Chapter 1 – INTRODUCTION

1.1 DOCUMENT ORGANIZATION

Much of this document focuses on the gas turbine engine simulation known as a cycle code. It is also referred to in this document as a "Zero-Dimensional" or "0-D" simulation. Other codes ranging from one-dimensional to three-dimensional numerical simulations which were originally discussed in the main chapters of RTO-TR-044 [1.1] are now discussed in the Annexes of this document. In fact, the material that is in RTO-TR-044 is been largely maintained within this document but has been expanded and reorganized to produce a more focused document on cycle analysis simulations.

The main document is arranged such that examples of the use of gas turbine engine simulations are presented first in ***Chapter 2***. This organizational structure allows the reader to decide which example most closely resembles his particular application. Once the reader has decided how he might use a simulation, he can dig further into the document to understand the ramifications of using the cycle code and what it might mean to his analysis process. Listed below is a brief explanation of each of the chapters and annexes so that the reader can select how he wishes to proceed.

Chapter 2 **(Applications)** focuses on application of gas turbine engine cycle codes as they are applied to:

- Fixed Wing Aircraft;
- Rotary Wing Aircraft (Helicopters);
- Marine (Ship) Propulsion;
- Vehicular Propulsion;
- Power Generation; and
- Performance Based Optimized Manufacturing.

Chapter 3 **(System Models)** introduces all the different types of cycles (Ideal Joule, Real Joule with and without reheat, regeneration) that can be utilized for gas turbine engines in the various applications (turbojet, turbofan, turboprop, and turboshaft). In addition, ***Chapter 3*** introduces the concept of the cycle code and how it is formulated.

Chapter 4 **(Component Models)** deals with how the various components (compressor, burner, turbine, inlet, nozzle, re-heaters, regenerators, clutches, secondary airflow, splitters and mixers, etc.) are modeled that are simulated within the cycle code. Each component modeling technique is detailed and provides a measure of how each is connected to each other.

Chapter 5 **(Examples of 0-D Numerical Simulations)** introduces several current cycle code systems and provides a Web link to those that can be downloaded for use by any interested individual.

There are five Annexes that go into detail on the following subjects:

Annex A **(Higher Order Models)** describes the 1-D dynamic modeling concepts along with applications for compression system and engine operability issues. In addition, 2-D, 3-D and CFD codes are discussed and several examples of applications are provided.

Annex B **(Advanced Topics and Recent Progress)** is for the advanced reader. This annex provides great detail into the recent research in computational modeling for all components especially for compressor performance and operability. Here one finds detailed information on subjects such as the effects of tip

clearance on stage performance, stationary and rotating distortion, surface roughness effects, thermal effects, and many other research areas of concern. Modeling of other components (turbine, combustor, inlets, nozzles, and secondary air systems) are treated in great detail as well.

Annex C **(Computer Platforms)** provides the reader with a look at the multitude of potential computer platforms that can be utilized in computing engine cycle analysis. This annex compares the different types of computers and operating systems as well as indicating the advantages of each. The reader is exposed to parallel computing concepts, zooming of higher fidelity models into the cycle code, distributed networking concepts, and user interfaces or GUIs.

Annex D **(Gas Turbine Simulations for Educational Purposes)** gives the reader an example of using an engine cycle code for to educate engineers. The example is taken from an engine manufacturer in-house training process and walks the reader through the process of how to teach gas turbine engine performance using a cycle code.

Annex E **(Glossary)** provides an in-depth explanation of the terms used in this document.

1.2 APPLICATIONS OF MATHEMATICAL ENGINE MODELS

Engine models are defined here as mathematical descriptions of the physical behavior of a turbine engine. These can either be *paper* engines in their design phases or *real* engines in operation. Engine components, such as the compressor, can also be separately modeled. During the design integration process, the component characteristics have then to be matched, for instance with respect to mass flow and shaft speed.

Figure 1.1 shows a conceptual relationship between the users of (mathematical) engine models and the creators of these models at various levels. The present document is addressed in particular to the model users in the upper level, and to those dealing with *preliminary engine and application design studies*. Those in the upper level tend to deal with *engine operation and maintenance*, while others deal with matters including health monitoring and test bench analyses, where model complexity can still be avoided while providing usable answers. Examples are performance sensitivity studies, mission analysis and the development of engine control systems.

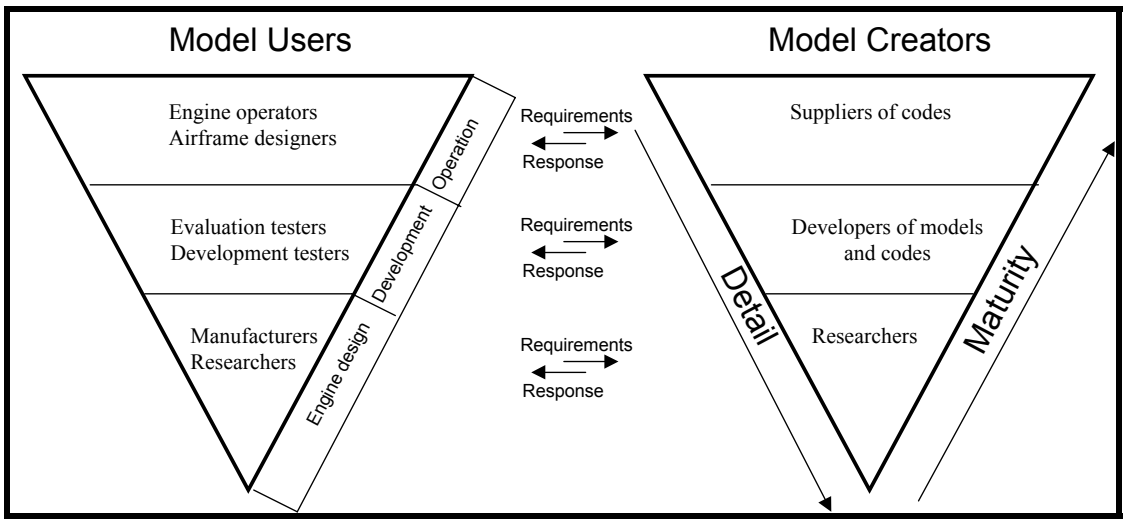

Figure 1.1: Engine Model Users and Creators.

For the operator, to support specific applications, such as engine diagnostics, the engine manufacturers usually supply engine-specific codes. For preliminary engine and application design studies generic tools are available, which are also in the public domain.

For engine maintenance, health monitoring, and diagnostics models the nominal condition of the specific engine is described by a mathematical model involving the indications of the various sensors (pressures, temperatures, shaft speeds) in the engine. Deviations from the nominal values indicate the state of health of the engine that can be used for diagnostics and repair on condition.

A dedicated computer model is then a very cost-effective tool to carry out an appropriate diagnosis to identify degraded or defective engine components. This application is current practice at major airline companies. Some have developed their own maintenance-on-condition system with add-ons to the basic health monitoring system offered by the engine manufacturer. The cost-effectiveness of the maintenance of military engine systems also increasingly benefits from these developments.

The application designers may use generic engine models for mission analysis as part of an application performance model in the preliminary design phase. In that case, engine sizing and sensitivity analyses are the key words. The engine designer may also do this exercise to identify requirements for possible new engines.

Other uses of engine models by the application designer are:

- To check and confirm projected engine performance data provided by the engine manufacturer while the engine is still in the design and test phase;
- To assess installation effects; and
- To assess engine performance.

Test bed engineers may also profit from a computer model that simulates their engine, and that can be run as a virtual engine in parallel to the actual engine. Such a *virtual* engine can also be used as a part of the software for (real time) aircraft flight simulators. For that application, modeling of the transient behavior (e.g. the response to a slam-acceleration) is essential. This applies, in particular, to flight simulators for the latest generation of fighter aircraft with high agility, in combination with close coupling of engine thrust and aerodynamics.

These real-time engine models are also useful for engine control design and development testing, including a hardware control system (e.g. a fuel control system) coupled to a *software* engine.

Another group of users is the evaluation and development testers. The evaluation testers generally represent the interests of future engine users, including the application designers and manufacturers. The development testers are part of the engine manufacturer's organization. They use the engine models to identify unsatisfactory component performance (like the health monitoring application mentioned earlier) and to 'tune' the whole-engine performance model made available as a performance *card deck* to the potential customers.

The engine manufacturers may use the relatively simple models in the early phase of the design only. In the detailed design phase highly sophisticated models are used, combined with in-house experience. These models are mostly based on computational fluid dynamics (CFD) describing detailed flow and combustion phenomena. In the present document these models will be referred to mostly in a qualitative way.

Researchers also make use of engine and engine component models. In many cases experimental work and theoretical modeling go hand in hand in that area. The research community may use this document to put their work into a wider scope. This also holds for trainees and students.

Figure 1.2 shows the cycle simulations used throughout the engine life cycle. The model users identified in **Figure 1.1** are now associated with the life cycle elements of the engine and the related activities. In the lower left hand corner rather simple cycle models, of the type suitable for preliminary engine and application studies are used. In the upper part of **Figure 1.2** the most sophisticated design tools are employed, constituting the latest state of the art of the engine designers. In the top right of the figure, the activities of the development and certification testers find their place. Mission and life analysis and health monitoring are found in the lower right hand corner as activities of the engine operators.

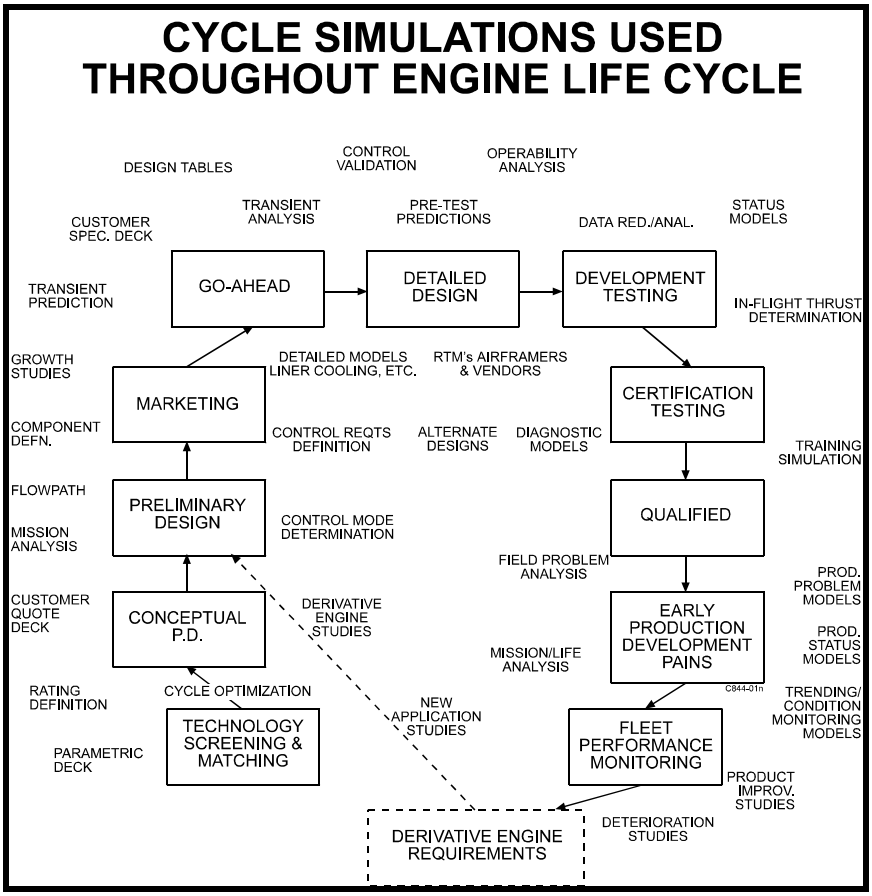

Figure 1.2: Engine Models used Throughout Engine Life Cycle.

1.3 INTRODUCTION TO TYPES OF ENGINE MODELS

A simple way of engine modeling is found in the performance data as provided by the engine manufacturer. These performance data are generally provided in the form of PC-based ***cycle codes*** from which performance charts or tables can be extracted. The charts are mostly three-parameter charts, using corrected parameters. These corrections are for engine inlet pressures and temperatures that are different from standard sea level conditions. An example is a chart where the corrected net thrust is given as a function of the flight Mach number for a series of engine pressure ratio values. Limits like the maximum turbine entry temperature or maximum shaft speed are included and form the operational limits of the engine. Simple thermodynamic relations can predict the performance of a generic gas turbine engine. Such a model may be *tuned* to a specific engine by using values for the component efficiencies that depend on the operational condition of the engine. On a test stand, engine component defects may show up when comparing measured pressures and temperatures with those of the *standard* engine model. An example is

a higher compressor exit temperature than expected for the measured pressure ratio, indicating degraded compressor efficiency.

In the above models, only thermodynamic parameters are considered, i.e. pressures and temperatures, as related to engine performance and performance analysis. The engine shaft speed is another important engine parameter. Modeling of the thermodynamics depends on the shaft speeds and vice versa, and requires knowledge of the actual design of the turbomachinery. In this case generalized semi-empirical engine component models (maps) may be used that relate the number of stages, the tip speed and the axial flow velocity (or specific flow) to the aerodynamic performance, say compressor pressure-ratio and turbine work. Since the maximum shaft speed is an important engine limit, inclusion of the engine shaft speed in an engine model is important for identification of its performance envelope.

One further step is to include the mechanical and thermal mass of the engine. In this case, the transient behavior can be studied; for instance, the responses of the engine to a sudden increase in fuel flow. The increase in back pressure in the combustion chamber while the compressor is still accelerating may then lead to compressor stall. To maintain safe operation and, at the same time, maximum responsiveness of the engine the behavior of the compressor should be known in order to avoid compressor stall while increasing the fuel flow.

These and other areas of interest to the engine designer lead then to component modeling. The present document will give attention to component modeling in the context of applications to whole engine performance modeling, and as a separate subject in a later chapter.

1.4 COMPUTERS, SOFTWARE, AND RECENT DEVELOPMENTS

All present-day gas turbine engine performance models are executed on computers, and the capabilities of modern computers have extended the applications and the range of use of the models. For users wishing to adapt models to their application, and to delve deeper into the present and future possibilities, a discussion of computers and software is provided. Because of the electronic format of the document, it has been possible to provide executable examples of some performance models. For those users wishing to model that which has not yet been modeled, and to examine the frontiers of the component and engine modeling technology, recent progress in the modeling of both whole engines and of the major sub-systems are described in ***Annexes A*** and ***B***.

1.5 REFERENCES

[1.1] RTO-TR-044, 2002, Performance Prediction and Simulation of Gas Turbine Engine Operation, RTO Technical Report 44, April 2002, AC/323(AVT-018)TP/29, ISBN 92-837-1083-5.