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The International Crossroads for Vertical Flight

Adapting a Small Ground Turbine to Very Light Airborne Applications: a "Lean" Approach

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Contents

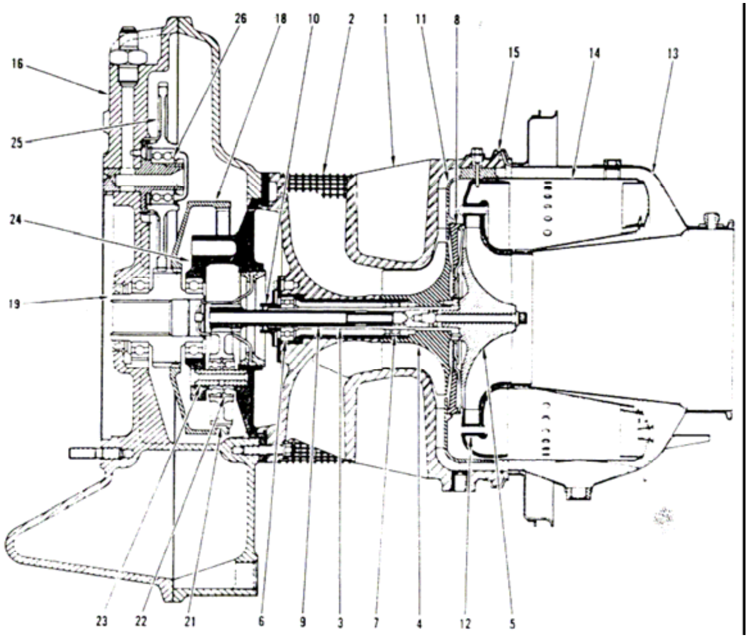
The Starting Point

SOLAR T-62T-32

ground based,

power generation gas turbine.

CHARACTERISTICS	VALUE
Rated Speed	61091 rpm
Rated power	90 hp
Gearbox output speed	6000 rpm
Weight (dry)	76 Kg
Maximum EGT	1180 °F
SFC at Rated Load, 60°F	0.496 Kg/hp-hr



The Objectives

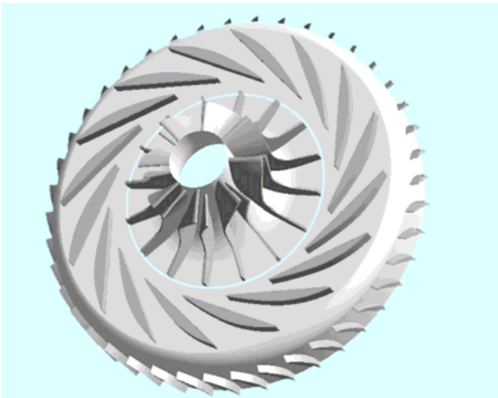
- To verify the feasibility of adapting a small gas turbine to very light airborne rotorcraft (UAV-VLR) applications

- To perform the necessary activities to actually install and test a small gas turbine in an experimental very light rotorcraft, including:
  - Review and improve the performance and efficiency of the turbomachinery
  - Assess and improve as necessary the structural integrity of the mechanical parts
  - Develop the necessary components
  - Reduce the weight of the equipped engine

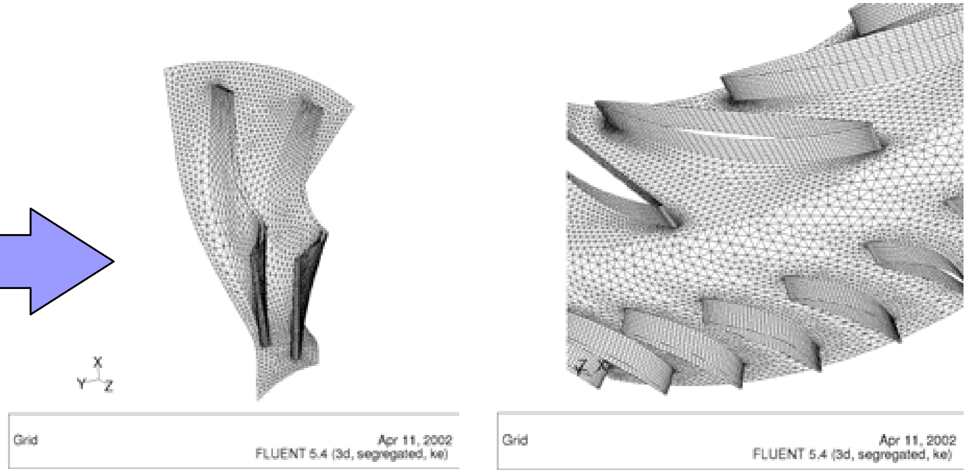
- To compare the turbine engine to the reciprocating engine (both gasoline and diesel) for these applications

Reverse Engineering and Modeling

Actual Compressor Impeller

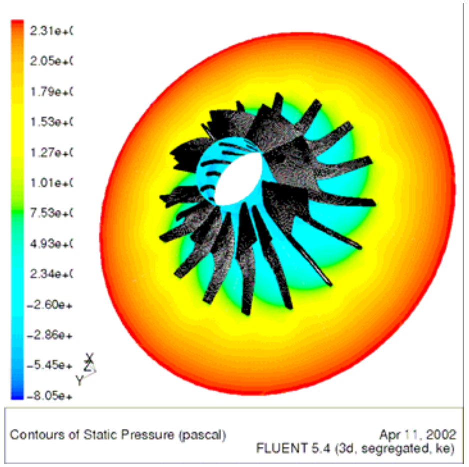


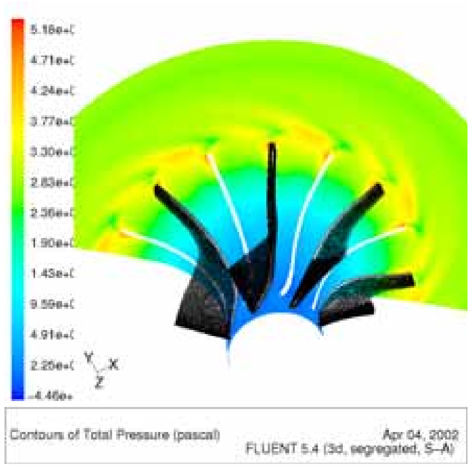
3D Model

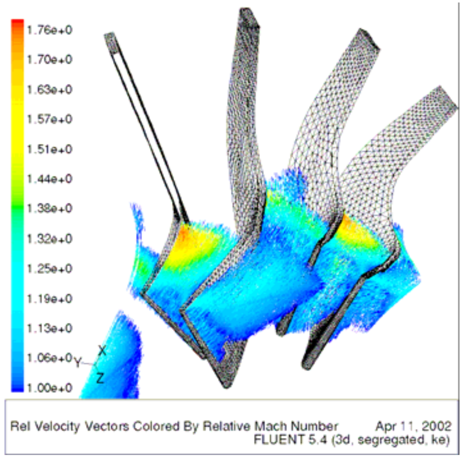


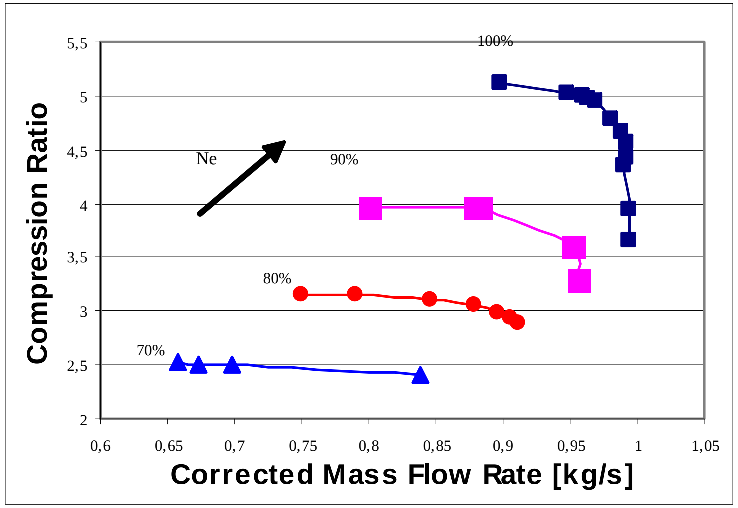
CFD Mesh

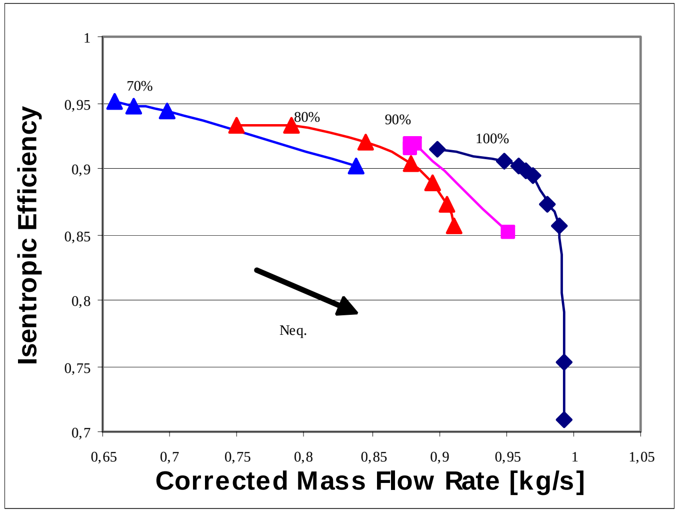
CFD Analysis



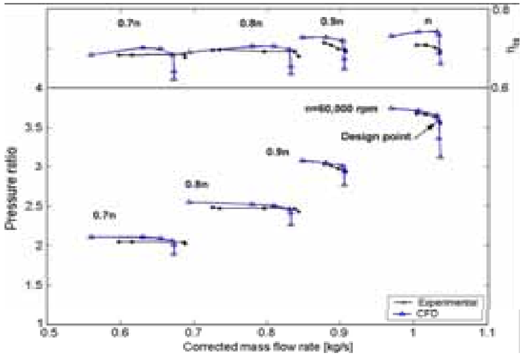


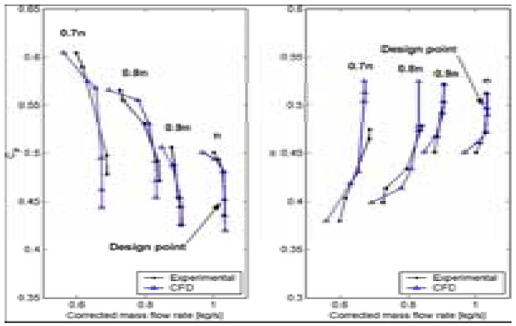






Performance Testing



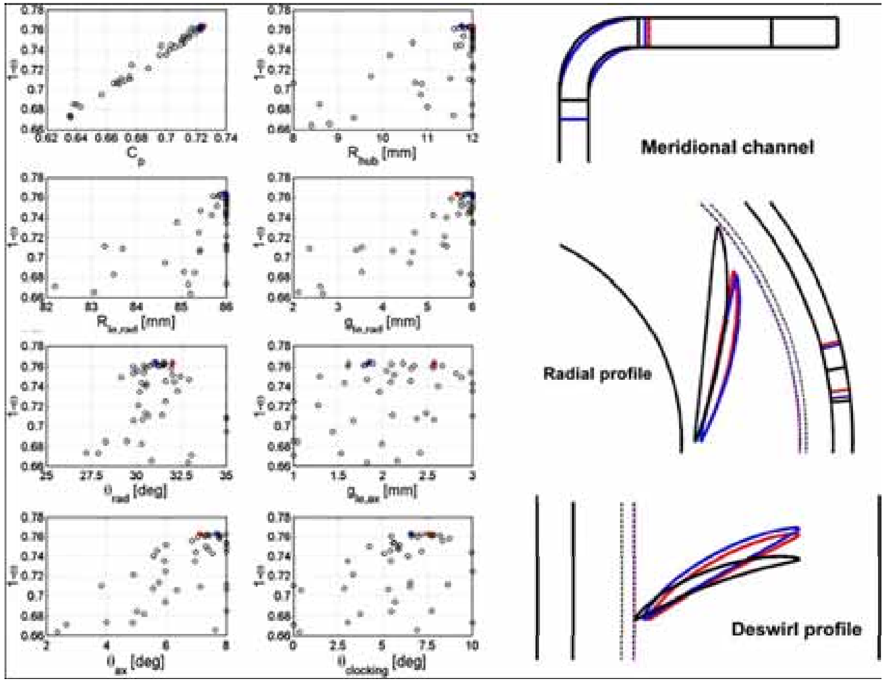


Instrumented Turbine on "Dyno" Rig

The experimental test showed that the compressor has quite a narrow operating range at all rotational speeds, and that the normal working point is very close to the choke line, the **corrected mass flow is 1.033 kg/s** and the **pressure ratio 3.6**.
In this condition, the **isentropic efficiency is about 0.70**.
At nominal rotational speed, predictions of the pressure ratio are in excellent agreement over the whole operating range, while those regarding the efficiency are less accurate, the maximum discrepancy being in the order of 4%.

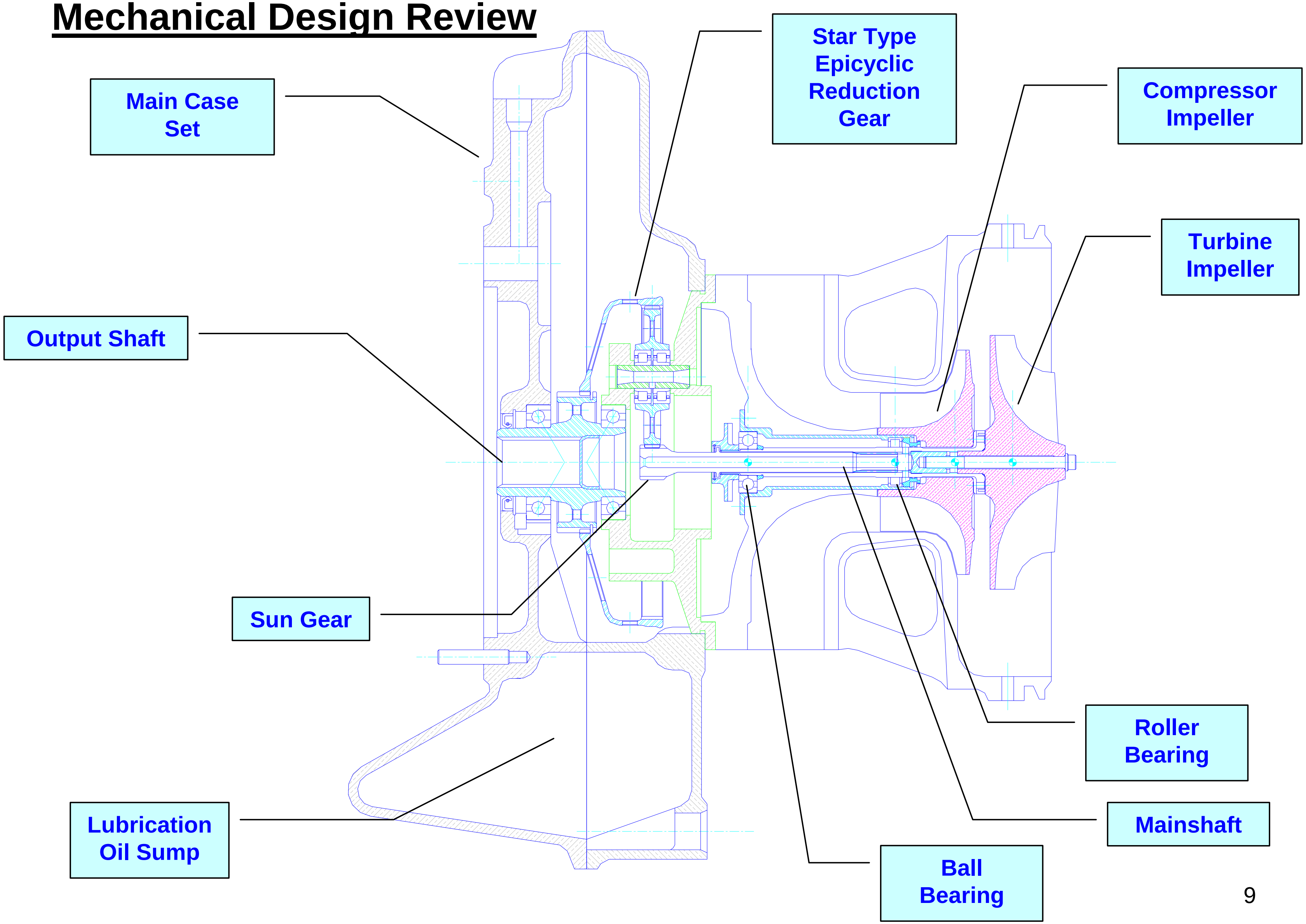
Optimization

Thanks to the optimization of compressor and diffuser design (up to Pressure Ratio of 6), turbine new materials (for example MAR-M247 since the max. temperature increases up to 914°C) and the results of our tests, a projected, optimized configuration was defined as shown in the table.

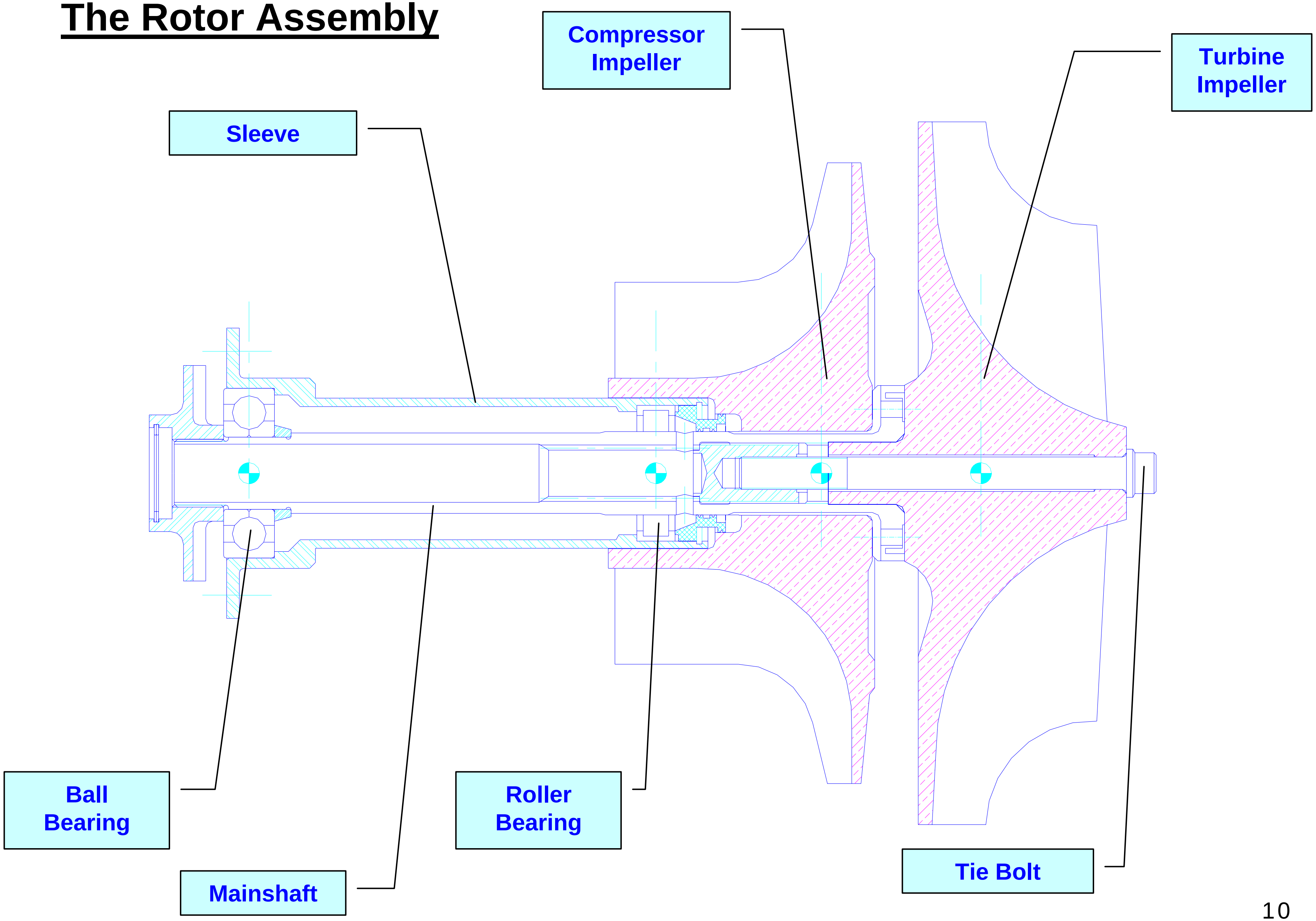


	T-62T-32 Existing and T-61A		**T-61B Projected**	
Power [hp]	80	135	80	135
Pressure Ratio	3.6		6	
TIT [°C]	660	814	744	910
Thermal Efficiency [%]	11	14	16.5	20
Fuel Consumption [Lit/hr]	60	83	42	61

Mechanical Design Review



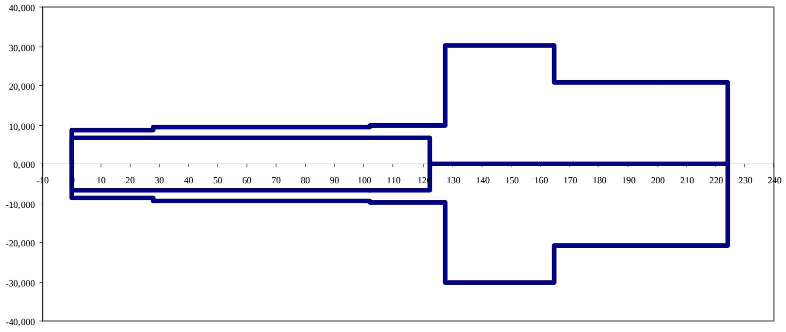
The Rotor Assembly



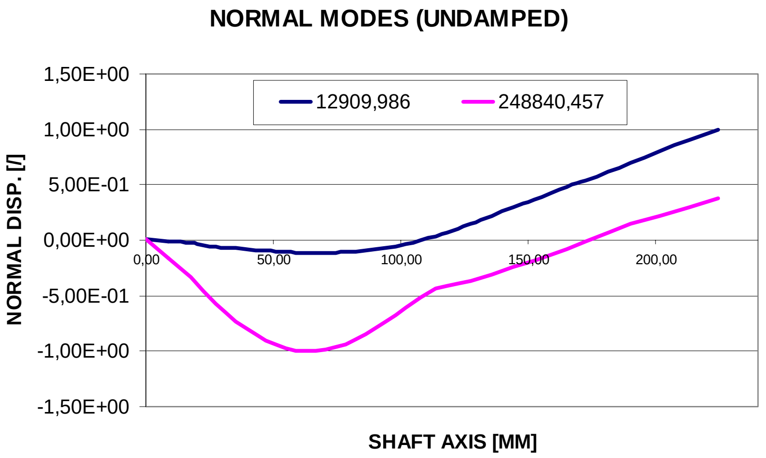
Rotordynamics of the Rotor Assembly 1

Slender shaft coupled to large rotors (high Jp) makes the gyroscpic effects determinant in the critical speed analysis.

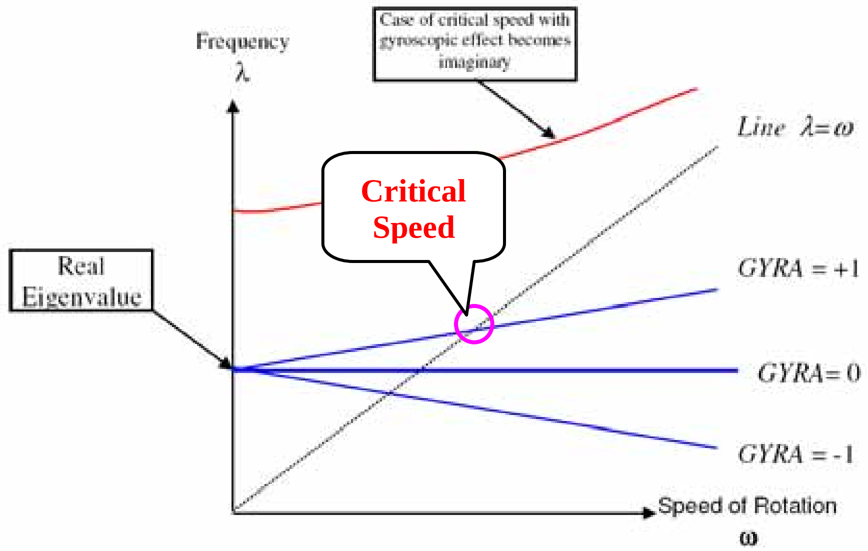
Mode	Description	Speed rpm	Percent %
1	Shaft bending	12900	21
2	Shaft bending coupled with roller bearing radial deflection	249000	407



2D model



Calculated Mode Shapes



Gyroscopic Effects

Rotordynamics of the Rotor Assembly 2

Placement of 1° Shaft Bending Critical Speed has been estimated to be away from critical or continuous operating conditions of the engine.

N.	Description	Turbine Speed rpm	Percent %
1	Self-Sustaining Speed	12218	20
2	**1st Shaft Bending Critical Speed**	**12900**	**21**
3	Ground Idle Speed	18327	30
4	Clutch Engagement Speed	30545	50
5	Nominal speed	61091	100
6	Maximum Speed	70255	115

Mainshaft Stress Analysis

1. Slender shaft with grooves, splines and holes:

   ⇒ High Kt

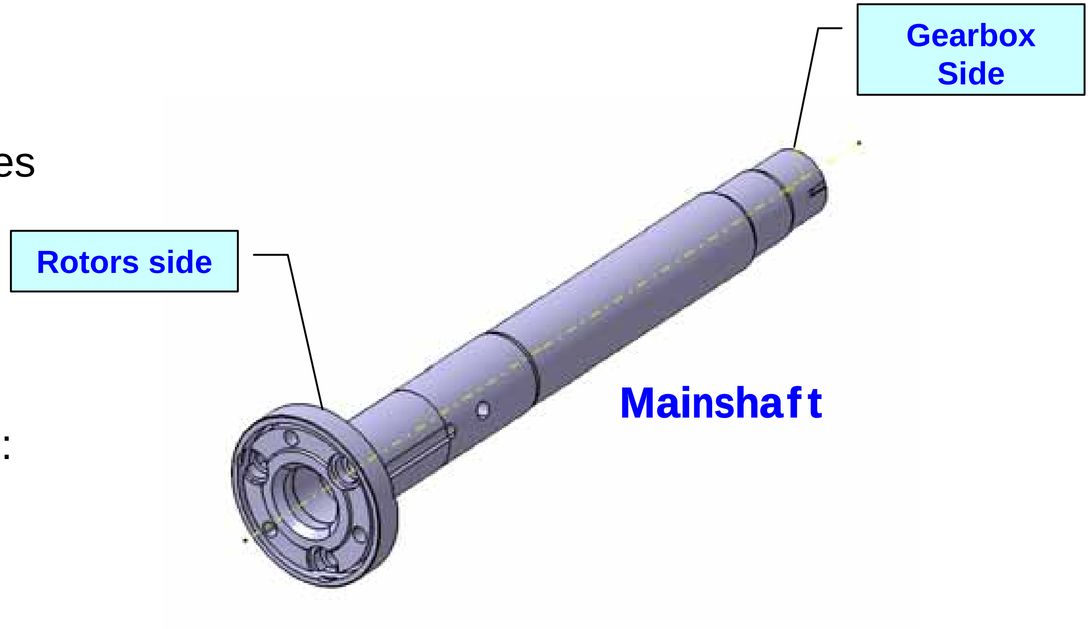
2. Large (High Jp) rotors connected:

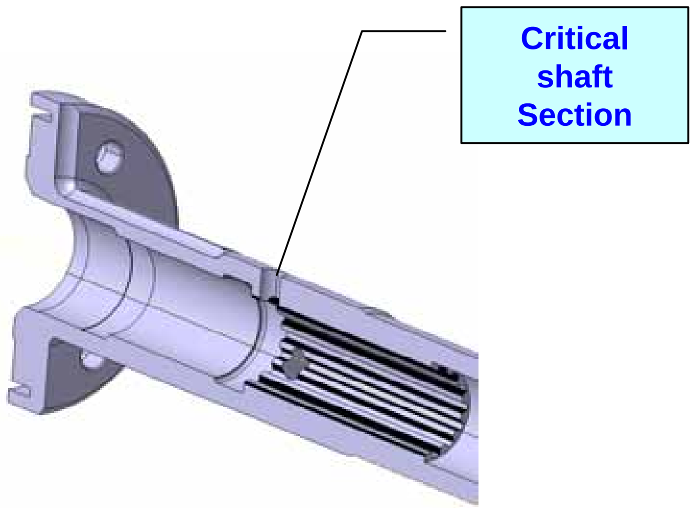
   ⇒ High gyroscopic moments

3. Combination of torque, unbalance, gyroscopic moment:

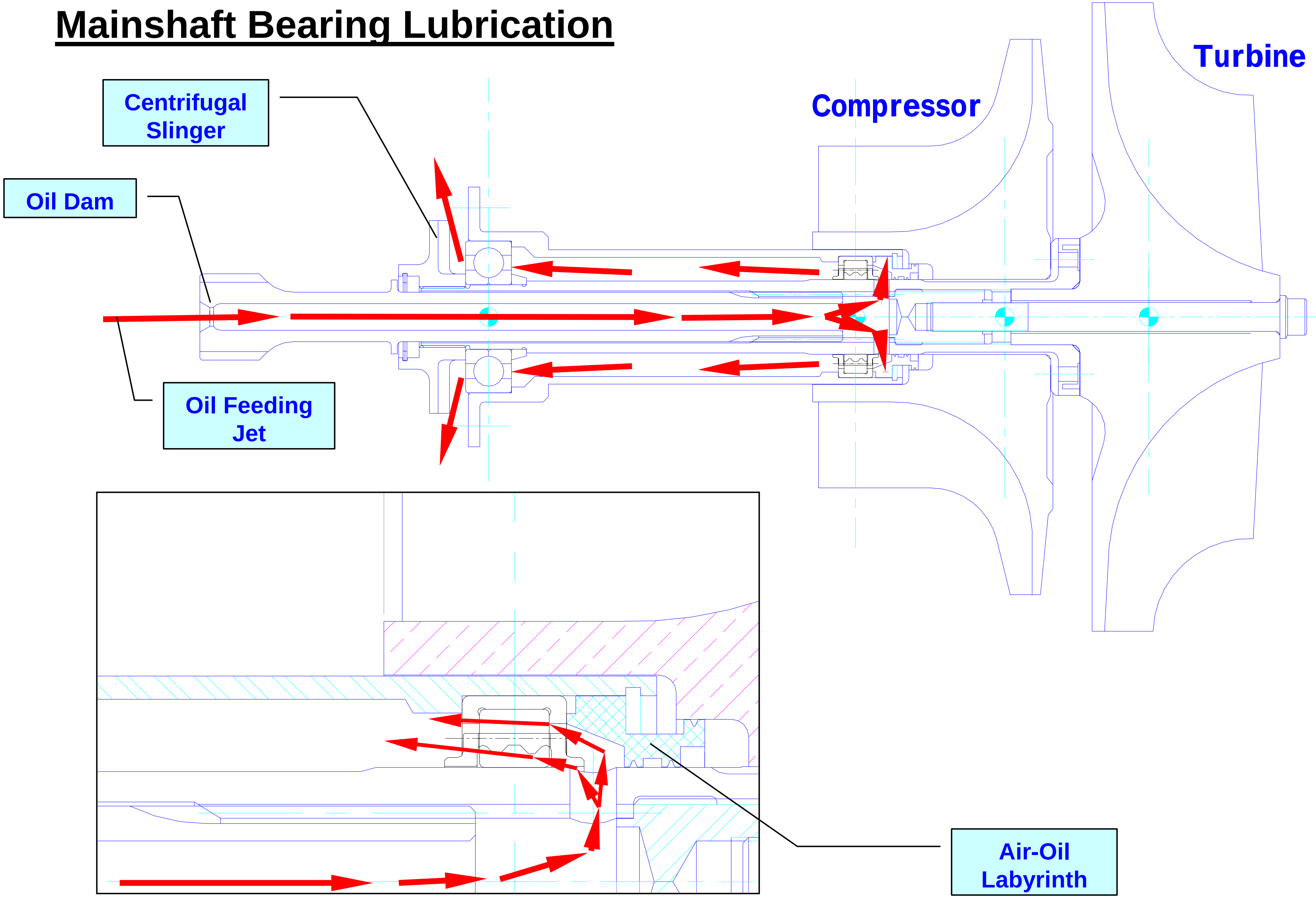
   ⇒ Critical shaft section between rotors and drive spline

⇒ **Limitations to the maximum yaw rate**





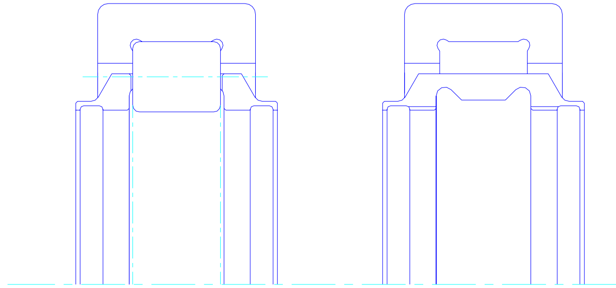
Mainshaft Bearing Lubrication



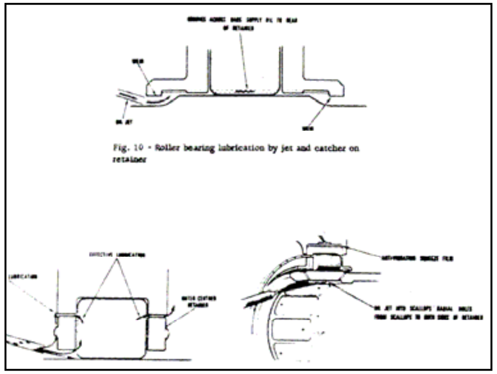
Mainshaft Bearings

Bearing Design Criteria:

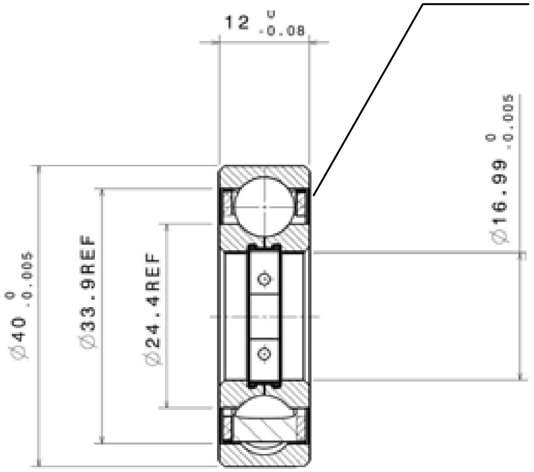
- •Operating Duty Cycle
- •High speed
- •High temperature
- •Gyroscopic loads
- •Skidding
- •Legacy mist lubrication



Cage Design Trade-off



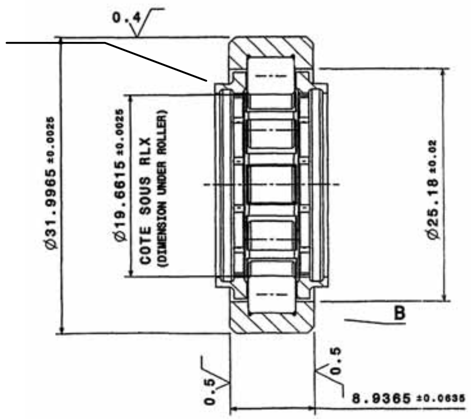
“Winglet Cage Concept (RR)



Outer Land Riding Cage

Final Ball Bearing Design

Inner Land Riding Cage



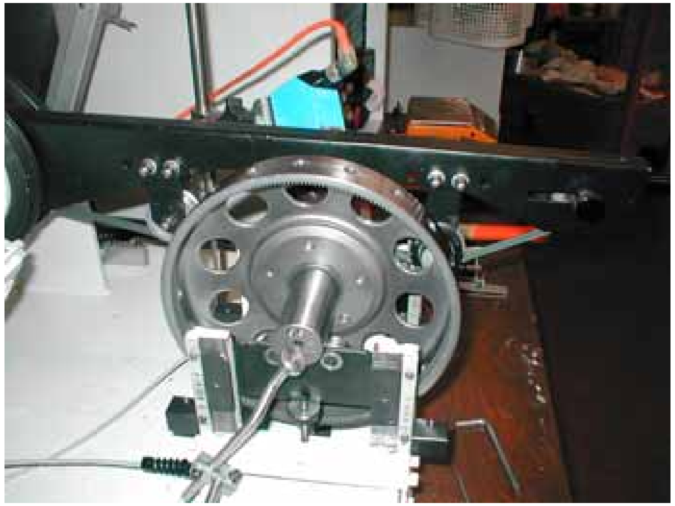
Final Roller Bearing Design

Dynamic Balancing

Lessons Learned:

1. Extremely careful design of balancing arbors and fixture
2. Suitable drive for spinning the rotors without generating parasitic vibrations
3. Rigid assembly balancing sequence involving individual parts balancing to Grade G2.5 or better according to ISO1940
4. Assembly centering checks and assembly balancing again to G2.5 or better

Rotor Assembly Balancing



Gear Balancing

Weight Reduction

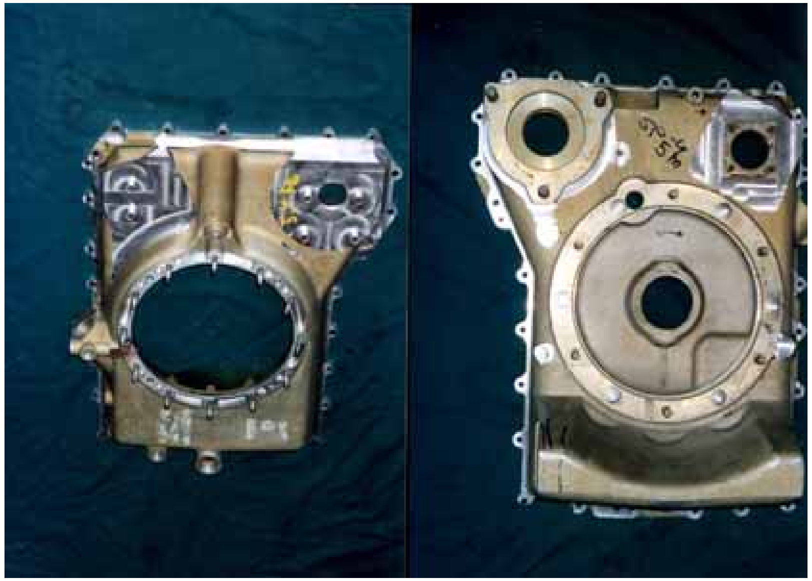
ACHIEVED WEIGHT SAVINGS		
COMPONENT	**Method**	**Weight Saving [Kg]**
Generator	Redesign	5.0
Electronic Engine Control	Redesign	1.2
Gear and bearings	Modification	3.2
Casings	Modification	2.7
TOTAL		**12.10**

PLANNED WEIGHT SAVINGS		
COMPONENT	**Method**	**Weight Saving [Kg]**
Casings	Redesign*	6.1
TOTAL		**18.30**

* Replace conventional cast aluminum with advanced Elektron 21 magnesium

Comparison between original and lightened gears

-3.2 Kg



Weight reduction of original casing

-2.7 Kg

Fuel Control

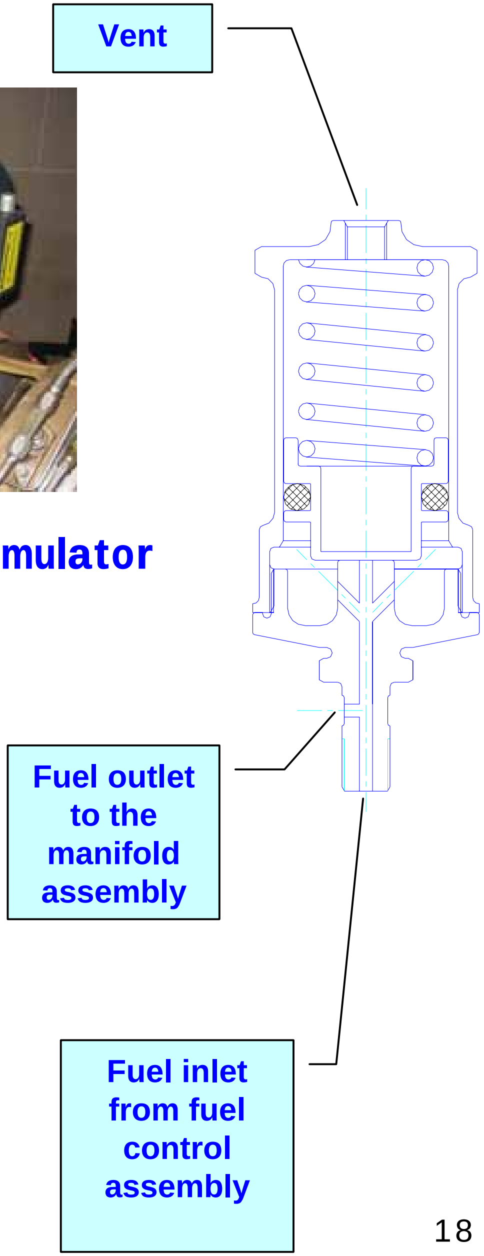
Purpose of the Fuel Accumulator:

1. Avoid engine shut down when passing from full power ("Flight", 100% rpm) to start ("Ground Idle", 30% rpm) by keeping pressurized the manifold circuit which otherwise would reduce sharply its pressure when the start circuit opens

2. Avoid engine shut down in case of engine overspeed (exceeding 115% rpm). In this case the fuel control would automatically select the start circuit to reduce speed. As before, this would reduce too rapidly the pressure in the main circuit with the risk of engine shutdown

3. Damp the power burst when passing from the starting mode to the full power mode

Fuel Accumulator



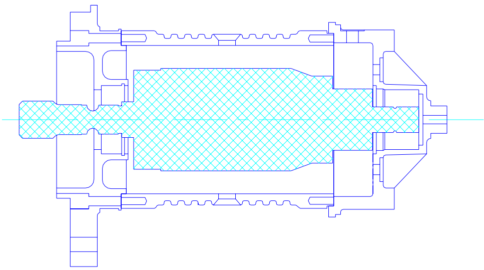
Electrical System

Original Starter

New EEC

Original EEC

New Starter Generator



Starter Generator

-5.0 Kg

Electronic Engine Control

- 1.2 Kg

The T61A Main Characteristics

CHARACTERISTICS	VALUE
Rated Speed	61091 rpm
Max. continuous power	90 hp
Maximum EGT @ MCP	915 °F
Take-Off power	130 hp
Maximum EGT @ TOP	1180 °F
Gearbox Output Speed	6000 rpm
Self Sustaining Speed	20%
Ground Idle Speed	30 %
Clutch Engagement Speed	50 %
Nominal Operating Speed	100%
Maximum Overspeed	115%
Weight (dry)	63 Kg
Fuel consumption at MCP, 60°F	62 L/h
SFC at MCP, 60°F	0.496 Kg/hp-hr

Full Scale Testing

Ground Testing ("Dyno" Rig):

•Vibration level check

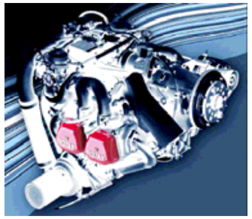
• Performance check

•Tuning

Flight Testing (Aviotecnica Prototype):

•300 hours on a single engine

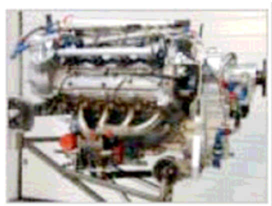
Comparison of Current Engines for UAV-VLR



Engine Model	T-61A	Rotax 914	Lycoming O-360
Type	Turbine	4 cylinders IC Turbocharged	4 cylinders IC
Fuel	Jet A1	Avgas or Unleaded	Avgas
Rated Power	130 hp	115 hp	180 hp
Torque Factor	1.25	2.00	2.00
Output Speed	6000 rpm	2300 rpm	2700 rpm
Weight (*)	63 kg	75 kg	118 kg
Fuel Consumption @ 75% P.	62 L/h	20.4 L/h	40 L/h
SFC @ 75% P.	0.458 Kg/h/hp	0.170 Kg/h/hp	0.213 Kg/h/hp

(*) To the turbine engine an additional reduction from 6000 rpm to about 2500 has to be added, but, on the other hand, to the reciprocating engine the cooling system (radiator, fan, water or fan and shrouds) has to be added, it is assumed that they are equivalent and therefore they cancel out in this comparison.
In addition the larger Torque Factor of reciprocating engines will have a “snowball” effect on power transmission and engine installation weights as well.

Comparison of Advanced Engines for UAV-VLR



Engine Model	T-61B	Thielert TAE-125
Type	Turbine	4 cylinders Diesel
Fuel	Jet A1	Jet A1
Rated Power	135 hp	135 hp
Torque Factor	1.25	2.00
Output Speed	6000 rpm	2300 rpm
Weight	57 kg *	135 kg
Fuel Consumption @ 75% P.	55 L/h	21.5 L/h
SFC @ 75% P.	0.391 Kg/h/hp	0.179 Kg/h/hp
TBO	2000 hrs	2400 hrs

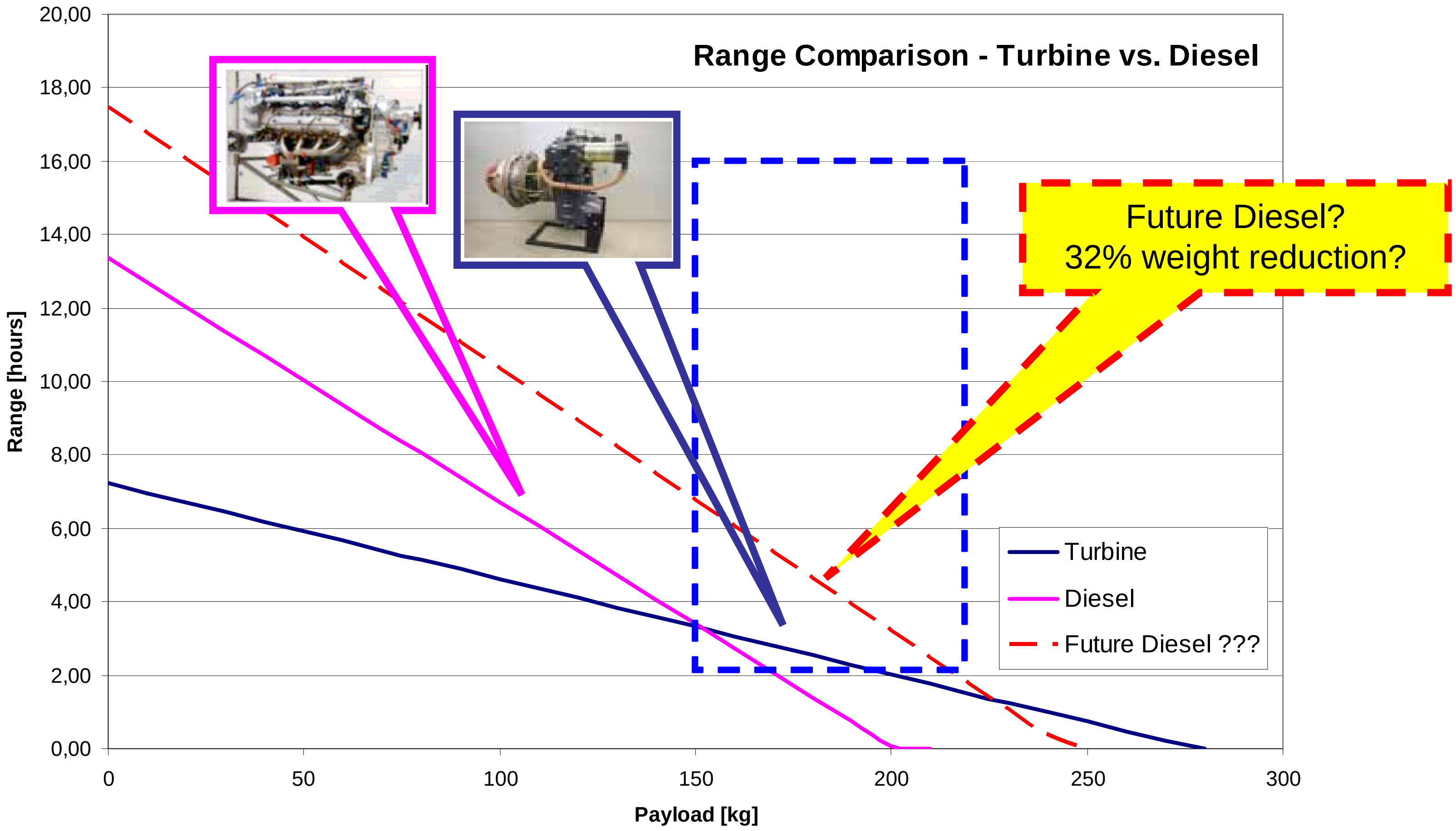
* Further 6.1 Kg of reduction by replacing the conventional cast aluminum casing material with advanced Elektron 21 magnesium

Comparison of UAV/VLR Rotorcraft Performance 1

Engine Model	T-61B	Diesel
Rated Power	135 hp	135 hp
Engine Weight	57 Kg	134 Kg
UAV Gross Weight	630 Kg	630 Kg
Fuel Weight	98 Kg	21 Kg
Fuel Volume	136 L	29 L
UAV Empty Weight *	295 Kg	295 Kg
UAV Payload	180 Kg	180 Kg
UAV Range	2.5 Hrs	1.2 Hrs

* Engine weight excluded

Comparison of UAV/VLR Rotorcraft Performance 2



Conclusions 1

It was demonstrated that a small gas turbine is suitable for very light airborne applications providing:

- Affordable costs
- High reliability
- Mechanical simplicity
- Easier and lighter cooling
- Low vibration level (no reciprocating masses)
- Steady torque (low torque modulation factor)
- Fast response/controllability to pilot inputs
- High power to weight ratios
- Readily available fuels

Conclusions 2

It was concluded by the authors that available diesel engines are not suitable for powering very light rotorcraft mainly due to their weight.

Probably, to make them suitable (a 30% weight reduction should be the minimum target), the following improvements should be introduced to an advanced future diesel:

- Avoid automotive engine derivative: engine must be designed for airborne use from scratch
- Adopt more advanced materials such as composites, titanium and ceramics
- Adopt advanced vibration reduction concepts
- Evaluate advanced concepts:
  - 2 strokes vs. 4 strokes
  - Turbocompound vs. turbocharging

Future Work

To further extend the applicability of small gast turbine to very light (manned or un-manned) rotorcrafts it is believed that additional work in the following areas has to be done:

- New turbomachinery (in particular the compressor-diffuser) with improved aerodynamics to increase efficiency
- High temperature material such as MAR-M247 for the turbine impeller
- Improved internal air sealing (replacement of labyrinth with brush seals)
- Optimized air intake and exhaust system
- Digital engine control
- Gearbox casing in magnesium to reduce weight by about 6 kg
- New mainshaft to increase strength and fatigue life
- Introduction of squeeze film damper for the roller bearing to reduce the vibrations, in particular during the critical speed crossing


Questions ?