Proceedings of ASME Turbo Expo
Land, Sea & Air
June 3-6, 2002, Amsterdam, , The Netherlands

GT-2002-30496

PRELIMINARY GAS TURBINE DESIGN USING THE MULTIDISCIPLINARY DESIGN SYSTEM MOPEDS

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ABSTRACT

A prototype preliminary design task for gas turbines is set up to outline the four major requirements a preliminary design program must typically meet: assessment of all major engine components and their interrelations; inclusion of all relevant disciplines; designing over several operating points; and model fidelity zooming at least for individual components. It is described how the ”MOdular Performance and Engine Design System” (MOPEDS) - MTU Aero Engines’ software package for the preliminary design of airborne and stationary gas turbines - fulfills these requirements. The program structure, the graphical user interface, and the physical models are briefly presented. A typical design example is carried out emphasizing the necessity for a numerical procedure to find a solution to the many variables and constraints that the design problem comprises. Finally, some dominating multidisciplinary effects are discussed.

INTRODUCTION

During the preliminary design phase of gas turbines the main parameters are fixed. These, in return, fix most of the risks and financial resources associated with the development, manufacture, and operation of the engine under concern. The preliminary design process must in contrast to that be carried out very quickly so that engine suppliers are able to evaluate numerous concepts with respect to the market requirements at a given short time. This brings up the need for an adequate software tool that accurately and quickly guides the designer through the preliminary design process. MTU Aero Engines uses such a software package. It is called ”MOdular Performance and Engine Design System” (MOPEDS).

The preliminary design of a new engine usually starts with the thermodynamic cycle. It is fixed so that all aircraft requirements are met at all relevant operating points of the flight mission. From the cycle the engine configuration is then derived. Subsequently all engine components are designed aerodynamically and mechanically with respect to a good matching of the components, well behaved off-design characteristics over the whole mission, low cost, ease of manufacture, reliability, noise legislation, emission regulation etc. Such a preliminary design process is characterized by three major features upon which MOPEDS is built: all major engine components and their interrelations are assessed; several relevant disciplines are considered; designing is done on several operating points and the off-design characteristics are adequately checked.

Once the preliminary design phase is completed its results must be smoothly fed into the detailed design process. For this reason more sophisticated methods are included in MOPEDS. These higher fidelity methods are typically applied for singu-

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lar components that are included in the company's work share. These methods are the ones used in the specialist departments, so that they provide the 'interface' through which the pre-design results are passed to the detailed design and vice versa. The designer in the specialist department is then able to add one higher order of detail to the design and, simultaneously by running MOPEDS, is able to see how his changes affect the performance of other components and the overall engine. Throughout the long lasting detailed design phase the overall engine behavior is monitored thereby. 'Model fidelity zooming', i.e. the application of models of different degrees of detail, is the fourth major feature of MOPEDS.

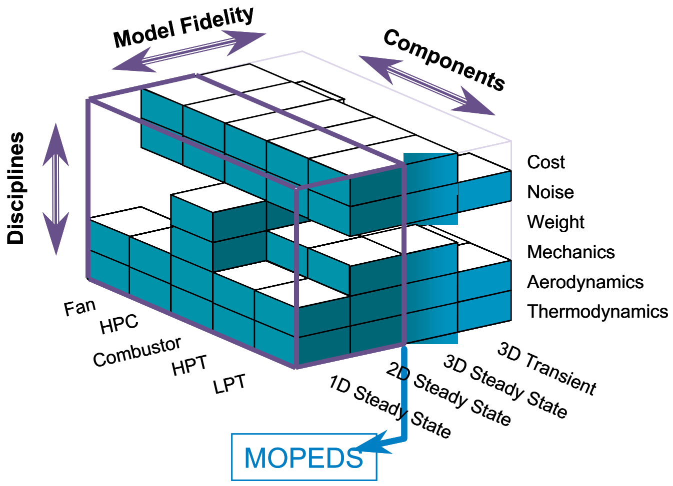


Figure 1. Cube adopted from (Claus, 1991).

Representative for several known multidisciplinary engine simulation systems, the popular Numerical Propulsion System Simulation NPSS (Claus, 1991) shall be mentioned. NPSS is made to model all engine components with several disciplines and the full range of model fidelities as is shown in figure 1. One of the strengths of NPSS is the ability to include highest fidelity methods such as multidimensional CFD modeling for several components simultaneously if not for all. Somewhat to the contrary, the preliminary engine design tasks are clearly the focus of MOPEDS, so that mainly lower model fidelity methods, such as 1d and 2d methods, are included so far. It is intended to thoroughly exploit the first order effects using this ability before any second order effects are tracked in the design process with higher fidelity methods. No attempt is made to model all-engine effects with high fidelity methods within MOPEDS.

(Halliwell, 2001) gives an excellent overview of the preliminary design task. Following his ideas, a prototype preliminary engine design task is described in section 1. The thus created prototype problem is used to emphasize the necessity for an integrated multidisciplinary tool and it is the measure for MOPEDS which is described in section 2. In the spirit of the prototype problem some exemplary pre-design results are then shown in section 3.

NOMENCLATURE

alt	flight altitude
BCR	cruise
BPR	bypass ratio
F_N	net thrust
MCL	max climb
Ma	Mach number
p_{25}/p_2	LPC core pressure ratio
p_{14}/p_2	fan outer pressure ratio
p_3/p_{26}	HPC pressure ratio
SFC_{BCR}	thrust specific fuel consumption at cruise
TO	take-off
w_2	fan entry mass flow
ΔT_{ISA}	delta to ISA temperature
$\eta_{HPC,MCL}$	isentropic efficiency HPC at max climb
$\eta_{HPT,MCL}$	isentropic efficiency HPT at max climb
ψ	stage enthalpy diff. divided by blade speed squared

$High\ Spool\ Speed_{MCL}$	HP speed at max climb
$Surge\ Margin_{MCL}$	surge margin at max climb
$\sum HPC\ Vanes + Blades$	Sum of HPC blades and vanes
$\sum Mass\ Disks\ HPC + HPT$	Sum of HPC and HPT disk masses

1 A PROTOTYPE PRELIMINARY DESIGN TASK

The prototype preliminary design task to be set up in the following can by no means be generic. The design variables, constraints, figures of merit, and operating points considered are generally completely different in number and type for each individual engine project. We still try to give some idea of the preliminary engine design task:

The engine design ideally starts with the aircraft and engine demands such as flight mission, number of engines, thrust and SFC requirements, maximum size and weight, installation requirements etc. fixed. These determine the engine's thermodynamic cycle which in return fixes the engine configuration. Say, for the prototype problem, a typical medium-sized commercial aircraft is considered whose engine cycle requirements can be met by an air-breathing, high-bypass ratio, two-spool, mixed turbofan engine. The major cycle design variables are then

overall pressure ratio
HP/LP pressure ratio split

fan outer pressure ratio
bypass ratio
inlet flow
turbine inlet temperature

Cycle constraints are derived from the flight envelope requirements or typically arise from temperature limits imposed to assure sufficient mechanical strength or to limit the cooling flow demand:

net thrust required
maximum HPC exit and HPT, LPT inlet temperatures.
maximum fan diameter.

A possible figure of merit is

minimum specific fuel consumption.

The preliminary aerodynamic design variables for turbo components are typically

rotational speed
stagewise distribution of reaction, loading, flow rate
flowpath radius ratios and flowpath slopes
blading parameters such as: pitch-to-chord ratio, aspect ratio, taper ratio, axial and tip clearance, profile thickness ratio, rel. trailing edge thickness, etc.

Typical aerodynamic constraints, especially for compressors, are

maximum rotor tip Mach numbers
minimum de Haller numbers
minimum surge margin
several geometrical constraints like limits on radius ratios

and possible figures of merit could be

maximum component efficiency
minimum number of stages
minimum number of blades
minimum component length.

Preliminary mechanical design variables for turbo components are typically

materials
blade profile area and moment of resistance
blade root geometry
disk geometry

typical constraints are

maximum metal temperatures
frequency bounds
maximum low and high cycle fatigue stresses

and figures of merit could be

minimum weight
minimum number of parts
minimum cost.

Variables, constraints and figures of merit for burner, ducts, nozzles, nacelle, shafts, bearings, etc. are to be considered also. Further constraints arise from noise legislations and emission regulations as well as maintenance costs, life cycle costs etc. This easily amounts to an order of one hundred variables and constraints and an overall figure of merit combined from several weighted individual ones.

An adequate preliminary design furthermore assesses all important operating points of the required flight mission. Each engine component is given a nominal design point where the independent design variables are specified. All other points in the envelope are formally treated as off-design points and the dependent variables can be taken to define constraints there. The design variables are then to be chosen to give balanced component characteristics over the whole flight mission.

The nominal design point is most conveniently chosen to be the point with the severest conditions or the strongest influence on the figure of merit. This usually amounts to a high speed and max through-flow point for the nominal aerodynamic design of compressors, nozzles and ducts, say max climb, and possibly a cruise point for the design of turbines. The severest mechanical integrity constraints generally arise at hot day take-off so that the mechanical designing is done there. Further operating points have to be considered that are relevant for external constraints such as noise legislation, for instance. An example of the important operating points is then

hot day take-off
standard day max climb
standard day cruise
sideline, cutback, approach

and others must be considered for burner design, assessment of emission limits, etc.

What makes the design task so challenging are the many design variables and constraints to be considered at several operating points of the flight mission. The strong coupling of the effects of all disciplines as well as the strong interrelation of all engine components puts up the need to consider all of the variables and constraints simultaneously. For instance, the limited take-off metal temperatures of the turbines are a direct function of the cycle variables set in the max climb cycle design point and the turbo component efficiencies. These component efficiencies, however, are a direct function of the aero design variables set at the aero design point max climb or cruise. This gives for these temperature constraints a direct dependence on several design variables of different disciplines set at different operating points. This problem can only be adequately tracked by an integral computer program that simulates these interrelations.

2 THE SIMULATION TOOL

The traditional way of solving the preliminary design task described in the previous section is to run several stand-alone programs, one for each subtask. A loop over a series of such individual programs is done until convergence is achieved. However, due to the time consuming process the mentioned strong interrelation of the engine components, the coupling of the disciplines, and the engine characteristics on all of the important operating points are not adequately captured. Often this shortcoming is very costly compensated for, when the loops must be closed in the subsequent detailed design phase.

MOPEDS was built to overcome this shortcoming. It focuses on the multidisciplinary, all-engine, multi-operating point modelling ability and extensively supports the designer so that he usually can arrive at a 'converged' design. The following section describes the underlying program structure before subsequently a brief sketch of the graphical user interface and the implemented physical models is given.

2.1 Program Structure

MOPEDS is an extension of the in-house performance program "MOdular Performance Synthesis" (MOPS) (Kurzke, 1992) and shares its program structure. Performance programs deal with all-engine effects so that their program structure generally is well suited for such a task and the thermodynamic performance is always the backbone for any preliminary design. It was therefore obvious to base MOPEDS on MOPS.

The program is divided up into the four levels

level 1: graphical user interface (GUI)
level 2: program control
level 3: modules
level 4: 'physical' modelling.

Each level contains a self-sufficient package of programs and data is passed exclusively through standardized interfaces between the levels. Level 1 contains the programs for the GUI which is described in section 2.2 in more detail. Level 2 routines control all input and output operations as well as the run time data transfer between the modules residing in level 3. Any purely mathematical operations like those necessary for a Newton-Raphson iteration are done in level 2 and all external programs are called from there. One of these is the commercial package iSight (Engineous). On command of the user a predefined MOPEDS slave process is passed to iSight at any point of the design process. iSight's full range of numerical procedures ranging from simple parameter studies to optimizations is thereby available at run time. On termination of the iSight subprocess the command is given back to MOPEDS and the necessary data is passed over by the control program.

Level 3 contains all the modules. As depicted in figure 2 the level 3 program structure forms a matrix whose columns represent the engine components, whose rows represent the disciplines, and whose elements are defined to be *modules*. Effectively, each module is a standardized subroutine that stand-alone contains all physical information associated with its position in the matrix. It has standardized interfaces for data transfer in vertical and horizontal direction and to the level 2 control program. Depending on whether its physical content is needed or not it is included in the configuration set up for a specific preliminary design task or not. Somewhat outside the matrix the so-called overall-modules reside which are responsible for data that can not be related to a single discipline or engine component, e.g. thrust and SFC evaluation or assessment of rotor dynamics. At run time a loop over the modules, which are successively called as is sketched in figure 2, is repeated until any iteration is brought to convergence at each operating point. An outer loop over all the operating points specified by the user then completes the process which in total is controlled by the level 2 control program. Each module's variables are uniquely defined at each operating point and are treated by the control program as independent or dependent variables, constraints, or figures of merit depending on the problem under concern. There is no limit on the number of operating points and variables to be considered by the user apart from his own choice to limit the complexity of the problem.

According to the module's self-sufficient character, all of the extensive descriptions of the module's underlying physics and its variables are directly implemented in the module's source code. From there it is automatically translated to html format to make it accessible for the user via the GUI (see section 2.2).

From within the modules the level 4 subroutines containing the 'physical' models (see section 2.3) are called through standardized interfaces. The level 4 programs are the 'specialist's' programs held and maintained by the corresponding departments. Any 'translation' of variables from MOPEDS definition to the level 4 definition is automatically done within the modules freeing the user from this task. The user may choose to be confronted exclusively with the MOPEDS nomenclature, which assures a unique definition throughout all of MOPEDS, or may use the level 4 nomenclature for the limited number of input data needed to configure the level 4 calculation. The first practice is possibly the preliminary designer's choice who sets up the whole MOPEDS process. The specialist who is concentrated on and is used to the level 4 program may choose the latter.

Any 'model fidelity zooming' is realized by selecting the corresponding level 4 routines included in the module. All necessary translation of data from one level 4 routine to the other is again automatically done by the module.

The modules are surely the physical heart of the tool and assure the full modularity of the tool. Practically any engine configuration can be set up ranging from simple single shaft engines to multi-spool, recuperated, inter-cooled, stationary or air-borne engines. All disciplines can be covered ranging from thermodynamics and aerodynamics down to noise and cost assessment.

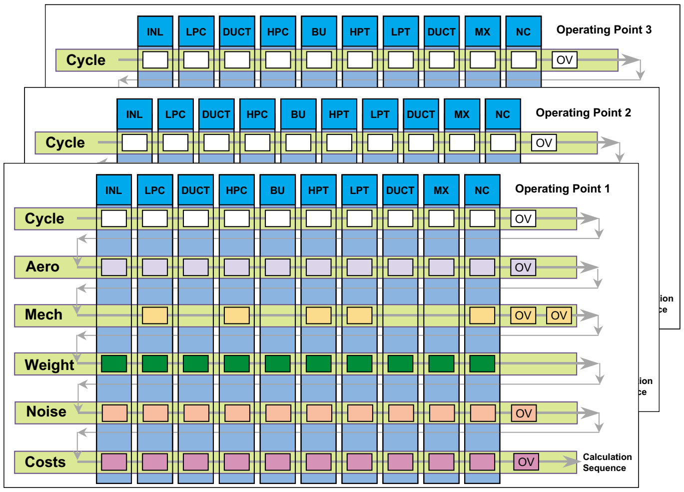


Figure 2. Modularity

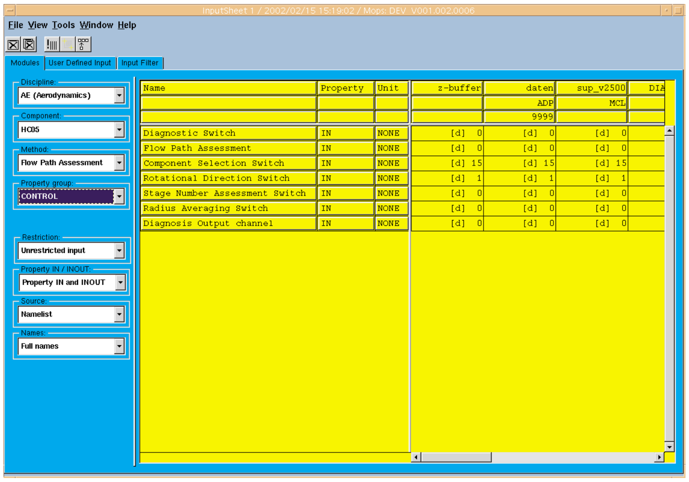
2.2 Graphical User Interface

The mentioned almost limitless flexibility has its price when it comes to setting up the design process, monitor its progress during run time and interpret the results. The provision of well organized input and output data sets as well as extensive help features eases this situation.

The control program of MOPEDS reads input data exclusively from ASCII files. With help of these lengthy but all flexible and well organized files the user may set up his design task. This includes the specification of the engine configuration, the input of all physical data, and the setup of the mathematical problem to be solved, i.e. the input of the iteration/optimization scheme, the number of operating points considered, the models to be used, etc. Input data sets for standard design tasks are provided so that the data generally must not be created from scratch. A strict file administration assures the reproducibility of any MOPEDS run.

The ASCII file system is manipulated through the graphical user Interface (GUI). The GUI consists of several elements. Two of them are the so-called *input sheet* and *output sheet* windows for modules. No matter which module is considered the user is confronted with the one input sheet shown in figure 3 and an analogous output sheet window. He is thereby freed from the numerous individual interfaces of the stand-alone programs that are included in MOPEDS. Furthermore, a description of all the modules' variables and physical models can be invoked from within these windows. An example of the sort of available information, that is directly provided from the modules' source code (see section 2.1), is shown in figure 4. The user is thereby well guided when specifying each module's input data and interpreting its results. Constraining himself to the proposed input values and judging the results as advised, he may even apply the modules' methods if he is not an expert.

A rather large collection of graphical outputs is provided. They are initiated from within the output sheet and they display the module's results. Examples of these outputs are turbine loading diagrams, velocity vectors, flow path geometries, stress and temperature distributions, noise levels, ICAO parameter distributions, etc. The commercial package TECPLOT (AMTEC) is directly linked to the output sheet to automatically produce the displays during run time. TECPLOT also provides the basis for subsequent postprocessing individually carried out by the user.



InputSheet 1 / 2002/02/15 15:19:02 / Mops: DEV V001.002.0006

Discipline: AE (Aerodynamics)
Component: HC05
Method: Flow Path Assessment
Property group: CONTROL
Restriction: Unrestricted input
Property IN / INOUT: Property IN and INOUT
Source: Namelist
Names: Full names

Name	Property	Unit	z-buffer	daten	sup_v2500	DIA
				ADP	MCL	
				9999		
Diagnostic Switch	IN	NONE	[d] 0	[d] 0	[d] 0	
Flow Path Assessment	IN	NONE	[d] 0	[d] 0	[d] 0	
Component Selection Switch	IN	NONE	[d] 15	[d] 15	[d] 15	
Rotational Direction Switch	IN	NONE	[d] 1	[d] 1	[d] 1	
Stage Number Assessment Switch	IN	NONE	[d] 0	[d] 0	[d] 0	
Radius Averaging Switch	IN	NONE	[d] 0	[d] 0	[d] 0	
Diagnosis Output channel	IN	NONE	[d] 0	[d] 0	[d] 0	

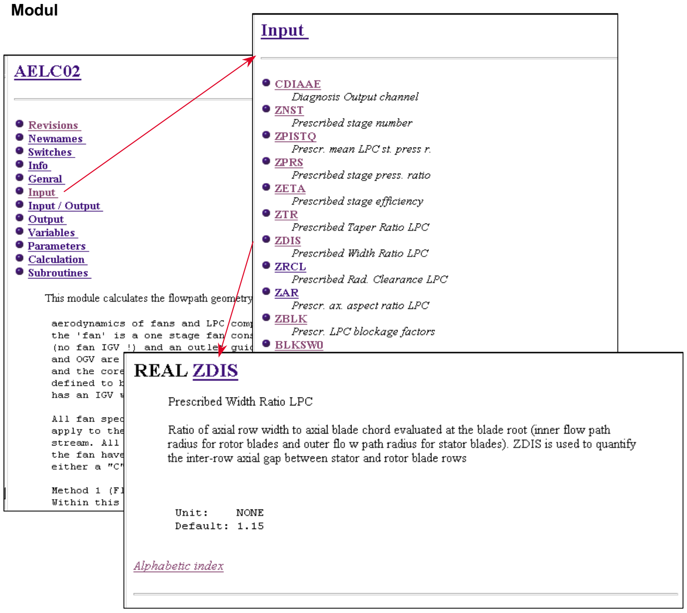
Figure 3. Input Sheet Window for Modules

2.3 Physical Models

All in MOPEDS included programs are the in-house developed and over the years validated programs of the specialists' departments. The currently available 'physical' models are subdivided into the disciplines

thermodynamics
aerodynamics
mechanics
weight assessment
noise assessment
cost assessment.

To give some idea of the models included so far they shall be very shortly listed as follows: Steady and unsteady '0d' performance



Modul

AELC02

- Revisions
- Newnames
- Switches
- Info
- Genral
- Input
- Input / Output
- Output
- Variables
- Parameters
- Calculation
- Subroutines

This module calculates the flowpath geometry

```
aerodynamics of fans and LPC comp
the 'fan' is a one stage fan cons
(no fan IGV !) and an outlet guid
and OGV are
and the core
defined to b
has an IGV w

All fan spec
apply to the
stream. All
the fan have
either a "C"

Method 1 (Fl
Within this
```

Input

- CDIAAE
  Diagnosis Output channel
- ZNST
  Prescribed stage number
- ZPISTQ
  Prescr. mean LPC st. press r.
- ZPRS
  Prescribed stage press. ratio
- ZETA
  Prescribed stage efficiency
- ZTR
  Prescribed Taper Ratio LPC
- ZDIS
  Prescribed Width Ratio LPC
- ZRCL
  Prescribed Rad. Clearance LPC
- ZAR
  Prescr. ax. aspect ratio LPC
- ZBLK
  Prescr. LPC blockage factors
- BLKSW0

REAL ZDIS

Prescribed Width Ratio LPC

Ratio of axial row width to axial blade chord evaluated at the blade root (inner flow path radius for rotor blades and outer flo w path radius for stator blades). ZDIS is used to quantify the inter-row axial gap between stator and rotor blade rows

```
Unit:    NONE
Default: 1.15
```

Alphabetic index

Figure 4. Online Help Feature for Modules

models for all relevant engine components. Meanline (1d) and through flow (2d) aerodynamic codes for the turbo components and ducts. Burner design and assessment of emissions in terms of ICAO parameters. Blade and blade root steady and unsteady mechanics assessed by 1d beam theory methods. Containment formulae constraining the mechanical casing design. 1d finite difference and 2d finite element codes solving the elasticity and heat conduction equations for disks. Shaft design and rotor dynamics based on beam theory methods and a parametric bearing design concept. Several weight assessment methods, some calculating masses from the laid out geometry and some based on simple correlations. Engine noise determined for single engine components and the overall system. Finally, several correlations for the costs of development, manufacture, maintenance and the life cycle of the engine.

Model fidelity zooming is readily applied for the 1d and 2d aerodynamic and mechanic models. The data transfer as well as the conversion of data from one level of accuracy to the other is fully automated.

The huge amount of design variables, some of which mentioned in section 1, that need to be specified as input to the many physical models, make it impossible to consider all of them simultaneously even with a tool like MOPEDS. For this reason a data base of generic component models has been set up. These generic component models contain all input data for a physical model in, as far as practical, dimensionless form to allow scaling of components correctly taking into account the corresponding similarity rules. It is then generally possible to consider only a very small number of design variables while fixing all others by the generic model. Most of the data base models set up for MOPEDS are geometric component models like those for turbo components whose geometry is non-dimensionally provided as radius ratios, area ratios, aspect ratios, pitch-to-chord ratios, etc. Since the generic models are usually set up with reference to already designed engine components, they can easily be read into MOPEDS when it comes to analyse a given engine. Figure 5 shows the general arrangement of an engine whose geometry is completely provided by generic models.

However, MOPEDS provides one other way to free the user from explicitly specifying the many design variables. So-called *knowledge bases* have been programmed for all input variables. These contain rules to set the input values depending on the situation. Examples of which are rules for typical stage-wise distributions of reaction, loading, and flow rate for turbo components. The user may invoke these knowledge bases for singular design values, several, or even all. A fully automatic engine design is done by invoking all of them. The example provided in section 3 makes use of such full automatic designs. Applying the full automatic scheme the designer is able to arrive at a first solution from where he can start to fine-tune his design.

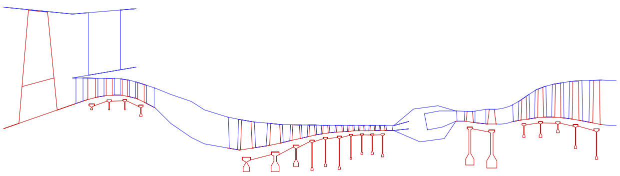


Figure 5. General Arrangement of an Engine to be analysed

3 APPLICATION EXAMPLE

MOPEDS is used to solve a simple artificial preliminary design problem. Say, the problem is to design a high pressure compressor upgrade for a given engine. Apart from rather small necessary adaptations, all engine components other than the HP compressor may not be changed and the underlying thermodynamic cycle is kept constant in terms of pressure ratios, mass flows, and thrust requirements.

The high-bypass ratio, two-spool, mixed turbofan engine considered in section 1 is taken as a basis and the problem is solved in the spirit of the design task sketched in section 1. However, several simplifications are made to keep the design problem easy:

Aerodynamic design is done only for turbo components based on meanline codes. Mechanical design is only carried out for blade roots and disks. It is also based on 1D methods. Besides thermodynamics, aerodynamics, and mechanics no further disciplines are looked at. The three mission points *hot day take-off*, *standard day max climb* and *standard day cruise* are considered. The thermodynamic cycle is specified at max climb and the aerodynamic design of all engine components is made there. All components can then simultaneously be run in off-design mode thermo/aerodynamically at all other operating points. Furthermore, aerodynamic meanline calculations are only done at the design point, where appropriate component maps are scaled accordingly. These maps are used at all off-design points, thereby avoiding any aerodynamic off-design calculations at run time.

The max climb design point is taken to be defined thermodynamically by

$$Ma = 0.8,\ alt = 10668m,\ \Delta T_{ISA} = 0,\ F_N = 25000N,$$
$$w_2 = 150kg/s,\ BPR = 5,\ p_{25}/p_2 = 3.0,\ p_{14}/p_2 = 1.7,$$
$$p_3/p_{26} = 13,\ \textit{fixed secondary air system}$$

and all of these values are kept constant.

The many aerodynamic design variables mentioned in section 1 are reduced to only the three

$$\textit{radius ratio HPC exit} \quad (1)$$
$$\textit{High Spool Speed}_{MCL} \quad (2)$$
$$\textit{number of HPC stages} \quad (3)$$

by taking all others from the MOPEDS knowledge base. The only explicitly defined aerodynamic constraint is

$$\text{minimum} \quad \textit{Surge Margin}_{MCL}. \quad (4)$$

The mechanical design is chosen to be done at hot day take-off rotation:

$$Ma = 0.2,\ alt = 0,\ \Delta T_{ISA} = 15K,\ F_N = 115000N.$$

In order to keep our example simple, the blading design variables like blade profile area and blade moment of resistance are taken from the same knowledge base that is used for the aerodynamic blade design. The blades and vanes are then simply mechanically analysed at take-off. A close coupling between aero and mechanical blading design is avoided thereby. Merely the blade roots and the disks are designed: materials and geometry are found during run time exactly fulfilling stress and temperature constraints at take-off and providing minimum weights. No independent mechanical design variables then appear. However, the constraint

$$\text{maximum} \quad \textit{Stresses}_{MCL} \quad (5)$$

formally stands which especially puts limits on the values of *radius ratio HPC exit* and *High Spool Speed*$_{MCL}$ beyond which the mechanical design is not feasible anymore.

The cruise point

$$Ma = 0.8,\ alt = 10668m,\ \Delta T_{ISA} = 0,\ F_N = 20000N$$

is used in the example to evaluate SFC there.

The design task's figure of merit is defined to be a weighted function of

$$\text{minimum} \quad SFC_{BCR} \quad (6)$$
$$\text{minimum} \quad \sum \textit{HPC Vanes + Blades} \quad (7)$$
$$\text{minimum} \quad \sum \textit{Mass Disks HPC + HPT} \quad (8)$$

The number of blades and vanes is hereby interpreted as some measure of costs in our simple example. The disk masses are taken as some measure of component weights.

The thus defined design task forms the basis for the following optimization and parameter studies. To set up a problem like this from scratch takes an experienced preliminary designer a few hours and run time on a typical workstation for each of the following studies is in the order of a few minutes.

It must be clearly said that the following results are meant to show exemplary results, that by no means are to be taken for granted in absolute terms. Preliminary design in general first of all provides trends and not absolute results and this is even more valid for the artificial prototype problem presented here.

3.1 Optimization

A numerical optimization scheme based on a coupled genetic and gradient based algorithm is used to solve the prototype problem. It is defined by the design variables (1) - (3), the constraints (4), (5) and the figures of merit (6) - (8). The optimization is started from some arbitrary initial solution that could represent the given gas turbine whose HP compressor is to be improved.

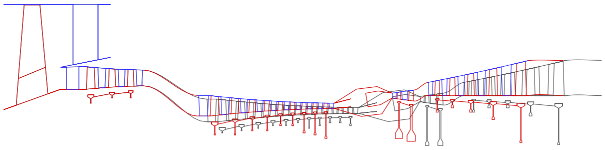


Figure 6. General Arrangement before (grey) and after Optimization (colored) .

In figure 6 the initial engine configuration and the optimized one are shown and table 1 compares starting values with optimal values. The improvements shown in table 1 are of course

Table 1. Optimization

	optimal value / start value
radius ratio HPC exit	0.91/0.89
$High\ Spool\ Speed_{MCL}$ [RPM]	13506/12000
number of HPC stages	9/11
SFC_{BCR}	0.96
$\eta_{HPC,MCL}$	1.03
$\eta_{HPT,MCL}$	1.02
$\sum HPC\ Vanes + Blades$	0.93
$\sum Mass\ Disks\ HPC + HPT$	1.4

strongly dependent on the initial solution and the choice of figure of merit. However, the example serves to illustrate the value of a tool as presented herein. Even though the investigated problem is somehow ’academic’, it comprises a truly multidisciplinary, multi-operating-point investigation of the overall gas turbine engine. A preliminary designer could by no means produce results like this - not to speak of a more realistic problem with more variables - in such a short time without an integral tool like MOPEDS.

However, there obviously can be several pitfalls when numerically investigating a problem of high complexity. Especially the physical accuracy of the used models must always be carefully checked. This is even more true if a numerical optimization is used that could exploit some model’s strange trends outside the model’s typical range of application. One means of checking the validity of a numerically obtained solution is to vary the design variables in it’s vicinity. Not only the optimum can be checked thereby but also the models by investigating their trends carefully. This shall be done in the following parameter studies. The parameters are deliberately varied over a wider range than is reasonable for a normal design to show how the models behave. Still, these parameter studies are another typical preliminary design result that can be achieved with MOPEDS - even though one might typically not vary the design variables (1) - (3) directly.

3.2 HPC Radius Ratio Variation

Varying the design variable (1) effectively means that the radial position of the HPC is changed. The HPC and HPT flow path annuli and the bladings in terms of blade inlet and exit angles, pitch-to-chord ratios etc. are then individually and fully automatically designed at each run by use of the knowledge bases. The engine’s LP components are left almost unchanged except for some adaptations necessary for the extreme HPC radius ratios. Minor LPT design changes automatically result from different LPT entry conditions during the parameter study.

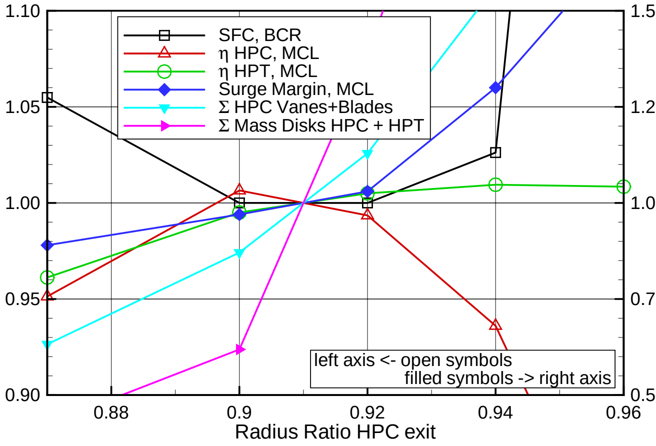


Figure 7. HPC Radius Ratio Variation. Dependent variables are divided by the optimal values of section 3.1

Some of the most dominant effects of this parameter study are shown in figure 7. First, an optimum of the HPC efficiency $\eta_{HPC,MCL}$ can be identified around radius ratio 0.9. For lower radius ratios the higher stage loadings ψ and the associated large profile losses become dominant so that $\eta_{HPC,MCL}$ falls there. At very high radius ratios the lower loading can no longer compensate for the increasing secondary flow losses and radial clearance losses caused by the ’short’ blades especially in the rear of the HPC. $\eta_{HPC,MCL}$ falls there again. The highly loaded HPT stages benefit from higher blade speeds over the full range of radius ratios. The SFC_{BCR} distribution directly reflect the $\eta_{HPC,MCL}$ and $\eta_{HPC,MCL}$ trends, since all other component efficiencies are merely unchanged. The exchange rates between SFC and the component efficiencies directly follow from the underlying thermodynamic cycle and the aerodynamic off-design characteristics.

The number of blades and vanes given in figure 7 is almost a linear function of the flow path radius since pitch-to-chord ratios and aspect ratios are almost constant for each run. The number of blades and vanes can be closely linked to the costs of manufacture.

The disks are strongly influenced by the increasing centrifugal forces at higher radius ratios which leads to larger and heavier disks as can be seen in figure 7. The disk temperature distribution has a minor additional effect: The mainstream gas temperatures and the secondary air system temperatures are affected by the HPC efficiency. This leads to higher disk hub and rim temperatures for the rear HPC disks and the HPT disks at lower HPC efficiencies. More stringent temperatures then generally lead to heavier disks.

3.3 High Spool Speed Variation

Exactly in the same spirit as before the design variable (2), the high spool speed, is varied leaving everything else constant. Merely the HPC and HPT bladings and disks are individually designed for each speed and some minor LPT design adjustments follow automatically.

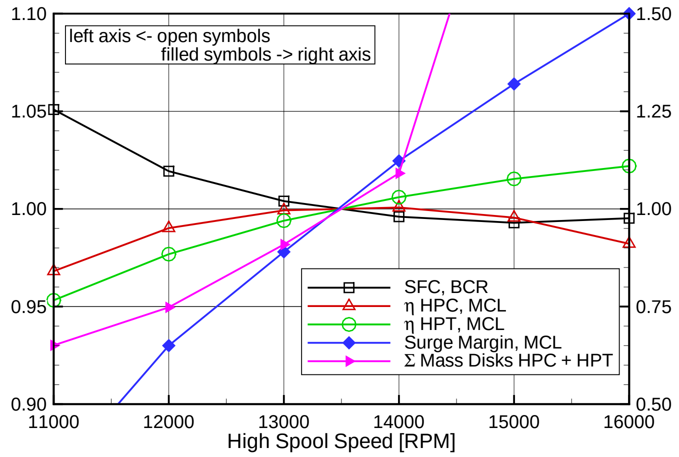


Figure 8. High Spool Speed Variation at MCL. Dependent variables are divided by the optimal values of section 3.1

The HPC, HPT efficiencies and the HPC surge margin are strongly affected by the spool speed as is seen in figure 8. High losses result from the high loadings at low speeds and the surge margin vanishes at some point. At higher speeds the loading is reduced but the Mach number losses become increasingly dominant so that an HPC efficiency optimum is again found. This, again is not the case for the highly loaded HPT. The disk design is equally strongly affected by the centrifugal forces changing with speed and at some speed no solution for the HPT disks can be found anymore.

3.4 HPC Stage Number Variation

Finally the design variable (3), the number of HPC stages, is varied leaving everything else constant. Merely the HPC flow path annulus design, the HPC blading design, and the HPC disk design are significantly affected by the varying number of HPC stages.

The typical strong dependence of HPC efficiency and surge margin on the different stage loadings, as a result of the variation of the number of stages, is observed in figure 9. Higher loads lead to drastically falling efficiencies and surge margins whereas only for very high number of stages the increased wetted area finally outweighs the benefit of lower loadings and reduces the HPC efficiency.

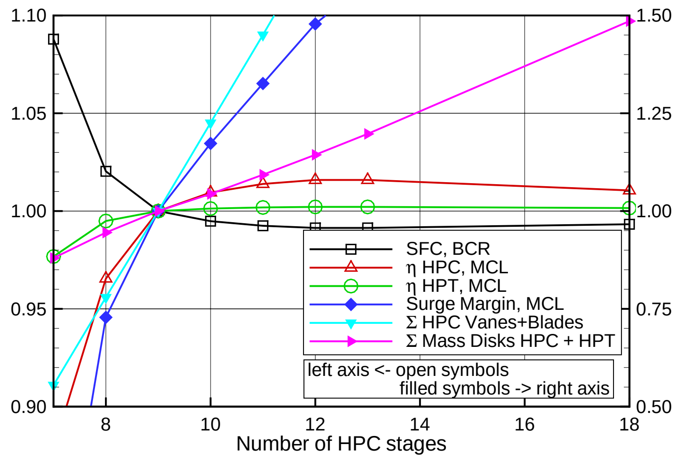


Figure 9. HPC Stage Number Variation. Dependent variables are divided by the optimal values of section 3.1

4 CONCLUSIONS

The overall engine performance is to first order dominated by the parameters set by the preliminary design. These main parameters must therefore be selected with highest care before any second or higher order effects can be exploited such as those catched with three-dimensional blade design, for instance. It has been shown that a solution to these main parameters can only be found with help of an integrated multidisciplinary tool such as MOPEDS due to the complexity of the problem. The complexity arises from the need to consider many design variables and constraints at several operating points of the flight mission. The strong coupling of the effects of all disciplines as well as the strong interrelation of all engine components furthermore puts up the need to consider all of the variables and constraints simultaneously. Any shortcoming in the preliminary design is generally very costly compensated for in the subsequent detailed design phase.

ACKNOWLEDGMENT

Representative for the many MTU colleagues joining the MOPEDS team over the last years, the authors want to especially acknowledge the contribution of Martin Ulmke, Arno Schlöder, and Markus Hartmuth who programmed the system structure and the GUI. Specially acknowledged are also the very fruitful discussions with Arthur Schäffler.

MOPEDS has been developed under the four year financial grant ’Bay08’ of the ’Bayerische Staatsministerium für Wirtschaft Forschung und Technologie’.

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