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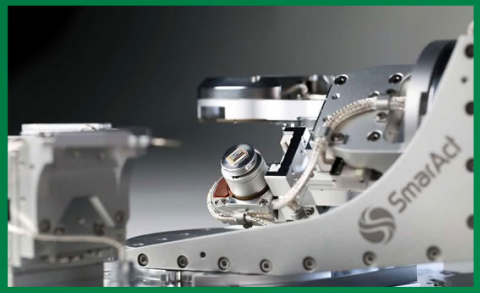
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Development and testing of a small scale stationary gas turbine engine core

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Abstract. With the advances in modern design, development and simulation tools, the design and development process of gas turbines has been significantly shortened. In addition, the experimental testing and validation phase can now be accomplished with fewer experimental prototypes. In this paper, the design, development and testing of a small-scale, stationary industrial gas turbine engine core will be described. Following the conceptual and preliminary design phases, the theoretical, numerical, and experimental methods to be employed during the detailed design, testing, measurement, and validation stages will be discussed.

1. Introduction

Gas turbines can be classified as stationary land-based industrial gas turbines, or as aero engines used in aircraft [1]. In terms of design and development, the key component of a gas turbine is the engine core. The term “engine core” refers to the assembly comprising compressor, combustion chamber, and turbine, where the power extracted from the engine shaft is used to drive the components such as generator, propeller, or fan. The stationary industrial gas turbines discussed in this paper are employed in a wide range of fields, particularly in energy and petrochemicals sectors, and require lower development and production costs compared to aero engines [2]. As with all engineering development projects, the development processes of gas turbine engines have been greatly accelerated through the use of design, analysis and simulation tools in conjunction with high-performance computing (HPC) systems. In particular, the application of HPC methods for computational fluid dynamics (CFD), finite element analysis (FEA), and structural dynamics has radically shortened the test and validation phases. HPC methods are especially critical during the transient analysis of gas turbine engines.

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2. Methodology

Modern engine development projects are carried out using modern computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE) methods with high-performance computing (HPC) tools. Conventionally, calculations begin with one-dimensional performance analysis methods and the methods that have been experimentally validated by the manufacturer in previous projects. Subsequently, as the design phase progresses, 2D and 3D high-fidelity computational methods are used. In the present small-scale gas turbine core engine project, the engine design parameters are determined using commercial software tools such as GASTURB™ [3] or proprietary in-house tools [4, 5]. Institutional memory plays a crucial role during the conceptual and preliminary design phases since the experiences gained in the previous projects are transferred into new developments.

In gas turbine development projects, a broad range of expertise, data repositories, design, analysis, and experimental capabilities along with the necessary hardware and software infrastructure is required. For instance, an engine development project requires the following competencies and capabilities: Performance, aerodynamic design, mechanical design, thermal design and analyses, material and strength analyses, fatigue analyses, control system design, rotor dynamics, lubrication, cooling and bearing analyses, testing, measurement and evaluation systems, component manufacturing, subsystem and system assembly and testing, and full engine testing.

3. Applications and evaluation

In the current project, the project phases consisting of the design, analysis, simulation, testing and measurement phases of the small-scale core engine named TMT-GT150, that has been developed by Turbomotor Technologies Inc. [6], will be described sequentially with examples.

3.1. Design

During the design phase, starting from the system architecture of the core engine, the conceptual design, preliminary design, and critical (detailed) design stages are realized through modern CAD/CAM/CAE and HPC tools. At the system architecture and conceptual design stage, decisions are made regarding the direction of airflow (reverse or straight), the type of rotating components such as compressor, turbine, or fan (radial or axial), the type of combustion chamber (annular or tubular), the number of stages for compressor and turbine, the number of shafts, material selection, fuel type, lubrication, bearing, and cooling systems. In the conceptual design stage, one-dimensional flow and various parametric analyses are performed. During the preliminary and detailed design stages, starting from one-dimensional, 2D and 3D analyses and simulations, development tests of increasing complexity are conducted.

System Architecture, Conceptual Design, and Preliminary Design: The system architecture and conceptual design of TMT-GT150 adopt a reverse-flow configuration (Figure 1, left), single stage radial compressor (Figure 1, middle) and single stage radial turbine (Figure 1, right).

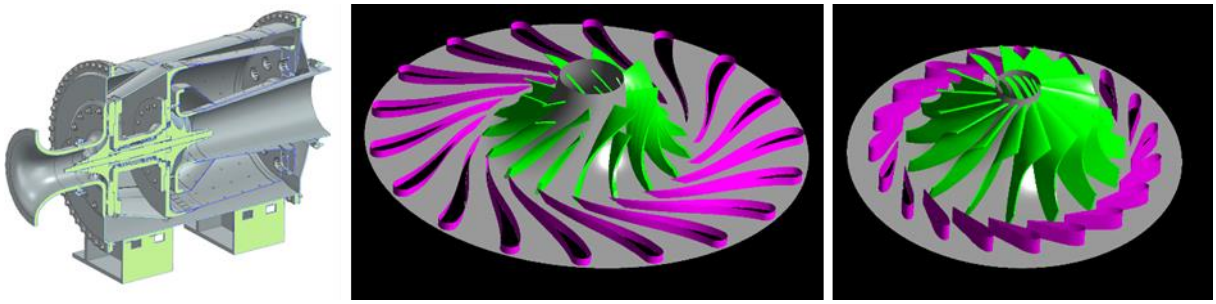


Figure 1. Conceptual design (left), and solid models of radial compressor (middle), and radial turbine (right) of TMT-GT150.

Mechanical Design: The mechanical design and digital mock-up, initiated from the early stages of the project, are made possible through the use of modern CAD/CAM/CAE and HPC tools. During this phase, the product tree (product structure) and configuration management should be initiated. As the design process progresses, lubrication, bearing, and cooling systems, as well as test/measurement instruments and test rig design must also be started.

3.2. Analysis and simulation

Performance: An example of one-dimensional thermodynamics cycle analysis performed using a commercial or in-house software is given in Figure 2. Under the current operating conditions, the inlet air mass flow rate is approximately 0.8 kg/s, the compressor pressure ratio is 4.1, and the engine shaft power reaches at 125 kW.

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288.15	101.325	
1	0.815	288.15	101.325	
2	0.815	288.15	101.325	0.815
3	0.815	481.10	419.486	0.254
31	0.815	481.10	419.486	
4	0.831	1186.00	405.517	0.421
41	0.831	1186.00	405.517	0.421
49	0.831	889.52	111.458	
5	0.831	889.52	111.458	1.327
6	0.831	889.52	111.458	
8	0.831	889.52	111.458	1.327
Bleed	0.000	323.11	137.028	

Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0.7410	0.7859	1.000	4.140
Burner	0.9800			0.967
Turbine	0.9280	0.9164	0.762	3.638
Generator	0.9500			

Spool mech Eff 1.0000 Nom Spd 80005 rpm

hum [%]	war0	FHV	Fuel
0.0	0.00000	43.323	Generic

PWSD	=	131.9	kW
PSFC	=	0.4299	kg/(kW*h)
Heat Rate	=	18625.1	kJ/(kW*h)
Therm Eff	=	0.1933	
WF	=	0.01575	kg/s
s NOx	=	0.08720	
incidence	=	0.00	°
XM8	=	0.3801	
A8	=	0.0093	m²
P8/Ps8	=	1.10000	
WBld/W2	=	0.00000	
P2/P1	=	1.00000	
WCLN/W2	=	0.00000	
WCLR/W2	=	0.00000	
Loading	=	100.00	%
e45 th	=	0.92800	
PW_gen	=	125.3	kW
P6/P5	=	1.0000	

Figure 2. Engine performance calculation of TMT-GT150.

Aerodynamics: Following the one-dimensional analysis, the traditional 2D analyses historically used in engine development stages are skipped, and 3D CFD analyses are directly started. With the use of CFD, the compressor and turbine blade geometries should be designed (or re-designed if required) to meet the target design performance specifications while minimizing the losses caused by shock waves and boundary layer separations. The CFD simulations are performed using Reynolds-Averaged Navier-Stokes equations with a choice of, say, k-ω transitional SST turbulence model, using a choice of a structured or unstructured mesh as shown in Figure 3. For both compressor and turbine simulations, total pressure and total

temperature at the inlet, and static pressure at the outlet are used as the boundary conditions. In Figure 4, the Mach number distributions of two different conceptual designs of compressor rotor and stator stages are given.

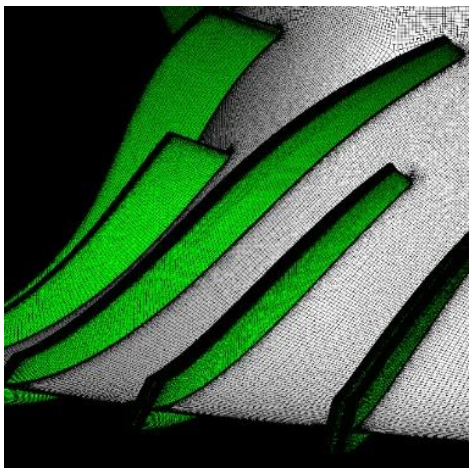


Figure 3. Close-up structured mesh view.

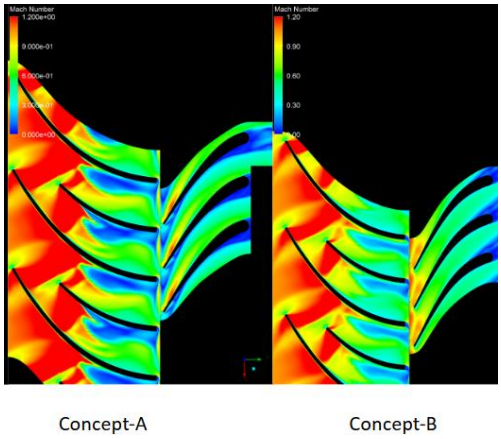


Figure 4. Mach number distributions for conceptual radial compressor designs at 90% span.

CFD Model and Solution - Compressor: In this instance, a total of 6.5 million mesh elements are used for the inlet, rotor, stator and outlet volumes. First cell height is set to be y+<5 to satisfy the SST transition turbulence model mesh requirement. The maximum mesh volume growth rate is 7.8, the maximum aspect ratio is 538, and the minimum face angle is 27 degrees. Coupled pseudo transient method is employed in the simulations. Convergence criteria for the residuals of mass, momentum, and turbulence level are set to be below 10^{-4}, which is achieved with a total of 350 iterations. The primary convergence criterion for the simulation is based on the variation of the efficiency, which varied between 78% and 78.3% over the last 150 iterations. The velocity vectors and the results are given in Figure 5 and Table 1, respectively.

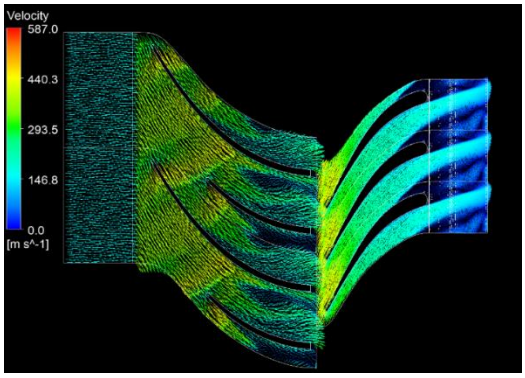


Figure 5. Radial compressor velocity vectors at 90% span.

Table 1. Radial compressor CFD results.

Parameter	CFD Result
Mass flow rate (kg/s)	0.85
Rotor compression ratio	4.546
Stage compression ratio	4.1
Rotor efficiency	86.3
Stage efficiency	78.2
Power (kW)	152

CFD Model and Solution - Turbine: A total of 6 million mesh elements are used for inlet, rotor, stator and outlet volumes. First cell height is set to be y+<5 to satisfy the SST transition turbulence model. The maximum mesh volume growth rate is 5, the maximum aspect ratio is 227, and the minimum face angle is 46 degrees. Coupled pseudo transient method is employed in the simulations. Convergence criteria for the residuals of momentum, mass and turbulence are set to be below 10^{-5}, which is achieved with a total of 150 iterations. The primary convergence criterion for the simulation is based on the variation of the efficiency, which varied between 91.85% and 92.05% over the last 50 iterations. The results are given in Table 2.

Table 2. Radial turbine CFD results.

Parameter	CFD Result
Mass flow rate (kg/s)	0.9
Stage compression ratio	3.67
Rotor efficiency	92.26
Stage efficiency	91.9
Power (kW)	348

CFD Model and Solution-Combustion Chamber: Optimization studies via CFD were performed to optimize the combustor geometry, flow conditions at the inlet and outlet, the placement and number of cooling holes, and the combustion efficiency to achieve efficient combustion. In the simulations, RANS equations were solved using various turbulence models. Figure 6 illustrates a polyhedral mesh, temperature distribution and velocity vectors in the combustion chamber.

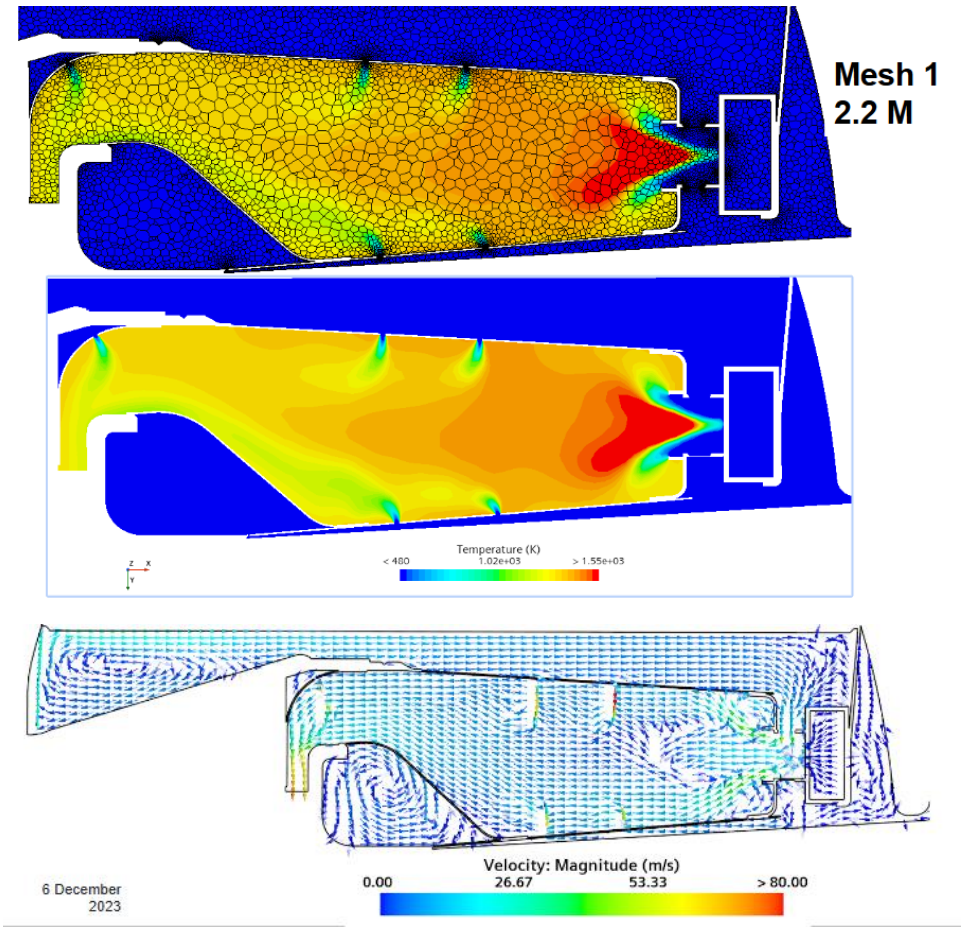


Figure 6. Combustion chamber polyhedral mesh, temperature distribution, and velocity vectors.

The hot gases generated by the combustion process increase the temperature of not only combustion chamber walls but also the entire engine. In terms of thermal analysis, the most critical temperature is the turbine inlet temperature which dictates the high temperature resistant material selection for turbine blades. This in turn has a significant impact on engine performance. In addition, high temperatures throughout the engine cause large thermal stresses and deformations. Figure 7 depicts the polyhedral mesh consisting of 1.54 million cells, which was used in the RANS simulation with k-ω transitional SST turbulence model. Figure 8 shows the temperature and velocity vectors distribution in the compressor, combustor, and turbine cross-section.

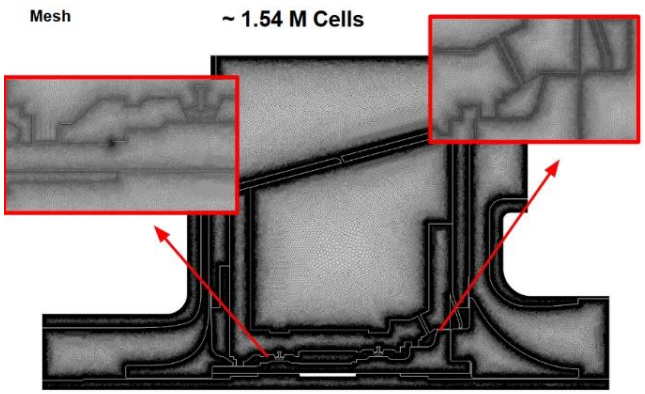


Figure 7. Unstructured mesh for compressor, combustion chamber, and turbine.

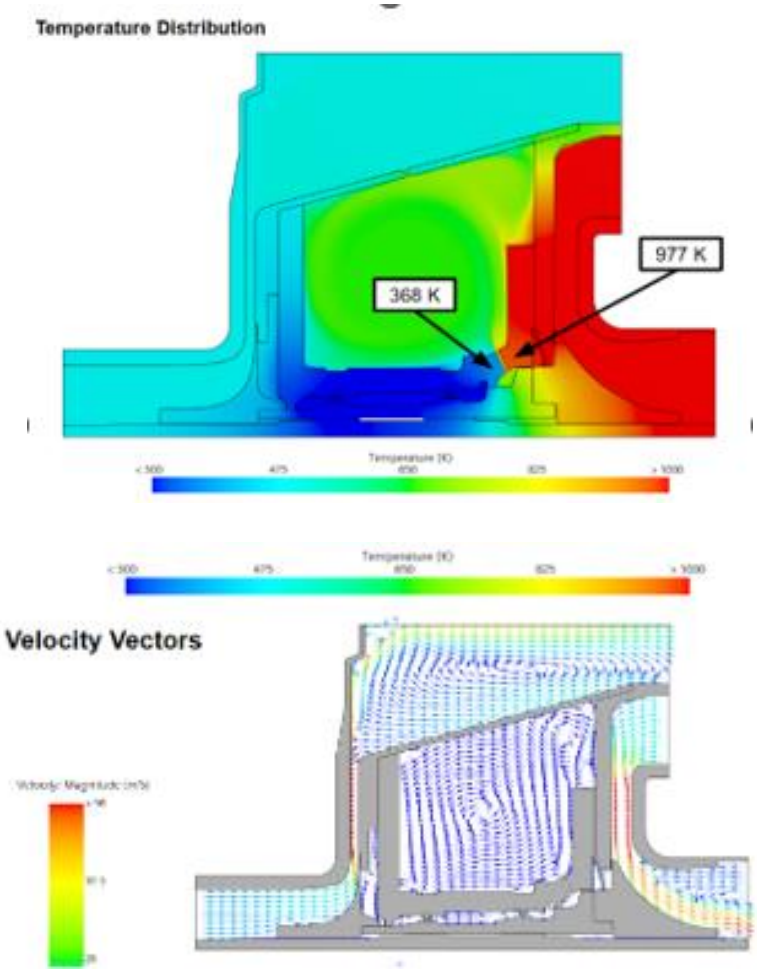


Figure 8. Combustion chamber temperature distribution (top) and velocity vectors (bottom).

FEA Analysis-Rotor Dynamics: As the rotor speed increases, resonances may occur when the rotor excitation frequencies and the natural frequency of the system coincide, potentially leading to structural damage. In rotor dynamics analysis, the natural frequencies of the core engine structure for the first, second, third, and higher bending and torsional modes are calculated using finite element analysis (FEA) methods. Figure 9, for instance, shows the first bending and torsional modes of the engine. A Campbell diagram as seen in Figure 10 can be generated by using

set of bending and torsional modes over the entire range of operating speeds and excitation frequencies [7]. Using this diagram, the critical rotational speeds and damping ratios near the engine's nominal operating speed that may cause resonances can be identified. If resonances are present at critical rotational speeds, design modifications, such as increasing the material and stiffness of the shaft and disk, or altering the blade geometry, or introducing geometric tapering to the overall structure can be implemented.

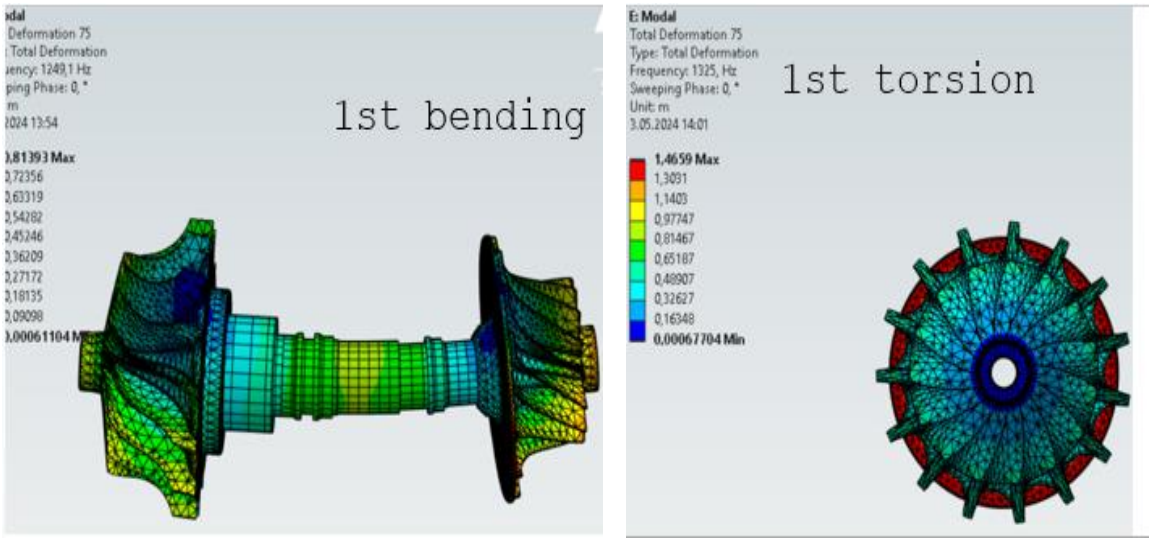


Figure 9. First bending and torsional modes.

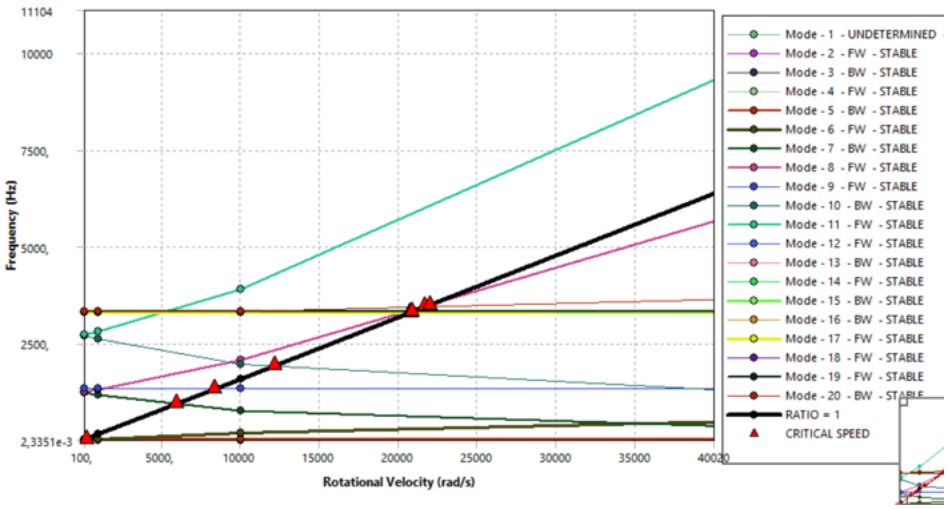


Figure 10. Campbell diagram.

Engine starter simulations: A gas turbine engine requires an initiation to rotate its core components during startup. Engine starters are used to initiate this external torque to accelerate the compressor to a speed that ensures sufficient airflow and pressure conditions required for fuel ignition and combustion [4, 8].

As emphasized previously, the engine tests and validations are crucial, especially during the critical design phase. Before advancing to the critical design, it is essential that the preliminary engine tests and simulations adopt the same operating and boundary conditions to ensure

accurate deductions [9, 10]. The engine starter may be of particular importance in this manner since it may have a significant impact on the compressor inlet. This is particularly important given the very short duration of preliminary engine tests. The engine starter, bellmouth and compressor inlet configuration of TMT-GT150 can be seen in Figure 11.

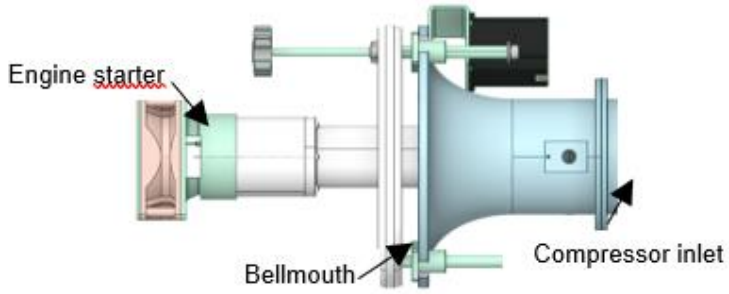


Figure 11. Engine starter and compressor inlet assembly.

In order to assess the influence of engine starter unit on the compressor inlet, CFD simulations are performed using the density-based k-ω SST turbulence model in a steady-state manner. The walls are assumed to be adiabatic, the mass flow rate is specified at the outlet, and atmospheric conditions (101325 Pa) are imposed at the inlet. The governing equations are solved using second order discretization schemes. Two cases are considered: one domain including the engine starter as shown in Figure 12 and another domain without the engine starter (not shown for brevity), in order to investigate the flow field and pressure drop.

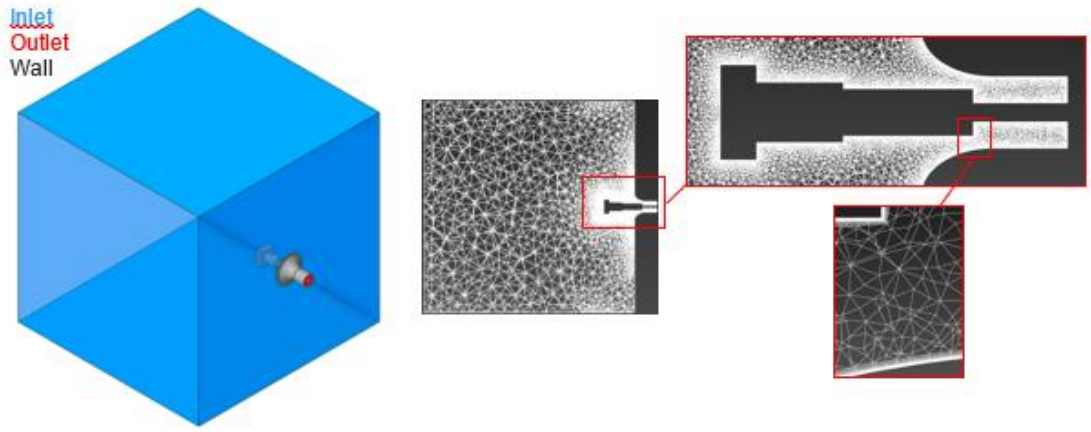


Figure 12. CFD domain and mesh for the engine starter simulation.

Figure 13 illustrates the Mach number distribution at the outlet of engine starter simulations, corresponding to the compressor inlet of the actual engine. As seen, the Mach number distribution is no longer uniform when the engine starter is present, which is attributed to the flow blockage caused by the starter and the shaft. The total pressure drop induced by the engine starter is approximately 4.3%. Therefore, when measurements are taken on the experimental test rig, it is crucial to account for the presence of the engine starter, as it remains installed during the measurements.

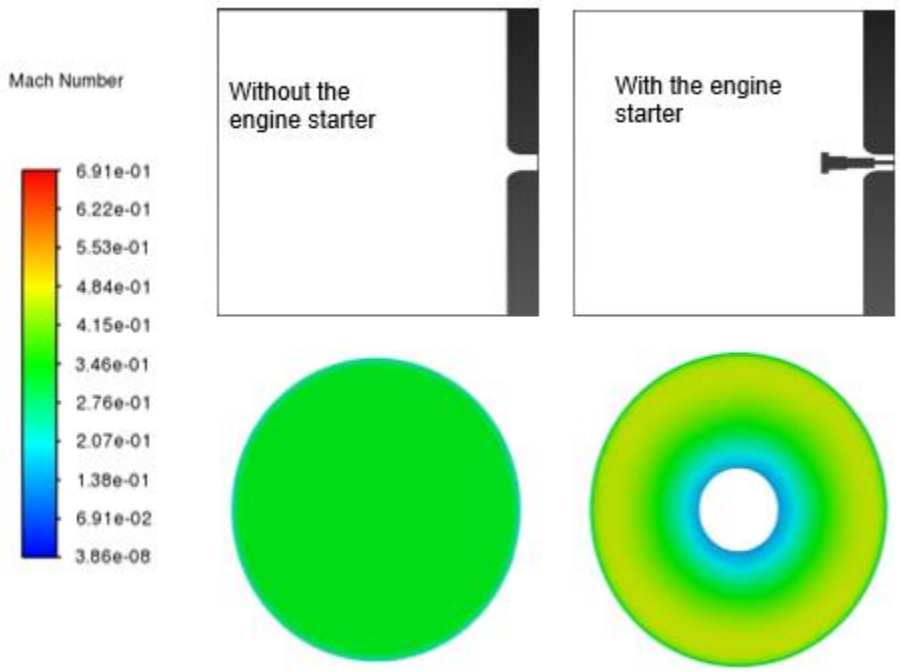


Figure 13. Mach number distribution at the outlet of engine starter domains.

4. Production, instrumentation and testing

After TMT GT-150 engine first prototype was manufactured under subcontract (Figure 14), instrumentation (Figure 15) and testing of the first prototype was initiated (Figure 16). Critical pressures and temperatures are measured at specific locations for monitoring (Figure 17) the engine state during engine test runs. In the preliminary engine start-up and testing, a staged increase of RPMs are employed with monitoring critical pressures, temperatures, air to fuel ratios etc. to ensure that the engine health is not endangered by any initial transient miscalculations.

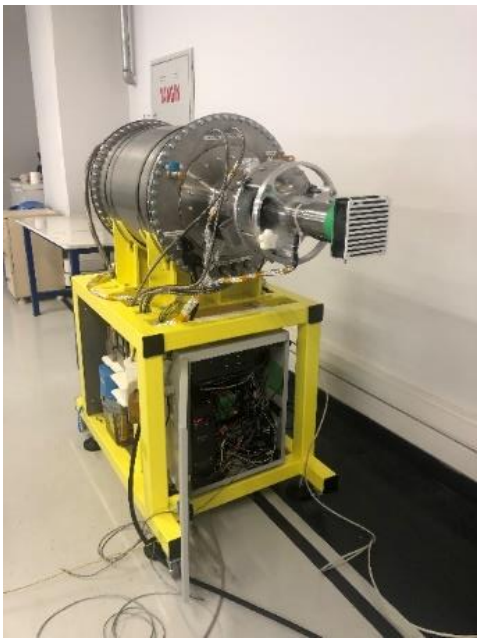


Figure 14. TMT GT-150 engine prototype.

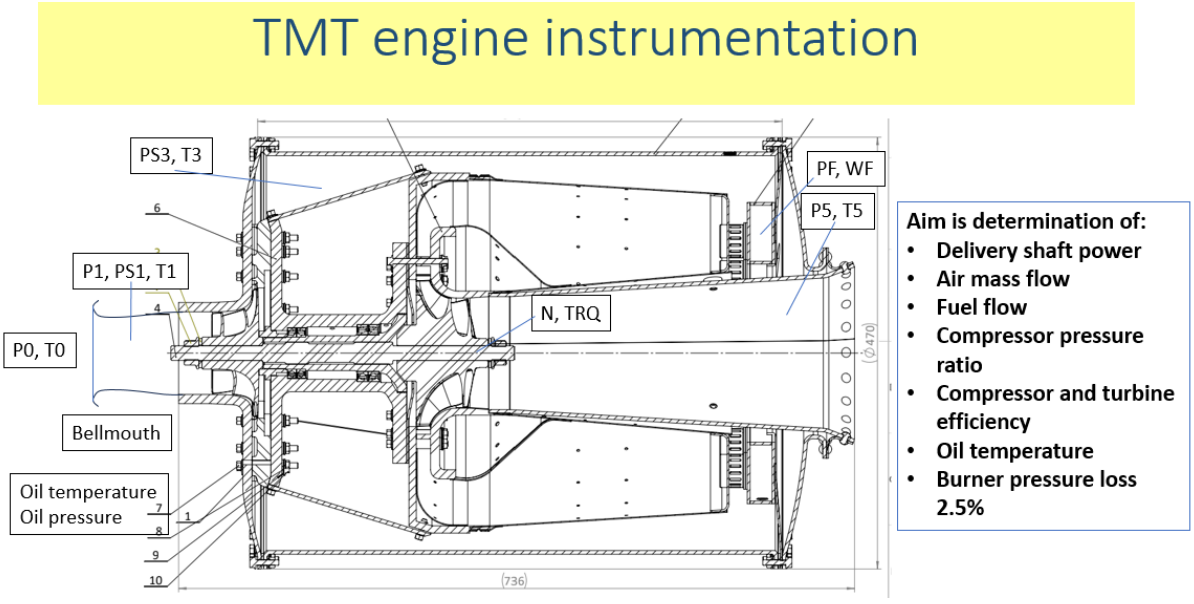


Figure 15. Instrumentation of the TMT GT-150 engine prototype.



Figure 16. Testing of the TMT GT-150 engine



Figure 17. Monitoring and control of the TMT GT-150 engine

Presently, the *First Engine to Test (FETT)* campaign is being carried out to widen the operating envelope. After completing this, the engine will be dismantled to inspect how much potential damage was done on the system in result of thermal, mechanical and inertial loads. This study will guide what kind of design, material and production changes have to be done on the new engine, to be called as the development engine now. After new design changes, the testing campaign for the new development engine will be conducted with addition of further parameters including measurement of vibrations, accelerations, torque and thrust values.

5. Conclusion

This paper has described the design, development and testing process of a small-scale stationary gas turbine engine core, TMT-GT150. Modern CAD/CAM/CAE and HPC tools have been employed throughout the conceptual design, preliminary design, and detailed design phases. The CFD analyses for the compressor, turbine, and combustion chamber have been presented along with thermal analyses, rotor dynamics FEA analysis, and engine starter CFD simulations. The first prototype has been manufactured, and instrumented. The *First Engine to Test (FETT)* campaign is currently underway to expand the operating envelope, that will guide the subsequent design iterations for the development engine.

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