engine performance test, measurements are generally recorded at operating points at which no exact calibration factors are known. This is an important drawback in the achievable accuracy for the GEM42 GPA tool.

### 4.3.1 Diagnosis accuracy

In order to get an impression of the effect of the residue error on the diagnostic accuracy that can be achieved with the GEM42 GPA tool, an experiment was performed. For both sources of error a certain contribution to the total error was quantified.

Based on information provided by the Royal Netherlands Navy, a scatter in a range of +/- 0.5% for the applied sensors was assumed. As an approximation of the error related to the

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\(^8\) At equal power setting the only difference in operating point is caused by deviating ambient conditions.

M.Sc. thesis H. Pieters
calibration factors, also a value of +/- 0.5% was assumed. This value is based on the observed trends and scatter in Figure 17 and Figure 18. The contribution of both sources of error to the total disturbance is calculated with Equation 6 [16]. The total error was calculated with Equation 6:

$$\varepsilon_{\text{total}} = \sqrt{\varepsilon_1^2 + \varepsilon_2^2}$$  \hspace{1cm} \text{Equation 6}

The errors are summed in Table 1.

<table>
<thead>
<tr>
<th>Remaining source of error</th>
<th>Scatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor noise</td>
<td>+/- 0.5%</td>
</tr>
<tr>
<td>Linear interpolation of calibration factors</td>
<td>+/- 0.5%</td>
</tr>
<tr>
<td>Total error</td>
<td>+/- 0.7%</td>
</tr>
</tbody>
</table>

AM analyses were carried out with disturbed measurement values. In this experiment a measurement set of the reference engine was applied. All values were subsequently disturbed by: +0.7% and -0.7% (for the total effect) and +0.5% and -0.5% (for the single effects) and analyzed with the GSP GPA tool. Figure 20 shows the analysis results obtained with these four different measurement sets.

Figure 20, input inaccuracy due to noise and interpolation of the calibration factors

The results in Figure 20 show that the effect of disturbance is significant on the majority of the condition parameters.

M.Sc. thesis H. Pieters
4.3.2 Effectiveness of the GSP GPA tool

In maintenance practice engine performance deviations become significant only if exceeding normal engine-to-engine variation, which is in the order of at least a few percent. If an engine does not pass the performance test, this usually implies a condition deterioration largely exceeding engine to engine variation. This is because healthy engine performance margins (e.g. EGT margin) have to be far beyond engine to engine variation.

Figure 20 indicates the GSP GPA is very well able to identify component performance degradation of more than +/- 2%. This makes the tool suitable as diagnostic tool in maintenance practice.
5 Diagnostic analysis methodology

This chapter describes the methodology that was developed to obtain a condition diagnosis of all turbo machinery components in the GEM42, despite of the limited number of performance variables that is measured in the gas path.

5.1 Limited measured performance variables

An AM calculation requires an equal (or larger\(^9\)) number of condition parameters and independent measured performance variables in order to find a unique solution for the extended set of model equations. In the GEM42 test facility of the Royal Netherlands Navy 8 independent performance variables are measured in the gas path, see Figure 21. This implies that in a single AM calculation at most map modifier values can be determined for 8 condition parameters. The GEM42 engine however consists of five turbo machinery components, implying that determination of 10 map modifiers is required (see section 3.3.2 and Figure 21).

The previous two projects ([11] and [14]) were concerned with a GSP GPA tool for the CF6 turbofan engine. Also in this engine the number of measured independent performance variables was limited. The number was too small to determine values for the map modifier of the condition parameters of all components. However, in case of a turbofan engine it is a reasonable option to leave the entire fan module out of the AM analysis. One justification for

\(^9\) If a larger number of independent measurement data would be available, the analysis becomes an optimization problem.

M.Sc. thesis H. Pieters
this exclusion is that the physical condition of the fan can partly be assessed by means of a visual inspection [14]. For analysis of the turbofan gas generator only, the number of measured performance variables was therefore sufficient. In the current case, this is not an option as the GEM42 engine is a helicopter engine. Its configuration does not allow an easy visual inspection of any of the turbo machinery components. It is therefore desirable to find a different method that determines the map modifier values for all 10 condition parameters, corresponding to the condition of the five turbo machinery components in the engine.

![Diagram showing measured performance variables and determined condition parameters before and after modification](image)

**Figure 22, with only 8 measurement values 10 condition parameters can be determined**

5.2 Dominant trends in analysis results

The analysis result obtained in an AM calculation depends on:
- Measurement values of the deteriorated engine
- Selection of variable condition parameters in the AM calculation

A solution to determine 10 map modifiers instead of only 8 (see Figure 22) is found by making use of the dominant trend that root cause components show in the analysis results. This trend was observed in the numerical experiments with AM calculations that were carried out with a large number of artificially obtained measurement sets. The actual deterioration will always persistently exert in the results of any selection of 8 condition parameters. The condition parameters not representing actual deterioration may show significant deviations from reference in some cases (where the condition parameters corresponding to the actual deterioration are not included) but never in all selection cases. The observation of a dominant trend in true root cause components is confirmed in ASME paper GT-2002-30031 (by K. Mathioudakis).

M.Sc. thesis H. Pieters
5.2.1 Numerical experiments

In a basic GSP model, the user can manually specify engine component deterioration, by imposing map modifiers (ETA and Wc) in the sub-models. This allows calculation of the associated effects on the engine performance. The artificial measurement sets applied in the numerical experiments were obtained this way. The calculated “deteriorated” values of the performance variable were used as measurement sets in the numerical experiments.

Each experiment consisted of the performance of eight analysis cycles with a single measurement set. In each analysis cycle a different subset of 8 condition parameters (out of the 10 to be determined) was applied. Figure 26 in paragraph 5.4 shows for each applied subset which condition parameter is included and which is excluded from analysis. Leaving one or more condition parameters out of the AM analysis numerically implies that the left out parameter values are equal to their reference values (map modifiers equal to zero).

As an example the results of one of the performed experiments are presented here. In this experiment measurement data of typical turbine deterioration were analyzed. The imposed deterioration was a 3% increase of corrected mass flow in the HPT (Wc4) and a 3% decrease of efficiency, also in the HPT (ETA8).

Figure 23 shows the results of the 8 analysis cycles. Only the map modifiers of six condition parameters (corresponding to the three turbines) are shown; the values of the remaining four parameters were always zero.

5.2.2 Observations

The condition parameter subsets applied in cycle 1, 2, 3, 5 and 6 all include both root cause condition parameters (Wc4 and ETA8). The obtained values for the corresponding map modifiers are -3% and +3% respectively, whereas the map modifier values of the remaining condition parameters are equal to zero.

The subsets applied in cycle 4, 7 and 8 only contain the condition parameter Wc4. The obtained map modifier values for Wc4 still are large, but not equal to 3%. Moreover, the map modifier values of the remaining condition parameters are much larger then zero. The dominant trend of the root cause condition parameters Wc4 and ETA8 is distinct.

From this and the other performed numerical experiments, three different situations with respect to the applied condition parameter subsets were distinguished (see also Figure 24):

- All root causes included:
  If all root cause condition parameters are included in the adaptive modeling configuration, the calculation quickly converges. Moreover, the exact deterioration is assigned to the map modifiers of the correct (root cause) condition parameters. The map modifiers of the remaining (non-root cause) condition parameters are zero.

M.Sc. thesis H. Pieters
Part of root causes included:
If only part of the root cause condition parameters is selected in the adaptive modeling configuration, still large map modifiers are observed for these parameters. However, the assigned values deviate from the exact deterioration values. Moreover, the remaining map modifiers are unequal to zero; their values alternate between (large) positive and negative values, dependent on the condition parameters in the subset selection.

No root causes included:
If no root cause condition parameters are selected in the adaptive modeling configuration\(^\text{10}\) the map modifiers may have any value. Moreover, their values alternate between (large) positive and negative values, depending of the condition parameters in the selected set. Apart from this analysis results were observed that show a combination of e.g. a very positive map modifier value for EtaLPC and a very negative map modifier value for EtaHPC.

\(^\text{10}\) This case is not demonstrated in the example.
5.2.3 Explanation

- In an adaptive modeling calculation the model equation set is most sensitive for system error reduction if the condition parameters that represent the actual engine condition deterioration (the root causes) are varied. If all root cause condition parameters are included in the set of 8 selected condition parameters, modification of these parameters leads to a strong error reduction. This forces the calculation in the dominant direction, resulting in correct adapted values for the root cause condition parameters. See also appendix E: Numeric solving method.

- If no (or not all) root cause condition parameters are included, non-root cause condition parameters need to be adapted to obtain a combination that satisfies the equation set. This leads to the observation that in different analysis cycles non-root cause condition parameters might have adapted values that alternate strongly between positive and negative values. Some calculated map modifiers might seem correct, whereas others are clearly unrealistic. In such a situation, there is no dominant direction for a solution.

- As long as the conservation laws are satisfied, any combination of condition deviations is a possible solution in an AM calculation. This explains the observation that some analysis results show e.g. a combination of a very positive map modifier value for EtaLPC and a very negative map modifier value for EtaHPC. The two map modifiers compensate each other and therefore the conservation laws are satisfied; the solution is numerically correct. In real life this is (nearly) impossible and such an analysis result should therefore be considered as incorrect.
5.3 Averaged analysis results

Because of the dominant trend of root cause condition parameters, averaging the analysis results of different analysis cycles provides a good first estimate of the complete engine condition diagnosis. The averaged results including all 8 analysis cycles are represented by striped bar in Figure 25. The averaged map modifiers of root cause parameters remain large, whereas the contribution of non-root cause parameters to the overall condition diagnosis is significantly smaller, due to the alternating character of these map modifiers throughout the different cycles.

![Graph](image)

**Figure 25, averaged values of cycle analyses in numerical experiments**

Due to unreliable cycle results the averaged condition diagnosis is not equal to the imposed +3 and -3 % deterioration, but still for a reasonable first indication. The next step is to use only those analysis results that contain the deteriorated engine conditions, the root causes. In this example, cycle 1, 2, 3, 5 and 6 are used. In Figure 25 the dotted bar indicates the resulting engine diagnosis. This diagnosis is equal to the imposed deterioration.
5.4 Condition parameter subsets

In theory 45 subsets \( \binom{n}{k} = \binom{10}{8} = 45 \) of different combinations of condition parameters can be formed to apply in an AM calculation. However, it should be noted that it is in general not possible to derive a solution for all possible combinations, since the system of equations can be ill conditioned for some of them [8], as will be explained in this paragraph.

In numerical experiments, many combinations of 8 condition parameters have been applied in the AM calculation. It turned out that five specific condition parameters should always be included (be variable) in the analysis subsets. In case of excluding (fixing) these parameters, the system was ill conditioned and no solution was derived. Those condition parameters are:

- ETA4 and Wc2 representing the condition of the LPC
- ETA5 and Wc2.3 representing the condition of the HPC
- Wc4 partly representing the condition of the HPT

This leaves the 8 subsets shown in Figure 26 that form well defined AM systems. The figure shows each subset in a different row and each condition parameter in a different column. The condition parameters that are not included in a subset are indicated with a cross.

![Figure 26, the eight applied predefined condition parameter subsets](image)

The requirement that certain specific condition parameters have to be variable in order to solve the system of equations is related to the measured performance variables to which the model is adapted. Equation 7, Equation 8 and Equation 9 are the formulas for corrected mass flow (Wc) and efficiency (Eta) for the compressor and turbine, respectively. The formulas show how the
values of condition parameters and performance variables are related analytically. The values of the performance variables measured at the inlet of a component define to a large extend the value of the adapted component condition parameter.

\[ W_{xc} = W_{aer} \cdot \sqrt{\frac{T_x}{T_{ISA}}} \cdot \frac{P_x}{P_{ISA}} \]

\[ \text{Equation 7} \]

\[ \text{Eta}_{\text{compr, is}} = \frac{\left( \frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1}{T_2 - T_1} \]

\[ \text{Equation 8} \]

\[ \text{Eta}_{\text{turb, is}} = \frac{1 - \left( \frac{T_1}{T_2} \right)^{\frac{k-1}{k}}}{1 - \left( \frac{p_1}{p_2} \right)^{\frac{k-1}{k}}} \]

\[ \text{Equation 9} \]

In case of the GEM42 engine both at the inlet and at the outlet of the components LPC and HPC, pressure and temperature are measured. If the condition parameters describing the condition of LPC and HPC would not be variable, this leaves no flexibility to the model to adapt to all imposed performance variables. The condition parameter Wc4 has in a similar limited freedom due to the fixed value of the fuel flow. On the side of the turbines however, there is much more flexibility in finding a solution set, because there only few performance variables are imposed.

Because the system of equations is relatively small, it is possible to explain the necessity of variation of these five condition parameters in an analytical way. This is described in Appendix D: Selection of condition parameter subsets.

During the numerical experiments also the number of parameters applied in a condition parameters subset was varied. This resulted in another important observation. If instead of the maximum number of 8 condition parameters 7 (or less) would be included in the subsets the adaptive modeling calculation did in general not find any solution at all.

In general one can say that there will always be certain restrictions to the condition parameter subsets that can be applied in an AM calculation in order to warrant enough flexibility in the system to find a solution.

M.Sc. thesis H. Pieters

56
5.5 Implementation in GSP GPA tool

5.5.1 Multiple analysis cycles
The observed dominancy of root cause condition parameters is used in the GSP GPA tool in order to provide a diagnosis of the complete engine on component level. For this purpose the GSP GPA tool has been extended with a functionality that can automatically perform multiple analysis cycles. In each analysis cycle a different predefined subset of eight condition parameters is applied (see the sets in Figure 26).

5.5.2 Diagnostic validity index
From the 8 different analysis results a single diagnosis needs to be deduced. For this purpose only those analysis results need to be selected, that contain all root cause condition parameters. In other words, the unreliable cycle results should be identified and excluded. The final diagnosis is calculated by averaging the selection of reliable cycle results.

An analysis result that consists of numerous unrealistic map modifiers generally does not contain all root cause condition parameters and should be excluded from the final average. It is however not easy to quickly assess a set of map modifier values and decide whether the values are realistic or not. This requires training and experience.

Therefore, a diagnostic validity index (DVI) has been defined to help the operator assess the validity of analysis results. This index is calculated for each analysis result. A DVI higher than zero indicates that the analysis result consists of one or more less realistic map modifiers. It is a guideline in the assessment of which cycle analysis results should be included and which should be left out of the final averaged diagnosis.

When calculating the validity index each map modifier value is assessed whether it is within a realistic range. E.g. when a component deteriorates, its efficiency (Eta) always decreases. A typical range for efficiency is therefore ≤ 0%. Map modifier values that are outside their realistic range generally indicate an unrealistic analysis result.

The red lines in Figure 27 indicate threshold values of +1 and -1%. Calculated values for e.g. efficiency higher the 1% would indicate an exceptionally good component condition (compared to the healthy reference engine), which is unlikely in a deteriorated engine. When the condition of a compressor deteriorates, typically the flow area decreases; a very positive value (≥1%) for Wc in a compressor is therefore unrealistic. When the condition of the turbine deteriorates typically the flow area increases; a very negative value (≤-1%) for Wc in a turbine is therefore unrealistic.

Because the exact efficiency of the reference components is not known, it is possible that the condition of a certain component turns out to be better than the reference, implying a positive efficiency value. Therefore, the operator can manually define the extremes of a realistic range (so called threshold values) for each condition parameter (see paragraph 7.2 User interface).

M.Sc. thesis H. Pieters
Figure 27 gives an impression of how a validity index is obtained from an analysis result. The light (upper) part of a bar indicates that part of the map modifier that exceeds the threshold. This part is added to a square root algorithm that calculates the DVI, as shown in Equation 10.

\[ DVI = \sqrt{\Delta ETA_i^2 + \Delta Wc_i^2} \]  

Equation 10

5.5.3 Final session diagnosis

In an engine test measurement data are recorded at several power settings. The GSP GPA tool contains a functionality to automatically analyze the measurement sets of all selected power settings. The final engine session diagnosis is deduced from the individual operating point diagnoses.

In theory the generated engine condition diagnosis should be similar at each operating point. In practice however, the analysis results show similar trends but often the map modifier values are not the same at different operating points. Measurement noise and the remaining calibration error due to linear interpolation are assumed to be the main cause of these differences (see paragraph 4.2).

In order to provide a guideline in the assessment of the viability of each operating point diagnosis, a diagnostic validity index is also calculated for each operating point diagnosis. The final session diagnosis is the average of the viable diagnosis, representing the overall engine condition on component level of a certain test session.

M.Sc. thesis H. Pieters
6 Results

The accuracy of the GSP GPA tool developed for the GEM42 was evaluated by analysis of existing test data and comparison of the obtained diagnostic results with the overhaul notes. In the following case studies the condition history of a single engine (KM9044) is analyzed over a period of 3 years. During this period the engine was tested 4 times in the GEM42 test facility of the Royal Netherlands Navy at military airport De Kooy in Den Helder. The analysis results and observed intermediate changes are discussed in three different cases, in chronologic order.

A performance index used by operators for the GEM42 is the power performance index, PPI. This index expresses the overall engine performance relative to a reference. When this index was available in the test data its value is also indicated in the analysis results of the following cases. See for more details on the P.P.I. Appendix C: Maintenance procedure Royal Netherlands Navy.

6.1 Case studies

6.1.1 Case 1

Figure 28 shows the diagnostic results of two tests carried out in August 2000 and February 2002. Shortly before the second test was performed the power turbine (PT) was replaced. In the graph the PT is represented by the purple bar (ETApt) and the olive bar (Wept).

The difference in condition diagnosis analyzed by the GSP GPA tool clearly shows an improved PT performance in the second test, as expected.

With respect to the preceding test in August 2000 the condition diagnosis of February 2002 also indicates a decreased HPC and HPT performance, which can be seen clearly in Figure 29, showing the difference between the two analysis results. The large negative value of the HPC corrected mass flow implies a reduced cross flow area in the compressor; the large positive value of the HPT corrected mass flow, implies an increased cross flow area in the turbine. Both symptoms indicated standard component deterioration.

The overall engine performance however had not improved sufficiently with replacement of the PT, as the dramatically bad PPI value (white arrow) in the second test indicates. Therefore, after the February 2002 test the engine was returned to the work shop.
After rejection of the engine in February 2002 it was decided, based on experience, to replace the engine's hot section module. The hot section consists of the HPC (ETAhpc, Wchpc), the combustion chamber and the HPT (ETAhpt, Wchpt). Figure 30 shows the diagnostic results of the February test (equal to Figure 28) and the March 2002 test, respectively. The decision to replace the engine's hot section after the February 2002 test is in accordance with the diagnostic analysis result obtained with the GSP GPA tool. See also Figure 31, showing the difference between the two analysis results.

The deviation of the corrected mass flow in the HPC is about -3% from the reference, which for a compressor indicates significant condition deterioration. The deviation of the corrected mass flow in the HPT is about +4% from the reference, which for a turbine also indicates significant condition deterioration.

The diagnostic results of the March 2002 test show a significant improvement of the hot section performance; the cross flow area of the compressor and the turbine improved. As indicated also by the improved PPI.
6.1.3 Case 3

Figure 32 shows diagnostic results of the tests carried out in March 2002 and in September 2003, almost 1.5 years later. Based on experience it was decided to replace the LPT module in order to improve the overall engine performance. The test of September 2003, performed after this overhaul action, turned out that the engine’s PPI value had decreased in stead of improved. See also Figure 33, showing the difference between the two analysis results. Replacement of the PT turned out not to have been the optimal maintenance action.

Diagnostic results obtained with the GSP GPA tool indicate that the performance of the newly placed LPT is worse than the LPT performance analyzed 1.5 years earlier. It is possible that the newly placed LPT was not in good condition. Moreover, the diagnostic results indicate that especially the performance of the PT is unsatisfactory. The large negative value of ETApt and very large positive value of Wcpt indicate a very low efficiency and a large cross flow area, both signs of significant condition deterioration of the PT. Changing the PT instead of the LPT therefore probably would have been more effective. In this situation, assistance of the GSP GPA tool in planning the work scope would have paid off.

M.Sc. thesis H. Pieters
Based on the information available in the overhaul notes one part of the diagnostic result can not be explained. Figure 32 shows in September 2003 an improved LPC efficiency with respect to March 2002. Such large improvement of component efficiency, without any performed maintenance action, is very unlikely. It is probable that a compressor wash was carried out just before September 2003. Compressor washing is an operational maintenance action that is regularly carried out to remove pollution from the compressor blades and always improves the components performance. However, this suggestion could not be verified because there was no access to the operational maintenance records.

Figure 32, case 3: March 2002 and September 2003

Figure 33, case 3 indicating differences between analysis results

M.Sc. thesis H. Pieters
7 GSP GPA tool for a fleet of GEM42 engines

This chapter presents the developed GSP GPA tool for the GEM42 engine. The implemented database is described in the first part. The second part gives an impression of the user-interface that was developed to guide the maintenance engineer through an AM calculation with the GSP GPA tool.

7.1 Database system

The GSP GPA tool developed for the GEM42 can accurately diagnose what component(s) is the root cause for engine performance deterioration at a certain moment in time. Accumulation of the available (analyzed) engine data opens a way for diagnostics on a fleet of engines. Comparison and trending of analysis results of different engine tests can improve the insight in the engine fleet condition and in engine deterioration processes.

For this purpose the GSP GPA tool has been extended with a database system that can file analysis result of an entire fleet. The database forms a start of the development of the engine fleet analysis tool. Additional functionalities for e.g. statistic analysis and data mining are opportunities for the future.

7.1.1 Structure

The database structure has been designed to store all engine performance data in a structured way and allow optimal flexibility in data selection. Figure 34 shows a screenshot of the developed Access database. It consists of 4 tables that are linked by one-to-many Master-Detail relations using primary keys, as shown in Figure 35.

The one-to-many relation implies that to each engine record in the ‘engine’ table, more then one session records in the ‘TestSession’ table can be linked; all test sessions performed with a certain engine are linked to the appropriate engine record. Multiple measurement records in the measurement table can be linked to each session record. This is important because generally in one test session performance variables are measured at different operating points (OP).

And finally to each measurement record (OP) multiple analysis records can be linked from the ‘analysis ‘table. All 8 analysis results calculated per operating point are filed in the last table. The final session diagnosis that is obtained out of a selection of all analysis results is saved in the ‘TestSession’ table.
Figure 34, diagnostic section of the data base structure

Figure 35, schematic picture Master-Detail database structure

M.Sc. thesis H. Pieters
7.1.2 Interface

The database structure allows flexible selection of the analysis results in many formats. Figure 36 shows a snapshot of the developed user-interface. With this 'history' interface (a selection of) the database information can be displayed. It provides several options to select and view diagnostic data of the engines in a single graph.

Diagnostic data selections can e.g. be:
- Trending all session diagnoses of a single engine
  This can provide insight in the (gradual) development of the condition performance of a specific engine through time.
- Trending component subsets
  This allows focusing on the condition development of specific components.
- Trending session diagnoses of multiple engines
  This allows comparison of deterioration processes between different engines.

Moreover, several lay-out options are available for the graph, such as:
- Displaying analysis 'Deltas'
  With this option performance changes with respect to the previous analysis results are displayed. This way it is easier to assess changes in the trends. In the case study analysis results in chapter 6 this option was used.
- Displaying the data point either in lines or in bars
- Displaying the bars in 3-D shape

![Figure 36](image)

Figure 36, window: user interface of the GSP GPA tool for fleet condition history

M.Sc. thesis H. Pieters
7.2 User interface

The developed methods to create an accurate session diagnosis of GEM42 test data have been implemented in the GSP GPA tool. A wizard has been developed to guide the user step by step. For this wizard new and adapted graphical user interfaces were created. In the following paragraph the main interfaces are presented in order to give an impression of the GSP GPA tool developed for the GEM42.

Figure 37 shows the wizard portal. In this interface the operator is given four options (see Table 2):

Table 2:

<table>
<thead>
<tr>
<th>GEM42 GPA tool option</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>New condition snapshot</td>
<td>Loading and analysis of new condition snapshot</td>
</tr>
<tr>
<td>Engine test sessions</td>
<td>Post processing of previously analyzed diagnostic data</td>
</tr>
<tr>
<td>Fleet condition history</td>
<td>Proceed to the fleet condition history interface (Figure 36)</td>
</tr>
<tr>
<td>Settings</td>
<td>User specification of units, calibration factors, measurement tolerances etc.</td>
</tr>
</tbody>
</table>
When the option to analyze new set of performance test data is selected the window (Figure 38) below appears.

![Figure 38, window: loading new test data to data base](image)

The window in Figure 38 allows the user to look into the database by navigating through the four tables (Fleet table; Engine table; Session table and Analysis table). In this interface test data for analysis can be selected.

- At **Load test data** (A) a test file can be selected.
- The **Fill database** -button at (B) starts loading the data of the selected test file into the database.
- The new loaded data will appear in the appropriate database tables. In the ‘Engine table’ a single test session is selected for analysis.
- The **Load test session for analysis**-button (C) starts loading the test data from the database to temporary store data for further processing in the GPA calculation.

M.Sc. thesis H. Pieters
After loading test data to the temporary data storage, the GSP GPA tool automatically shifts to window Figure 39.

Figure 39, window: selection of operating point for analysis

Figure 39 gives an overview of the test data selected for analysis.

- Section ‘D’ displays some specific data about the engine and the test session that is going to be analyzed.
- Depending on the varying number of operating points in the test, section ‘E’ shows a check box for each operating point. The operating points to be analyzed can be selected in this check box.
- The arrows in section ‘F’ allow the user to scroll through the test data displayed in the table.
- The Load test data-button (G) opens the database navigator interface of Figure 38.
- With the next-button at ‘H’ the analysis of the selected measurement sets starts.

The GEM42 GPA tool automatically performs the 8 analysis cycles with the predefined condition parameter subsets. If multiple operating points are selected, the tool automatically performs the analysis procedure with the measurement sets of all selected operating points. The result of each analysis cycle is saved in the analysis table of the database.
After finishing the analysis procedure the window displayed in Figure 40 appears.

This window shows the analysis results of each analyzed operating point. In this interface the user specifies what cycle results should be included in the final session diagnosis. As explained in chapter 5, a DVI is calculated for each analysis cycle result, to guide the operator in this selection procedure.

- Section 'I' displays the 8 sets of analyzed map modifier values, calculated for a single measurement set (single operating point).
- Section 'N' shows the averaged value of each column.
- In section 'J' the user can predefine the threshold values applied in the diagnostic validity index algorithm.
- Section 'K' indicates the DVI values for each cycle analysis. The DVI values that are close to 0 indicate reliable analysis results.
- Unreliable analysis results can be excluded in section 'L'. By de-selection of the cycle record, the cycle is excluded. This results in changed averaged values ('N').
- Based on these averaged values a DVI is calculated for each operating point, as displayed in section 'M'. The operating points selected in this table are included in the final session diagnosis.

M.Sc. thesis H. Pieters
The next-button opens the window in Figure 41. In this interface similar information is displayed as in the previous interface. Only now, the cycle results are displayed in a graph which might be, in comparison to the table with numbers, more intuitive for the operator.

- Section 'O' again displays the 'Analysis table' in which cycle results can be in- and excluded from further analysis.
- The save-button at 'P' saves the averaged values of all included cycle results as a single final session diagnosis in the 'session table'.

With the next-button the fleet condition history window (Figure 36) appears allowing the user to compare the newly obtained session diagnosis with other diagnoses in the database.
8 Conclusions

- The GSP GPA tool is able to effectively identify component deterioration of turboshaft engines, even with limited accuracy and availability of measured performance variables.

- The GSP GPA functionality has been successfully demonstrated on the GEM42 turbo shaft engine. Calculated component condition data correspond to available maintenance notes.

- In maintenance practice, if an engine does not pass the performance test, this usually implies a condition deterioration largely exceeding engine-to-engine variation, which is in the order of at least a few percent. The GSP GPA is very well able to identify component performance degradation of more than +/- 2%. This makes the tool suitable as diagnostic tool in maintenance practice.

- A method using multiple analysis cycles was developed. The method, that generates values for all condition parameters even with limited availability of measurement data, has proven to be effective.

- The methodology of multiple analysis cycles is applicable to other engines. However, the combinations and number of condition parameters that are applied in an AM calculation are restricted in order to warrant enough flexibility for adaptation of the model.

- The extension of the GSP GPA tool with a database system provides a useful tool for comparison of analyzed component conditions throughout the fleet. When a large number of analysis data is stored in the database, statistic analyses, trending and data mining can be performed. At the current stage, only limited analysis functionality has been implemented.
9 Recommendations

- For further validation of the GSP GPA tool, more performance test data taken shortly before and after maintenance actions in combination with the maintenance notes are required. This allows comparison of the analyzed changes in component performance with the maintenance findings without the unknown effects of intermediate engine operation.

- The functionalities integrated in the current GEM42 GPA tool, such as the multiple analysis cycles method and the database system, are currently engine specific; only specific Excel files can be loaded to the database and only the 8 condition parameter subsets specified for the GEM42 engine can be analyzed. It is desirable to develop a more generic format of these functionalities in order to allow easy implementation in any GSP engine model.

- Further optimization of the GSP GPA tool accuracy can be achieved by using more accurate component maps in the engine model. Moreover, accuracy can be improved by adding additional intermediate points to the calibration functions. This reduces the interpolation intervals and enhances a closer approximation of the applied calibration factors.

- The diagnostic validity index (DVI) provides a guideline for the assessment of analysis results. However, still a considerable amount of knowledge of engine performance deterioration processes is required in order to obtain the best diagnosis out of the multiple analysis cycles. This is mainly due to the scatter in both the measurement data and the calibration functions. It is desirable to further develop functionalities to guide the operator in assessing the analysis results.

- The integrated database forms a strong base for further development of the engine fleet analysis tool. Performance of fleet trending and statistics might identify similar trends or governing component problems. This can improve the overall insight in engine performance deterioration processes. For this purpose database storage of a large number of (analyzed) performance data is required.

- To accommodate trending of the performance of individual engines through time, it is desirable to explicitly store the engine specific initial conditions with respect to reference. Imposing these condition (deterioration) values allows tracking of changes in engine component condition relative to the beginning of its service life.

- The database system can be further enhanced by routines combining analyzed test bed data and “on wing” (P.P.I.) recorded performance data in search for correlations between the two performance indicators. For this purpose, P.P.I. algorithms replacing manual chart readings can improve the accuracy of the P.P.I. values.
• Enhancement of the graphical user-interfaces developed (i.e. the data entry 'wizards') will enhance user-friendliness of the GSP GPA tool.

• In the current set-up pressure losses in the combustion chamber and leaks in the gas path are left out of the analysis. In future, the GSP GPA tool can be extended by defining also pressure losses and leaks as component condition parameters. With 'bench-mark' measurement sets, the analysis results obtained with both the current and the extended GSP GPA tool can be compared, in order to assess the effect on diagnostic accuracy. This will also indicate whether combustor pressure losses and or leaks indeed play a significant role in engine performance degradation.
Literature


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[16] Natuurkundig Meet Practicum, handleiding, Faculteit Technische Natuurkunde TU Delft
OPDRACHT

Naam : H.Pieters
Classificatie : afstudeeropdracht
Datum : 07-10-2004
Begeleiders : ir. W.P.J. Visser (Delta Consult)

Onderwerp: Toepassing GSP gaspadanalysetool voor diagnose en trending gasturbinen

Inleiding
Gaspad analyse mbv moderne gasturbin simulatietools vormt een krachtig middel ter diagnose van gasturbin-componenten. Voor GSP zijn geavanceerde numerieke methoden ontwikkeld voor gaspad analyse waaronder ‘adaptive modelling’ technieken. Het nieuwe GSP ‘generic adaptive modelling’ component is geëvalueerd met gegevens van bestaande motoren, in het bijzonder met testcases van de CF6 proefbank van de KLM. In paper GT2004-53721 (zie bijlage) gepresenteerd op de ASME IGTI Turbo Expo 2004 te Wenen zijn de resultaten van dit werk beschreven.

Delta Consult is geïnteresseerd in industriële toepassing van gaspadanalyse met GSP. Hiervoor dienen de volgende vraagstukken opgelost te worden:
- Hoe dient de technologie aangepast te worden aan operationele (i.p.v. testbed) condities: dit betekent een smallere set van on-wing (vliegtuig/helikopter) c.q. in het veld (industrieel) gemonitorded performance data met andere betrouwbaarheidsmarges?
- Hoe dienen de resultaten geïnterpreteerd te worden voor een gehele vloot van gasturbinen, dit in relatie tot de uitkomsten van testbed performance tests.
- Hoe dient de verkregen resultaten geïnterpreteerd te worden t.a.v. maintenance concept? Voor de KLM motorshop betekent dit bijvoorbeeld het leggen van de relatie tussen ‘work scope’ (type overhaul, i.e. het product van de motorshop) en GSP component conditie waarden.
- Hoe kan trendanalyse gepleegd en gebruikt worden voor optimaliseren van het onderhoud?
- Hoe dient de GSP software user interface (GUI) uitgebreid te worden voor industriële toepassing?

Doelen
- Het onderzoeken van de mogelijkheden en problemen van gebruik van het GSP gaspadanalyse tool voor een vloot van operationele gasturbinen.
- Ontwerpen/implementeren van additionele GSP functionaliteit/user interface voor dit doel.

Opdracht
Uw werkzaamheden bestaan, gezien het voorgaande, uit:
1. Een kennismaking met GSP en de gaspadanalyse/adaptive modelling componenten.
2. Verzamelen operationeel geregistreerde performance gegevens voor GSP gaspad analyse voor een vloot van motoren bij de nader te bepalen gebruiker.
3. Aanpassen/verbeteren (c.q. doen van voorstellen t.b.v.) GSP adaptive modelling component voor analyse van operationele gasturbinen.
4. Demonstreren GSP gaspadanalyse en trending functie op een vloot van gasturbinemotoren. Zelf uitvoeren van code-aanpassingen in GSP (Borland Delphi7) is gewenst maar kan ook in samenwerking met Delta Consult medewerkers gebeuren.

Rapportage
De resultaten van de studie dienen te worden vastgelegd in een Engelstalig rapport, voorzien van een copie van deze opdracht en een summary van opzet en resultaten van het onderzoek.

Begeleiding
Het werk zal in nauw overleg met Delta Consult en in samenwerking met de nader te bepalen gasturbinengebruiker gebeuren (bijv. KLu, KM, KLM of een industriële gasturbinengebruiker). Standplaats is Delta Consult vestiging SKF Nieuwegein.

Appendix A
Hoogleraar,  

Prof. ir. J.P. van Buijtenen

Begeleider,  

ir. W.P.J. Visser

Appendix A
Appendix B: GEM42 technical background

The GEM42 engine was designed especially for helicopter application and powers the Westland Lynx helicopter. This helicopter is equipped with two GEM42 engines. It has a free power turbine as nearly all helicopter gas turbines, but is different to the majority of turboshaft engines in that it features a two-shaft gas generator.

Figure 42 shows the cross section of a GEM42 engine featuring: an axial four-stage low pressure compressor (LPC), driven by an axial single-stage low pressure gas generator turbine (LPT); an high pressure centrifugal compressor (HPC) driven by an axial single-stage high pressure gas generator turbine (HPT); and an axial two-stage power turbine (PT) driving the output shaft, which passes to the front of the engine. The combustor is reverse flow annular and the drive is through a reduction gearbox, in the case of the GEM42.

The choice for the two-shaft gas generator design can be explained as follows. Turboshaft engines for helicopter application face a number of special performance requirements including very rapid response rates and a need for good part load fuel economy in case of application in multi-engine helicopters like the Westland Lynx. The latter requirement tends to demand high pressure ratios.

These requirements justify the arrangement of the gas generator. The twin-spool design makes it a flexible engine with exceptionally fast, surge free response to power demands. Moreover, high pressure ratios can be achieved without application of variable geometry or blow off.

Application of variable geometry would require an extensive control system. In case of a small engine the costs for such a system are a significantly high proportion of total engine costs. Moreover, air off-takes and leakages tend to be more critical in small size gas turbines. A draw back for the application of a two-shaft configuration is however the increased complex bearing and sealing arrangement. Mechanical losses and wind losses of rotating components are relatively large in small components.
Appendix C: Maintenance procedures Royal Netherlands Navy

A GEM42 engine can be sent into maintenance for several reasons such as the number of flight cycles of critical components, in case of a low PPI margin or on request of the pilot.

Each component has a specific service time, after which maintenance inspection is dictated by the OEM. This time depends on the type of component, its operating conditions and the engine usage. For example, the HPT is exposed to extremely high temperatures. This causes its condition to deteriorate in general faster then other components and reduces its service time.

When one of the components has reached its service time, the engine is sent into maintenance.

The power performance index (P.P.I.) is a GEM42 specific performance indicator to assess the overall engine condition. The index is expressed in percentage. For safe operation the value must be above a certain minimum value.

The P.P.I. value is based on the ratio of power turbine inlet temperature (T4.49) and high pressure spool speed Nh at certain ambient conditions. In a P.P.I. check, T4.49 and Nh are measured together with the ambient pressure and ambient temperature. In a specific PPI chart (see Figure 43) the values of Nh and T4.49 are corrected for ambient conditions. This way a PPI value is derived.

The P.P.I. is generally determined during engine operation, as an in-flight check procedure.

In the engine maintenance procedure of the Royal Netherlands Navy it is common practice to send the engine directly into maintenance for inspection, without a preliminary performance test. Maintenance actions are performed based on experience of the maintenance staff.

Only in special circumstances, such as deviant behavior of the engine or an extremely low P.P.I. value the engine is first tested in the ground test facility. There the P.P.I. is determined again in order to verify the in flight obtained PPI values. On board, the instrumentation often is less accurate.

The P.P.I. value is always checked after maintenance actions in order to verify whether the engine performance is sufficient.

Apart from the P.P.I. related variables a large number of other performance variables are measured during the performance test in the ground test facility (see Definitions and Nomenclatures, page 12). In order to pass the performance test an engine performance of at least 835 kW with out crossing temperature limits is required.
Figure 43, chart used to determine P.P.I. value corresponding to certain T4.49 and Torque
Appendix D: Selection of condition parameter subsets

Chapter 5 states that it is in general not possible to derive a solution for all possible combinations of condition parameters, since the system of equations can be ill conditioned for some of them. This is related to the performance variables to which the model has to adapt to. This appendix explains the necessity of variation of specific condition parameters in an analytical way.

In case of the GEM42 engine the following 5 condition parameters have to be included in the subset (be variable) in order to warrant a well conditioned equation set:

- ETA4 and Wc2 representing the condition of the LPC
- ETA5 and Wc2.3 representing the condition of the HPC
- Wc4 partly representing the condition of the HPT

This leaves the 8 subsets shown in Figure 44 that form well conditioned systems.

The mass flow air ($W_{air}$) is equal in all turbo components and its value has an important effect on the condition parameter values of each component. For example, the values of corrected mass flow in the LPC and the HPC are linked by the value of $W_{air}$, as shown in Equation 11:

$$W_{air} = W_{2.3c} \cdot \left( \frac{p_{12.3}}{p_{ISA}} \right) = W_{2c} \cdot \left( \frac{p_{12}}{p_{ISA}} \right) \cdot \left( \frac{T_{12}}{T_{ISA}} \right)$$

Equation 11

Figure 44, predefined subsets for analysis
With the values for $P_{t2}$, $P_{t2.3}$, $T_{t2}$ and $T_{t2.3}$ measured, the values of $W_{c2.3}$ and $W_{c2}$ are dependent in the value of $W_{air}$.

Equation 12 is the formula of conservation of energy over the combustion chamber. With the values of pressure and temperature before the combustion chamber imposed, the only unknown variables are $W_{air}$ and $T_{t4}$. This makes $T_{t4}$ also dependent on $W_{air}$.

$$\dot{w}_{fuel} \cdot LHV \cdot \eta_{cc} = \dot{w}_{air} \cdot c_p \cdot (T_4 - T_3) = \dot{w}_{air} \cdot c_p \cdot T_4 - \dot{w}_{air} \cdot c_p \cdot T_3$$  \hspace{1cm} \text{Equation 12}

With 'A' fixed and $T_{t3}$ and $P_{t3}$ measured, the value of $P_{t3}$ also depends on $W_{air}$ (Equation 13). With this function and the assumption of constant pressure loss in the combustion chamber (Equation 14), also $P_{t4}$ is known.

$$\dot{w}_{air} = A \cdot \rho \cdot \sqrt{\frac{2c_p T_{t3} \left( \frac{P_{t3}}{P_{s3}} \right)^{\frac{k-1}{k}} - 1}{\frac{p_{s4}}{p_{s3}}}}$$  \hspace{1cm} \text{Equation 13}

$$p_{s4} = p_{s3} + \Delta P_{cc}$$  \hspace{1cm} \text{Equation 14}

Equation 15 is the formula for corrected mass flow in the HPT:

$$W_{at} = \frac{T_4}{\sqrt{\frac{p_{s4}}{p_{s3}}}} \cdot \sqrt{T_{ISA}}$$  \hspace{1cm} \text{Equation 15}

With $P_{s4}$ dependent on $W_{air}$, and the fact that (Equation 15) this would mean that if $W_{c4}$ cannot be varied it is claimed that:

$$W_{air} \cdot T_4 = W_{air} \cdot \sqrt{T_4}$$

This makes the system of equations very inflexible. This is the reason why $W_{c4}$ should always be included in the subset.
Appendix E: Numeric solving method

GSP uses a Newton-Raphson based solver to solve the model system of equations. In this appendix the Newton-Raphson solving method is explained in brief.

**Newton-Raphson solving method**

Equation 16 shows \( n \times n \) system of equations in which \( f \) are the error equations, \( \varepsilon \) is the system error vector and \( s \) is the vector of system variables. In case of an off-design calculation \( s \) consists the systems *states* whereas in an AM calculation \( s \) consists both the systems *states* and the map modifiers.

\[
\begin{bmatrix}
  f_1(s_1) + f_1(s_2) + \ldots + f_1(s_n) \\
  f_2(s_1) + \ldots \\
  \ldots \\
  f_n(s_1) + \ldots + f_n(s_n)
\end{bmatrix}
\begin{bmatrix}
  \varepsilon_1 \\
  \varepsilon_2 \\
  \vdots \\
  \varepsilon_n
\end{bmatrix}
\leq
\begin{bmatrix}
  \mathbf{0} \\
  \mathbf{0} \\
  \vdots \\
  \mathbf{0}
\end{bmatrix}
\]

Equation 16

With the Newton-Raphson method, changes in the system error \( \varepsilon \) are assumed to be linearly related to changes in \( s \), provided that the changes in \( s \) are small.

\[
\varepsilon = J \times \Delta s
\]

Equation 17

In Equation 17, \( J \) is an \( n \times n \) matrix of partial derivatives of \( \varepsilon \) with respect to \( s \), the so called Jacobian matrix:

\[
J =
\begin{bmatrix}
  \frac{\partial \varepsilon_1}{\partial s_1} & \frac{\partial \varepsilon_1}{\partial s_2} & \ldots & \frac{\partial \varepsilon_1}{\partial s_n} \\
  \frac{\partial \varepsilon_2}{\partial s_1} & \frac{\partial \varepsilon_2}{\partial s_2} & \ldots & \frac{\partial \varepsilon_2}{\partial s_n} \\
  \vdots & \vdots & \ddots & \vdots \\
  \frac{\partial \varepsilon_n}{\partial s_1} & \frac{\partial \varepsilon_n}{\partial s_2} & \ldots & \frac{\partial \varepsilon_n}{\partial s_n}
\end{bmatrix}
\]

Equation 18

The values in the Jacobian matrix (Equation 18) are obtained by subsequent calculation of the derivative of the system error to each state variable.
A non-homogenous system of linear equations such as Equation 17 has a unique solution if the determinant of the systems matrix is nonzero [12]. The non-zero determinant of the Jacobian matrix results therefore in a unique solution for Equation 19.

\[ ds = J^{-1} \times \epsilon \]

Equation 19

Subsequent performance of Equation 17 and Equation 19 is called an iteration step. After every step the error reduction is evaluated. As long as the error per step diminishes, the applied Jacobian remains unchanged. In general however, the relation between changes in s and the error reduction is non-linear, see Figure 45. Therefore, during the calculation several new Jacobian matrices are obtained, to redirect the calculation toward the solution. The system of equations is solved when the remaining error is within tolerable limits.

![Figure 45, non-linear relation between (system) error and state variable](image)

Linear solving methods, e.g. applied in linear GPA, do not take into account the non-linear relation between (system) error reduction and state variable. This makes this type of methods significantly less accurate and only applicable close to the design point.
Appendix F: Program mini-symposium

"RR GEM42 gas path analysis"

Delta Consult/SKF Mini-symposium

1 June 2005, 1:00 - 6:00 pm
SKF Business & Technology Park:
Kelvinbaan 16
3439 MT Nieuwegein, The Netherlands

The mini-symposium offers insight in advanced diagnostic methods for the Rolls-Royce GEM42 engine of the Westland Lynx helicopter using measured performance data and associated operator experiences.

Following successful development of gas path analysis capabilities in the Gas turbine Simulation Program GSP developed at National Aerospace Laboratory NLR (www.gspteam.com), GSP has been applied for gas path analysis on the GEM42 engine. The work has been performed at Delta Consult Nieuwegein with a major contribution from Hanneke Pieters of Delft University of Technology who did her master thesis on the subject.

With the mini-symposium we would like to present the results of the work alongside overviews of operator experience. With a subsequent forum discussion, opinions from different parties can be exchanged. We hope to encourage communication among operators, universities and industry on the subject, thereby serving the gas turbine operator community in general and GEM42 operators specifically.

Agenda:
13:00 : Welcome and coffee/tea
13:30 : Introduction  Wilfried Visser Delta Consult
13:45 : Royal Netherlands Navy operational and maintenance experience on the GEM42 engine,
        RNLN
14:20 : Royal Navy (RN) and British Army Air Corps (AAC) operational and maintenance,
        experience on the GEM42 engine,  UK MOD
15:00 : Break
15:15 : GEM42 gas path analysis with GSP adaptive modeling,
        Hanneke Pieters/Wilfried Visser Delta Consult
15:45 : Forum discussion
16:15 : Drink
17.00 : Closure