Multi-Objectif Optimization of a Turboprop Thermal Cycle

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Extended Abstract

When designing of a new turboprop for appropriate flight conditions and requirements, the objective is to determine the optimum cycle parameters in terms of turbine inlet temperature (TIT) and compressor pressure ratio (CPR), in addition to the power turbine temperature ratio (TTR) that depends in how to divide gas enthalpy between shaft power and jet. However the selection of the best thermodynamic cycle for a turboprop engine is a very hard task, owing to many involved parameters and constraints. Thus, optimization tools are inevitable to explore the whole design space and to reach feasible solutions as quickly as possible. Furthermore, the design optimization of a turboprop cycle must be considered in view of mechanical design considerations. While high TITs are thermodynamically desirable, they need using of expensive alloys and cooled turbine blades, leading to increased complexity and cost. On the other hand, higher pressure ratio must be considered in the issue of increased weight and complexity of the engine.

Many studies were undertaken by several authors to determine the turboprop's optimum cycle parameters; all of them were based on parametric analyses, using extensive parameters variation.

The present work focuses on the development of a numerical approach to select an appropriate turboprop engine matching with the power requirement of a given aircraft, and accordingly the optimum propulsion cycle parameters, involving two objectives (minimum fuel consumption and maximum power), in addition to several constraints. The optimization technique used herein is based on NSGA-II algorithm, which is a robust stochastic population based algorithm. The developed tool offers versatility in implementing a variety of operating conditions and objective functions, and considering technology constraints.

Performance optimization of a gas turbine engine is defined to be one, or a combination of: minimizing fuel consumption while maintaining power levels, maximizing power and maximizing engine life by reducing turbine blade temperature while maintaining power levels. Combining these objectives for optimization led not to a single solution as considering each objective separately, because these objectives are generally conflicting. For example, reducing fuel flow will lead to reductions in thrust levels. A tradeoff surface is then determined (Pareto front) without considering objective functions weighting, using NSGA-II algorithm, which uses Pareto dominance criteria. In the present study the objective function retained is a combination of performances cited above. So, we intend optimizing for the minimum fuel consumption and the maximum power at cruise, while maintaining a given takeoff power and a low entry temperature for low pressure turbine to account for engine life. Having takeoff power as an optimization constraint, that means our engine model must be able to operate at both design and off-design conditions.

Finally, a set of alternative optimal solutions were obtained, and in view of additional subjective criteria, three design alternatives for the considered engine configuration of a given technology level are proposed. The obtained results illustrate the sensitivity of the engine performance analyser to both cycle parameters and design constraints.

Keywords: Multi-Objective Optimization, Genetic Algorithm NSGA-II, Gas Turbine Performance, Turboprop.

I.TURBOPROP CYCLE MODELLING

Gas turbine engines can be modelled at various levels of details, however, due to their low computational burden, only simple aerothermodynamic models are considered in this contribution. The Single-Spool, Free Turbine turboprop configuration considered herein is shown in Fig.1, which illustrates the layout and stations numbering of turboprop.

1)Parameters Derivation

It is supposed that the total pressure and temperature are uniform at each preceding stations and that they completely characterize the state of gases at a given position. However, at upstream (0) and exit (9), the static conditions and velocities are considered.

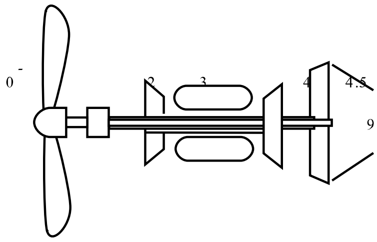

FIG. 1 Single- spool, free turbine turboprop

The thermodynamic properties, specific enthalpy h , specific heat constant pressure Cp and the ratio of specific heats γ for air and typical hydrocarbon fuel JP- 4 combustion products, which are modelled as perfect gases (but not calorically perfect), are function of working temperature and fuel- air ratio f. In cold regions of a gas turbine, calculations with perfect gas $\gamma = 1.4$ are satisfactory. However, in the hot regions, results deviate noticeably. Thus, extensive use is made of polynomial fits for the temperature dependencies of fluid properties.

Rotating machinery compression/expansion ratios π are related to temperature ratio by means of isentropic and polytropic efficiencies, which account for losses and real effects.

1)Engine Performance

In the design mode, the key design parameters of the engine such as compressor pressure ratio and turbine inlet temperature are specified. The conservation laws are naturally enforced; For instance, the power required by the compressor determines the enthalpy drop in the HP turbine. This set of equations leads to a direct non- iterative calculations of the engine cycle and performance parameters.

In off- design calculations, engine cycle and performance depend on the operating point referred to the flight conditions and the throttle ratio. The conservation laws are translated into a set of compatibility equations solved using an iterative process. The matching procedure is based on turbine- exhaust nozzle matching and turbine- compressor power matching.

II.OPTIMIZATION PROCEDURE

In such multi- objective optimization problems, objectives are usually incommensurate and in conflict with one another. This means that, in general, a multi- objective optimization problem does not have a single solution that could optimize all objectives simultaneously. Because of this, a multi- objective optimization is not to search for a single optimal solution but for efficient (non- inferior, non- dominated or Pareto- optimal) solutions that can best attain the prioritized objectives as greatly as possible.

Genetic Algorithms (GAs) rely on the analogy with the laws of natural selection and Darwin's principle of survival of the fittest. A population of chromosomes evolves in the course of successive generations toward the best individual. The evolution is guided by three genetic operators: selection, crossover and mutation. The individuals can survive, reproduce or die, according to their fitness (the value of the objective function to be optimized).

A.Non- dominated Sorting Genetic Algorithm- II (NSGA- II)

GAs select individuals according to the values of the fitness function. However, in a multi- objective optimization problem, several criteria are being considered. The evaluation of the individuals requires that a unique fitness value, referred to as a dummy fitness be defined in some appropriate way. To achieve this, by application of the definition of non- dominance, the chromosomes are first classified by fronts. The non- dominated individuals of the entire population define front 1; in the subset of remaining individuals, the non- dominated ones define front 2, and so on (fig.2).

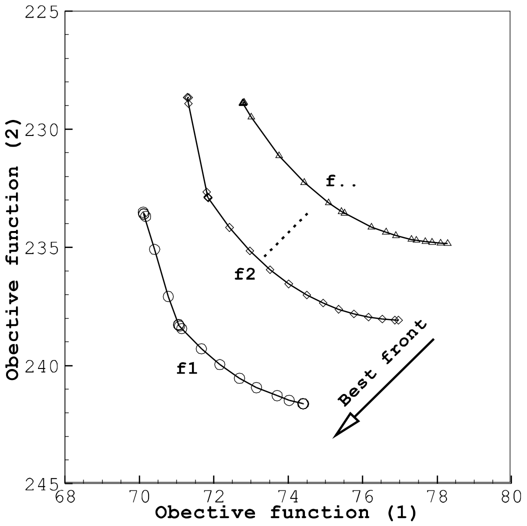

FIG. 2 Ranking of population by fronts

For the present work, the engine performance simulation tool has been coupled with an optimization subroutine based on a semi-stochastic population based algorithm (*NSGA-II*). This algorithm uses an elitist approach that permits keeping the best solutions found during previous generations. Furthermore, it uses a ranking technique based on the non-dominance, and it does not need any parameter adjustment or objective function weighting.

In order to guide the optimization process towards settings that ensure the “must-meet” performance requirements or real-world properties constraints, such as the maximum permitted temperatures, the constraints’ violations are penalized using appropriate *penalty function*, which can provide distinction between feasible and infeasible solutions.

III.APPLICATION TO TURBOPROP ENGINE

We intend to determine a set of optimum cycle parameters for a turboprop variant matching with propeller driven aircrafts. The design point is selected in cruise flight. The propulsion cycle design parameters include compressor pressure ratios *(CPR)*, turbine inlet temperature *(TIT)* and power turbine temperature ratio *(TTR)*. Moreover, many design constraints should be observed. Engine designs with less power than required at the take-off and cruise will not be acceptable. The compressor will eventually cause a constraint due to the exit temperature limit. Another constraint is that of the low pressure turbine entry temperature $T_{t4.5}$ limit.

In our case study, the multi-objective optimization problem can be stated for the given flight conditions as follow:

Find the following design parameters: $X = \left[CPR, TIT, TTR\right]^t$

That minimizes: $F = \left[PSFC, W_{sp}^{-1}\right]$

where, *PSFC* is the Power Specific Fuel Consumption and W_{sp} is the Specific Power.

Subject to the design limits and constraints given in Table1 and Table 2 respectively.

TABLE 1

DESIGN VARIABLES SPACE

Lower limit	Design variable	Upper limit
7	OPR	25
0.5	TTR	0.8
1100	TIT (K)	1205

TABLE 2
DESIGN CONSTRAINTS

Design constraint	limit
T_{t3} (K)	≤750
$T_{t4.5}$ (K)	≤1050
Takeoff power (hp)	≥4700
Cruise power (hp)	≥2000

IV. RESULTS AND DISCUSSIONS

Figure 3 shows the obtained feasible domain and the tradeoffs surface (Pareto front). All points on this front are non dominated solutions and constitute engine alternative designs.

From Fig. 4 it is clear that TIT is at a maximum tolerated value (imposed mainly by the throttle ratio). This trend confirms that higher TITs are always favorable for both specific fuel consumption and specific power.

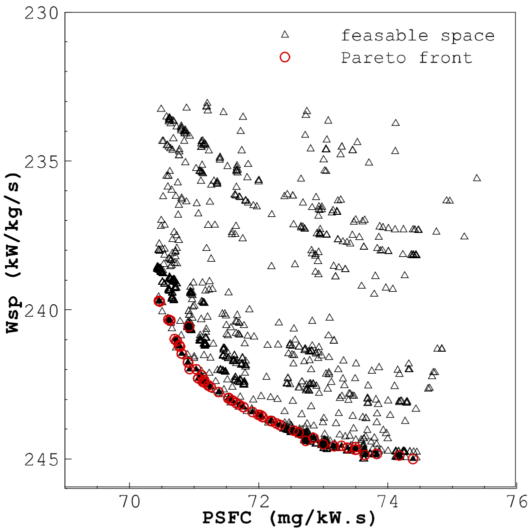

FIG. 3 Feasible domain and Pareto front

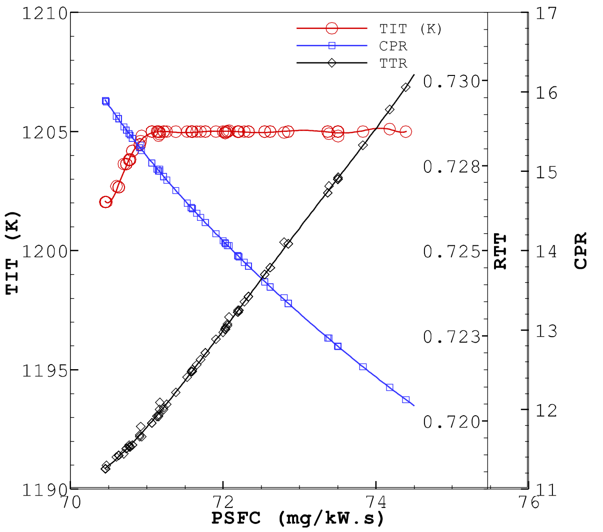

FIG. 4 Optimum cycle variables

Furthermore, as illustrates by the Fig. 5, the optimization is guided by the minimum required takeoff power and maximum LP turbine entry temperature constraints. One can see that the compressor exit temperature limit T_{t3} is not a strong constraint to the optimization process in these conditions.

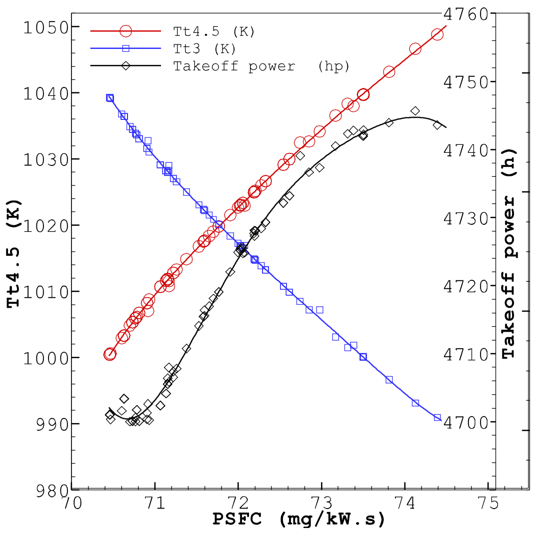

FIG. 5 Constraints variation

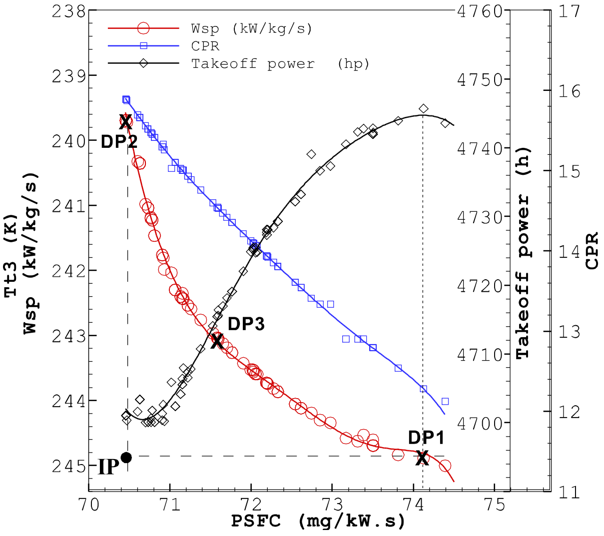

FIG.6 Design points

Figure 6 shows the Pareto front, where all points on the front constitute an optimum design for the candidate engine, the final selected design points will depend on some design choices. If one takes into account the operational criterion of maximum power at take-off, thus point (DP1) on Fig. 6 will constitute a good choice. On the other side, if one is interested in improving the specific fuel consumption the point (DP2) is another choice. Furthermore, if we are interested by a compromise between performance and engine life of the engine, point (DP3) constitutes a good tradeoff that permits getting a benefit in both fuel consumption and specific power and better life for the components .

V.CONCLUSION

In order to perform design optimization of a turboprop thermal cycle, the engine performance simulation tool has been coupled to an efficient optimization routine based on NSGA-II algorithm. The obtained results illustrate the sensitivity of engine performance to both cycle parameters and design constraints. Optimization carried out for the free turbine turboprop configuration of a given technology level three design choices, and in the same time highlighted how the compressor- exit temperature and LP turbine entry temperature guide this optimization process.