**Micro Gas Turbine**

**Technology**

Research and

Development

for European

Collaboration

**Turbomachinery**



# Acknowledgments

This document was produced by the European Turbine Network (ETN) in order to identify a number of key areas that require substantial R&D efforts for micro turbines from the European community to become competitive in the energy sector worldwide.

The manuscript was produced by Wilfried Visser from the Technical University of Delft (TUDelft) and co-authored by Pietro Zunino from University of Genoa (UNIGE).

The European industry involved or interested in the development of micro turbine technology has identified a number of key areas that require substantial R&D efforts for micro turbines to become competitive in the energy industry. These include recuperator technology, turbomachinery, system integration, multi-fuel combustion technology and material technology. These areas correspond to the working groups defined in the minutes of the ETN meeting on MGT technology held in Brussels 8 October 2015. This document presents potential work areas and proposed project outlines for European collaboration to improve MGT technology, based on the input of the member of the MGT Turbomachinery working group.

Contributions to this document were provided by the organisations listed below:

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| --- | --- |
| Technical University of Delft | http://www.se.ewi.tudelft.nl/dmcd2011/images/TU-Delft_logo.gif |
| University of Genoa | http://www.lingue.unige.it/eventi/metaphor2016/images/Logo_unige_08_intestato.jpg |
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# Introduction

Microturbines are small gas turbines used for small-scale power generation at one point in a distributed network or at a remote location. These power sources typically have rated power outputs between 25 kW and 500 kW. Relative to other technologies for small-scale power generation, microturbines offer a number of advantages, including: a small number of moving parts, compact size, light weight, low emissions, low electricity costs, potential for low cost mass production, and opportunities to utilize waste fuels. They have been commonly used in many engineering fields.

The current challenging performance targets for microturbines include fuel-to-electricity efficiencies of 40% or higher, capital costs less than $500/kW, NOx emissions reduced to single parts per million, several years of operation between overhauls, lives of 40,000 hours and fuel flexibility [7-8].

A schematic diagram of the TURBEC T100 Micro turbine is shown in following figure 1 [9], where the different components are:

1. Electric Generator
2. Air inlet
3. Combustion chamber
4. Recuperator air by-pass
5. Compressor
6. Turbine
7. Regenerator
8. Heat exchanger



Figure 1 – Schematic draw of the TURBEC T100 Micro turbine system [9]

Typical operating conditions are:

* Combustion chamber pressure = 4.5 bar
* Turbine Inlet Temperature = 950°C
* Turbine exit gas temperature = 620-650°C
* Exhaust gases temperature = 80°C
* Rotation speed = 70000 rpm

# MGT efficiency

MGT efficiency is a key factor for competitiveness in relation to alternative prime movers for most if not all application areas.

## Power generation

For ground based power generation, there is competition from many alternative technologies such as small piston engines, fuels cells and Stirling engines. These are all focused on energy saving and often in cogeneration configurations. Especially for the very small scales MGT’s (below 100 kW), efficiency is often lower that most alternative prime movers and competitiveness is maintained using the specific benefits of the gas turbine including fuel flexibility, power density, low emissions, low noise.

## Cogeneration

MGTs used in co-generative applications have proved to be a promising technical solution for a high efficiency energy conversion. Even though global energy efficiency of micro-gas turbines is usually high, due to the use of waste heat for cogeneration, electrical efficiency is lower than other competing technologies such as reciprocating internal combustion engines. As a consequence, an effort should be made to enhance its performance. This target can be obtained by increasing the firing temperature in order to improve Brayton cycle thermodynamic efficiency or by means of an integrated and optimized design of micro-turbine components (centrifugal compressor, radial inflow turbine, recuperator etc). Both these approaches are object of researches even though they have different impact on machine manufacturing process. The first approach requires the use of advanced materials for the hot gas path components, such as ceramic turbine impeller and casing and nickel based super-alloy recuperator, since cooling techniques, such as those used in larger heavy duty GT, are hardly implementable with radial turbomachines. On the contrary, components redesign with advanced optimization techniques enables to keep the current technology for components manufacturing leading nevertheless to important performance enhancement.

## UAV/small aircraft propulsion

For aircraft propulsion it is entirely different: there is a rapidly growing demand for small scale light and efficient propulsion systems for UAV’s. The leading market here is military which means information on development projects is mostly classified. However, also the civil UAV market is growing rapidly and may well eventually inherit technology from the military projects. Currently, the MGT development resources may well be largest in the military sector. Therefore, also future ground based MGT technology may well come from the aircraft UAV engine, similar to the current aero-derivative industrial gas turbines. It is clear that for UAV operational requirements such as range and endurance, improving engine efficiency is key (except for some very specific application such as missiles).

## Efficiency drivers

Many textbooks give excellent theoretical backgrounds on gas turbine design and performance and how these relate to efficiency [**1**, **2**, **3**]. Summarized, the key parameters of the gas turbine cycle determining efficiency are

* Cycle pressure ratio,
* Turbine entry temperature (TIT),
* Turbomachinery component efficiencies.

Turbomachinery efficiency is always maximized. However, for cycle pressure ratio and turbine entry temperature, depending on the cycle configuration, often optimal levels exist. An example is the recuperated cycle where best cycle efficiencies are obtained at moderate cycle pressure ratios. This optimum then is depending on TIT and the turbomachinery component efficiencies (in [**4**] for example, the optimum pressure ratio is around 3.0).

There are a number of other effects that usually are less dominant including

* Pressure losses
* Thermal losses
* Heat transfer effects
* Combustor efficiency
* Bearing losses
* Gas/air leakage losses
* Electric losses (power electronics, generators).

# Necessary Technology Developments

If the objective is the development of generic MGT technology strengthening the European MGT industry competitiveness, then primary focus should be on improving turbomachinery efficiency and costs. For turbines, also maximum gas temperature levels will be important. As a result, the MGT efficiency work package will involve:

* Improving aerodynamic efficiency using advanced fluid flow analysis and simulation.
  + Geometrical design optimization of impellers, blades, vanes, volutes etc. In [**5**] an example is given of a project focused on systematically increasing micro turbine efficiency.
  + A specific aspect here is the small scale effects. Losses become increasingly large at low Reynolds numbers [**6**].
* Minimizing tip clearance
  + This involves structural design issues and also relates to rotor dynamics and bearings
* Reducing bearing losses
  + This may include the development of advanced bearing solutions such as air bearings
* Reducing other non-aerodynamic loss effects, such as windage losses, thermal losses
* Development of cooling concepts allowing higher turbine inlet temperatures for higher cycle efficiency
* All these developments must be accompanied with efforts to minimize costs. Apart from military applications, competitive cost levels for MGTs will be essential for commercial success. For turbomachinery, the high-volume/low cost manufacturing technology from the automotive turbocharger industry may well be adopted.

# Working group member contributions

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| WP title | TPG | UNIGE (TPG) | UNIGE (DIM) | MTT | KIT | ECL | IMP | CUL | DUT | RO3 | MITIS |
| Turbomachinery design optimization |  |  | X | X | X | X |  | X | X | X | X |
| Tip clearance minimization |  |  |  |  | X | X | X | X |  |  | X |
| Research focused on small scale effect losses |  |  |  |  |  |  | X |  | X |  |  |
| Relation manufacturing tolerances, costs and efficiency |  |  |  |  |  |  |  |  | X |  | X |
| Cycle optimization | X | X | X |  |  |  |  |  | X | X | X |
| Air bearings |  |  | X |  |  |  |  | X |  |  | X |
| Application system optimization |  |  |  |  |  |  | X |  |  |  |  |
| Usage profile optimization |  |  |  |  |  |  |  |  |  |  |  |
| Cooling and thermal management concepts | X | X |  |  |  |  | X |  | X |  |  |
| Small losses minimization |  |  |  |  |  |  |  | X |  |  |  |
| Electric efficiency |  | X |  | X |  |  |  |  |  |  | X |
| Performance retention and condition monitoring | X | X |  |  |  |  |  |  |  |  |  |
| Rotor dynamics |  |  | X |  |  |  |  | X |  |  | X |
| Component simulation and matching |  | X | X |  |  |  |  |  |  | X |  |
| MGT and component testing |  | X | X |  |  | X | X |  |  | X |  |

## University of Genoa (TPG)

The Thermochemical Power Group (TPG) of the University of Genoa has wide experience on performance evaluation and optimization. This activity is usually carried out with different in house software to evaluate system efficiency including exergetic and thermoeconomic analyses to show the components affected by the most significant exergy decay (power gap analysis). Moreover, the main performance parameters of plant components (e.g. recuperator effectiveness, compressor and turbine efficiency values, etc.) are investigated by TPG for different mGT based layouts to show the importance of component degradation or fault on the entire plant. Also the wide experience of TPG in diagnostics can be essential for performance monitoring during mGT operations.

The TPG of the University of Genoa is interested to collaborate with the ETN partners on the following topics related to mGT efficiency improvement:

* cycle analysis with improved components in both steady-state and transient conditions;
* thermoeconomic analysis and optimisation;
* power gap analysis to evaluate the low efficient components (or plant parts);
* design improvement of component integration to increase system efficiency;
* experimental tests on real turbomachinery at innovative operating conditions;
* diagnostic aspects on the mGTs including the development of apt tools for data validation, fault detection, data reconciliation and other topics (e.g. development of GUIs);
* efficiency issues in advanced mGT based cycles (e.g. CSP or mHAT plants).

## University of Genoa DIME-UNIGE (DIM)

The DIME-UNIGE (Department of Mechanical, Energy, Management and Transportation Engineering of the University of Genova) has gained experience both in computational methods and experimental techniques for turbomachinery components design and analysis working in several EU funded projects in cooperation with international companies in the field of aero-engines.

As far as concerns the experimental and numerical modelling for aerodynamics of MGT, the expertise of University of Genoa DIME, can be summarized in the following:

 Experimental instrumentations: directional miniature pressure probes, fast response miniature pressure transducers, 2-D and 3-D hot-wire anemometry, multisensory hot-film anemometry (HWA), 2-D and 3-D Laser Doppler Velocimetry (LDV), stereoscopic and time-resolved particle image velocimetry (PIV), liquid crystal and infra-red thermography

 Experimental facilities and test rigs: wind tunnels for large-scale investigations, two wind tunnels for detailed cascade investigations, a transonic wind tunnel, a centrifugal compressor model, a two-stage axial research turbine, two wind tunnels for aerodynamic investigations of low-emission injection-systems for aero-engine applications.

DIME-UNIGE has also a number of commercial, open-source, and in-house developed numerical codes for the simulation of the unsteady flows within turbomachinery components and several work-stations for multi-core parallel calculations. The available codes allow the numerical simulation of high-speed flows within turbomachinery components, and the focusing on turbulence modelling, transition prediction, unsteady rotor/stator interactions, as well as conjugated heat-transfer within bladed channels. Moreover, multi-objective optimization tools based on evolutionary algorithms are also available and have been used to carry out a multi-disciplinary optimization of centrifugal compressor and radial inflow turbine. The parameterized geometry can be optimized considering both fluid dynamic performance, thermal behavior and mechanical constraints such as maximum allowable stress and avoiding resonances. This enables to conjugate, within the same development tool, different design technical aspects leading to an efficient and reliable design flow.

DIME-UNIGE could contribute to the research with the multidisciplinary optimized design of the high efficiency radial turbine, as well as, to contribute to the overall thermo- mechanical design of the optimized MGT as a whole.

DIME-UNIGE Laboratory of Aerodynamics, Combustion and Turbomachinery is also available for component testing components as well as the complete MGT prototype.

A MGT dedicated test rig is under development based on a commercial micro gas turbine that is being modified in order to allow separate thermo-fluid-mechanical tests on the optimized components and on the optimized micro gas turbine as a whole.

DIME-UNIGE, based on its own expertise on turbomachinery, is developing a computer code for the prediction of off design performance of the gas turbine components and of the matching for the prediction of the MGT operating performance maps.

## Micro Turbine Technology b.v. (MTT)

MTT operates its MGT at ~4 kWe. One of the challenges is to increase the efficiency of the *electrical power output* of the MGT, which can be reached by:  
o   Using more efficient turbomachinery components, research is performed on optimizing current designs for MGT applications.   
o   Improvements in electrical generator technologies  
o   Increasing maximum turbine inlet temperature (TIT), which could be achieved by a combination of active cooling and thermal barrier cooling.  
The other challenge relate to efficiency of MTT is to optimize the *thermal efficiency of the application in which the MGT is used*. Often also the overall efficiency is of importance for MGT applications. Then thermal insulation and heat recovery issues are research topics to address.

## Karlsruhe Institute of Technology (KIT)

For optimization of aerodynamic design of turbomachinery, advanced computational techniques, such as LES, can be used to deeply investigate boundary layer development and its interaction with Coriolis forces due to rotating reference frame as within compressor and turbine impeller. In this field, the Karlsruhe Institute of Technology KIT at the Institute of Fluid Mechanics has a long lasting experience in the modelling and application of Large Eddy Simulation and related aspects for rotating machinery. The advantage of LES is that a large fraction of the turbulent effects as wells as rotation and curvature effects especially in rotating machinery a resolved instead of modelled as in the classical RANS approach. The advantage of a very accurate prediction is especially useful in part load conditions, here the flow field stalls and strong instability of the first (rotating stall) or even second type (surge) usually happens. This improved predictive capability on the other hand goes along with a much higher computational time. In order to keep the wall clock times for the calculations small a parallelization of the LES codes is mandatory. For that the KIT, Institute of Fluid Mechanics has developed a highly parallel and efficient solver. Moreover, especially for the compressor wheel, performance prediction strongly relies on medialization of the unsteady phenomena and their mutual interaction as for the inherent unsteadiness of rotor-stator interaction. For this reason advanced harmonic balance methods can dramatically speed-up unsteady computations and this approach can be implemented at the end of the optimization loop where usually, due to resource limitations, only steady RANS solvers are employed. In this field, the Karlsruhe Institute of Technology KIT has recently implemented the so called harmonic Balance Method. With this method the unsteady Navier-Stokes equations are Fourier-transformed into a coupled system of steady N-S equations. Therefore the computational times are reduced dramatically compared to the full unsteady calculation at least by a factor of ten and more. In contrast to the steady mixing plane approach used nowadays the unsteady rotor-stator interaction is taken into account. By further extending this approach for slowly varying periodic flows called quasi periodic flows also transient flow fields such as rotating stall and surge can be calculated by a fraction of the computational times compared to full unsteady calculation. In contrast to LES the turbulence effects must be modeled by conventional turbulence model of k-epsilon or k-omega type.

## Ecole Centrale de Lyon (ECL)

Ecole Centrale de Lyon has long been working on analysis and design of centrifugal compressors and several tools for the optimized design of these machines has been developed. In particular the proposed approach for this task is based on several advanced features such as: geometry morphing and mesh deformation, meta-model construction based on derivative database, self-organising maps for Pareto front analysis within multi-parameter multi-objective optimization. Once the compressor geometry is optimized a thorough flow analysis is performed in order to evaluate the compressor aerothermodynamics performance at design and off design operating points. CFD (Computational Fluid Dynamics) applied in turbomachinery offers various categories of simulations: RANS (Reynolds-Averaged Navier-Stokes), LES (Large Eddy Simulation) and hybrid methods as ZDES. ECL proposes to perform simulations and to analyze the results. Although the numerical results typically prove to be reliable at stable operating points, they can fail in predicting accurately the surge onset. ECL expertise in the analysis of the mechanisms inducing stall and surge is proposed in the frame of the present project.

The Turbomachinery group has various test rigs including one which characteristics fit with the size and operating conditions of the compressor as designed in a pre-design step. The test rig includes sensors for health monitoring and specific instrumentation for investigating the unsteady internal flow. Moreover the rig is versatile in order to simulate the system in which the compressor is installed.

## IMP PAN (IMP)

Also transonic and supersonic aspects have to be considered in order to avoid the underestimation of additional losses related to shockwaves above all in strong off design conditions. IMP PAN has a long lasting expertise in transonic flows. Recent participation in European projects allowed IMP PAN the research on transonic cascades of compressors and turbines. The development of turbomachinery introduces a need for flow control. Flow control methods have been analysed numerically and experimentally at IMP PAN, especially in transonic conditions for shock wave – boundary layer interaction.

IMP PAN has recently built a new test section for the study of compressor and turbine cascades. The laboratory has been equipped with all modern methods as PIV, LDA, PSP and TSP. The group is experienced in the investigations of flow and heat transfer. Especially the enhancement of heat transfer is the point of interest.

IMP PAN has also built a test section for biogas turbine investigations. The test section has been equiped with microturbine Turbec 100 kW and measurement system of inlet/outlet flow conditions. Investigations can be carried out for wide range of fuel composition.

In addition, for turbine wheels, it is necessary to correctly evaluate the thermal and centrifugal deformation due to the combined action of high temperature field and high rotational speed, in order to take into account the mismatch between cold and hot geometries. The use of abradable materials for clearances reduction and its impact on manufacturing costs and performance has to be investigated.

The heat transfer phenomena have to be properly modelled since their effects grow with the reduction of the overall dimensions of the machine. This requires to consider the layout of the machine components in order to properly consider their thermal boundary conditions within the design procedure.

## City University London (CUL)

* Effect of the Internal heat transfer from the turbine to the compressor and its effect on the MGT efficiency
* Alternative turbomachinery arrangements to increase the dynamic stability and MGT efficiency
* Different Bearing technologies and their effects on the mechanical losses and dynamic stability in the MGT

Improvement in the aerodynamic design of the compressor and turbine including leakage consideration to increase overall MGT efficiency.

## Delft University of Technology (DUT)

At DUT Power and Propulsion group, efforts are devoted to the development of new methodologies for the design of power and propulsion systems and components, whereby optimization techniques are applied to system models integrating detailed models of components (e.g., turbomachinery and heat exchangers), and to the automated fluid dynamic design of turbomachinery. Much of the work is performed in collaboration with industrial partners.

Micro gas turbine technology has a specific focus at Propulsion and Power group. Research is performed for design and optimization of systems/cycles, turbomachinery and combustion of advanced micro and mini gas turbines. For power generation micro turbines, turbomachinery designs are optimized using advanced CFD simulations. The group is involved in the development of the Stanford University SU2 open source CFD modelling environment including adjoint optimization. For aircraft propulsion, research is focused on high-efficiency micro turbines for UAVs.

The group has a substantial role in the development of the [GSP](http://www.asimptote.nl/software/GSP-DUT) Gas turbine Simulation Program (www.asimptote.nl/software/GSP-DUT). GSP has global recognition in the gas turbine community as a versatile gas turbine system simulation tool. System simulation work is performed for engine diagnostics (gas path analysis), analysis and optimization of combined cycles, including novel concepts with ORCs as gas turbine bottoming cycles.

[CycleTempo](http://www.asimptote.nl/software/cycle-tempo/) (www.asimptote.nl/software/cycle-tempo/) is a tool for modelling of energy systems on the highest level including combined cycles.

## University of Roma Tre (RO3)

The Research Group (RG) of Fluid Machinery and Energy Conversion Systems of the Department of Engineering is actively involved in the following research topics:

* Energy conversion systems: optimization of design and operation of power plants, design and analysis of plant components (compressors, expanders, heat exchangers, cooling systems), development of methodologies and models for status recognition and diagnosis of GT components, advanced power production systems;
* Development of small turbo-expanders for steam and organic working fluids, cold tests of turbochargers;
* Assessment of innovative MGT cycles for solar applications;
* Theoretical and experimental investigations of fuel emulsification and combustion of emulsified fuels
* Development of high-temperature solar receivers for Dish-MGT systems, including thermal energy storage.

The Research Group has developed in-house software codes for the optimized design and the analysis of components for combined cycle power plants. Moreover the RG has various commercial codes for CFD analysis of turbomachines and heat exchangers. Various test benches have been built in the last years: in particular the RG has a test bench for the development of unconventional micro turbo-expanders, a solar facility for small-scale high and medium-temperature tests, a laboratory for emulsion characterization equipped with a test bench for prototype of on-board emulsification systems for liquid fuels adopted in GTs and Diesel Engines.

According to the RG expertise, Roma Tre can give a contribution in:

* Turbomachinery design and optimization;
* Component simulation and mayching;
* Cycle optimization;
* MGT testing

## Mitis

Mitis is currently developing a 1kWe microturbine based microCHP system for residential applications. Mitis initial R&D activities have focused on the development of a compact high efficiency and low cost recuperator integrated with a flameless combustor for natural gas. Current work is now targeting the turbomachinery components development. Mitis has the capabilities to perform advanced CFD modelling and optimization, prototype manufacturing, and experimental testing. Mitis is interested in research activities to increase the efficiency of the system (increase TiT, components efficiency optimization), life improvements (material and structure design), reduction of cost of components manufacturing, reduction of cost of electric components.

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# Appendix A Considerations for the development of a recuperated MGT

As discussed in the previous paragraphs, the optimized design of components enables to reach important efficiency targets with a negligible impact on the technology, on the manufacturing process and on the materials used.

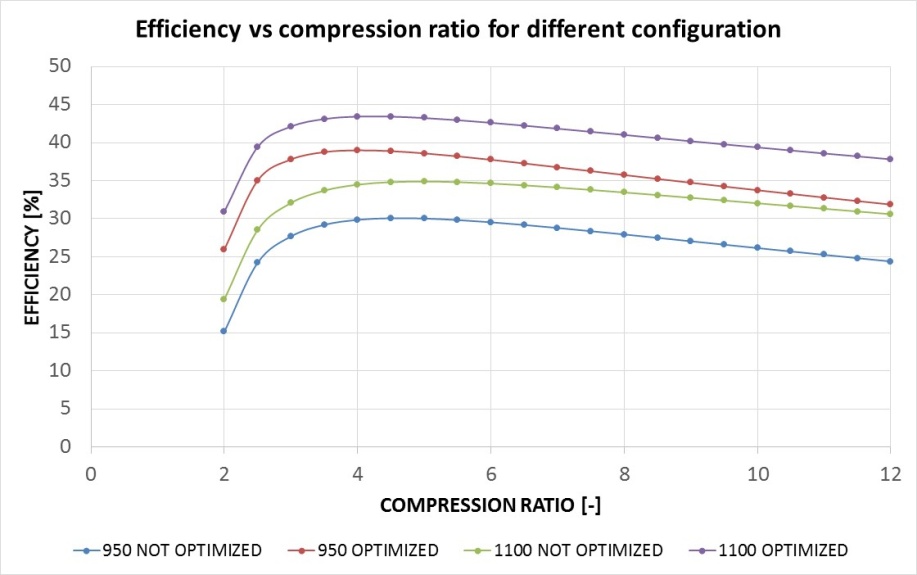


Figure 1: Comparison of efficiency enhancement obtained by means

of firing temperature increase or components optimisation.

Figure 1 clearly shows the impact of firing temperature increase and component optimization on the MGT electrical efficiency. In particular, 950°C and 1100°C has been considered as the representative values for, respectively, nickel based super-alloy and ceramic radial turbine impeller. An optimized and integrated design for compressor, turbine and recuperator has been considered for enhancing efficiency values from current commercial machines to state of the art for advanced applications.

A way to achieve the goal of enhancing MGT efficiency is the employment of an integrated design procedure for the whole machine, considering the mutual interaction of the components, employing multidisciplinary optimization (MDO) techniques, able to satisfy on one hand the requirements of obtaining high efficiency for all MGT components, and on the other hand to guarantee the safe operation of the machine imposed by technological and mechanical integrity constraints.

Advanced simulation models for mechanical analysis and assessment have to be developed, especially in case of adoption of ceramic material for turbine impeller. Static and dynamic analyses have to be integrated in the multidisciplinary optimization calculation cycle, but more advanced and detailed analyses will be carried out for the optimized sample. In particular, transient conditions represent a key factor for assessing the Low Cycle Fatigue (LCF) and minimizing the clearances.

Additionally, a good understanding of bearings and shaft operation is required, in order to avoid underestimation or overestimation of their efficiency, which can hopelessly compromise the quality of design procedure.

Related to the shaft and the bearings, another important topic is the rotordynamic behavior of the machine: the shaft layout strongly affects the eigenfrequencies of the system, which can occur at a speed lower than the operating one, therefore in the start- up phase the bearings should be able to damp the vibration amplitudes of the shaft. In turbomachines shaft layout and compliance of the bearings, i.e. their stiffness and damping, influence critical speeds and out-of-balance response of the rotor. Bearings must provide sufficient damping to operate with vibrations of acceptable amplitude in nominal conditions and, for supercritical rotors, to overcome the critical speed without damage. In addition, for fluid film bearings, instabilities generated due to the fluid and its interaction with other parts (whirl, whip, hammering) must be avoided.

Furthermore, by operating in very critical conditions, such as at low Reynolds numbers, with small relative roughness and small tip clearances dimensions, additional efforts have to be considered and evaluated. In fact, a flow regime characterized by low Reynolds numbers implies a strong influence on turbulence development and, consequently, its modelisation becomes very challenging.