Design Competition:
High Efficiency Gas Turbine Engine

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Introduction

The engine is a high efficiency design, consisting of an axial compressor, two combustion chambers separated by a reheat turbine, and a multi-stage turbine. Intake gasses are directed into the compressor by way of a precisely engineered nozzle. The gasses then enter the first of three compressors, a low pressure compressor followed by intermediate and high pressure units. Combined, the axial compressors achieve a pressure ratio of 37. The compressed gas then enters the first of two combustion chambers. The combustion chamber increases the air's thermal energy through adding fuel to the main air stream and igniting the mixture. The high energy gas flow is then expanded in the high pressure, single stage reheat turbine. More heat energy is then added to the gas flow in the second combustion chamber before being expanded back to atmospheric pressure in the multi-stage turbine. Finally, an application specific diffuser reduces exit losses.

Project Tasks & Design Procedure

The first design task was to perform a thermodynamic analysis on the entire machine. This thermodynamic analysis was used to determine the state points at the component inlets and exits. It was then possible to perform a stage by stage analysis to determine the dimensionless stage parameters and flow angles using the four nonlinear equations of state.
The next design task was to use a solid modeling software package to generate a virtual representation of the gas turbine. Each component, from the blades to the shaft and combustion chambers, had to be modeled and assembled to illustrate one part's compatibility with respect to another. The solid modeling also facilitated some preliminary mechanical analysis of the shaft, rotor, and bearings.
The final design task was to perform Computational Fluid Dynamic (CFD) analysis on the engine and selected components. The CFD analysis illustrated the flow performance attributes and drawbacks associated individual component geometries.

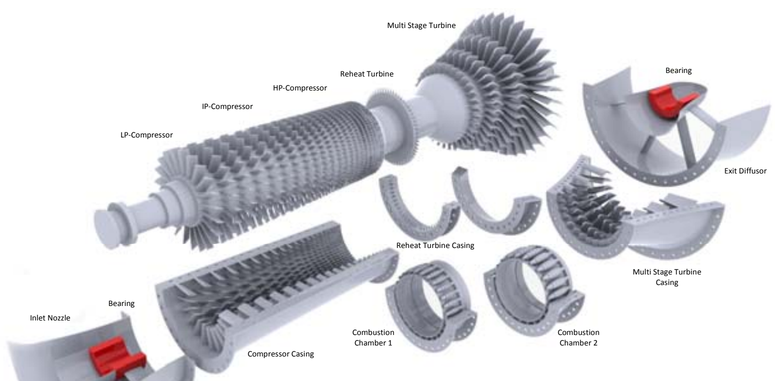

Fig. 1 Explosion view of the engine

Computational Fluid Dynamics & Rotor Dynamics

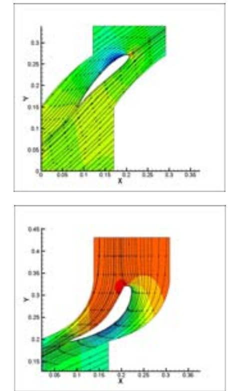
Fig. 3 Pressure distribution with stream line tracers around compressor and turbine blade

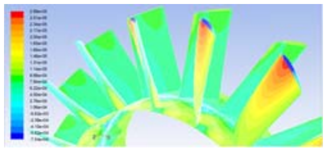
Fig. 4 Pressure distribution on the surface of compressor blades

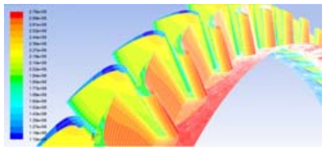
Fig. 5 Pressure distribution on the surface of turbine blades

The CFD analysis verifies the compressor and turbine blade design by solving the equations of fluid dynamics (Navier Stokes equations, energy equation, continuity equation, etc.). Usually the CFD method does not give an exact solution for the problem, but the result is an indicator of the design quality. In this case, the pressure distribution of the compressor blade shows a strong decrease of pressure on the suction side, which might result in separation.

The pressure distribution on the turbine blade shows a pressure distribution, which is similar to a rectangle, which would be the optimum.

As sketched on the right, you can see the rotor dynamic analysis of the Engine with critical speeds that have to be passed fast. The operational speed is 4,482 rpm, which provides a substantial safety factor.

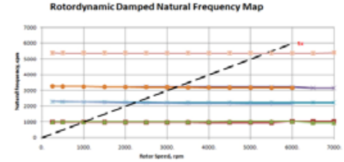

Fig. 6 Rotor dynamics map with critical speed-frequency interaction

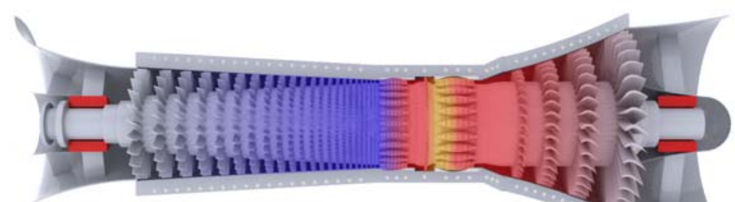
Fig. 2 Top view on the engine

Axial Compressor

The axial compressor of the Engine has 22 stages with blade heights ranging from 380 mm at the inlet to 38 mm at the exit. Each blade has an axial twist to accommodate the changing flow velocity with respect to the radial equilibrium direction.

Several important graphs for the compressor are shown below. These are the compressor map, the blade pressure distribution, the velocity diagram and the compressor blade nomenclature.

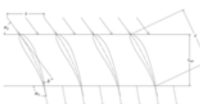
Fig. 13 Compressor blade nomenclature

The compressor has to be run between the dangerous surge and choke limit.

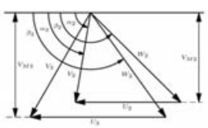
Fig. 14 Compressor velocity diagram

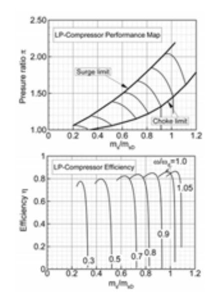

Fig. 15 Compressor map, Ref. [1]

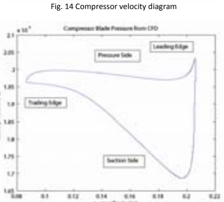

Fig. 16 Pressure distribution around a compressor blade

References:
[1] Meinhard T. Schobeiri, Turbomachinery Flow Physics and Dynamic Performance, Springer-Verlag, Germany, 2005.

Thermodynamics

Thermodynamic analysis is an essential starting point for the design of a high efficiency gas turbine. Analysis begins with the given values that will be specified by the client at certain critical stages.
From these given values, enthalpy, entropy, and temperature values can be calculated for the inlet and exit of each major component. Two independent thermodynamic state points are necessary to define any other thermodynamic property.
The data obtained through this type of analysis will yield engine performance values such as overall thermal efficiency and total net power.
The rise of efficiency comes from the larger area under the process line through the reheat turbine and the second combustion chamber.

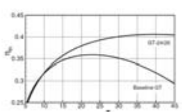
Fig. 7 Engine efficiency diagram, Ref. [1]

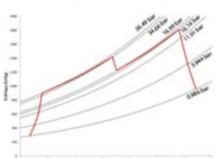
Fig. 8 Thermodynamic cycle of the engine

Axial Turbine

The reheat and multi-stage turbines convert the air flow's kinetic and potential energy into rotational energy of the rotor. A portion of this rotational energy is used to drive the compressor, while the remainder is used to generate electrical power with an attached generator.

The shown sketches exhibit a turbine stage velocity diagram and the turbine blade nomenclature.
The pressure distribution around the blade tells a lot about the quality of the geometry that the turbine blades have. As more it looks like a rectangle as better the blade will function for efficient energy conversion.

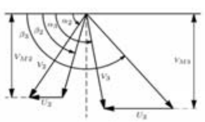
Fig. 9 Turbine velocity diagram

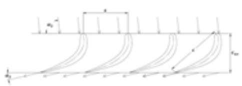
Fig. 10 Turbine blade nomenclature

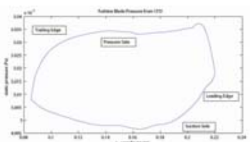
Fig. 11 Pressure distribution around the turbine blade

Combustion Chamber

Each combustion chamber has twenty four flame holders, a combustion liner, and an outer casing. The gas flow leaving the compressor is divided into primary flows, entering the flame holder inlet, and secondary flows, moving between the flame holder and the liner. The secondary flow serves as a thermal barrier between the high temperature flame holder and the cooler liner and casing. The secondary flow then merges with the primary flow via mixing ports in the flame holder.
At the inlet of the flame holder is a swirl generator that imparts strong turbulence and vorticity to the incoming gas stream. A fuel injector, positioned directly behind the swirl generator, imparts swirl to the injected fuel stream that is opposite to the swirl of the air stream to promote uniform mixing prior to combustion.


Fig. 12 Combustion chamber