Magnetic Bearings for Smart Aero Engines

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Abstract

It is estimated that approximately 3 million flights occur in Europe each year with a total fuel consumption of some 30 million tonnes of kerosene. Furthermore, in the face of increasing demand from business users and the general public, air transport is currently experiencing, and is expected to maintain for the foreseeable future, annual growth rates of over 5%. Future aircraft gas turbine engines must therefore provide increasing cycle performance, with increased reliability but at reduced weight in order to minimise both fuel consumption and emissions. Among the various initiatives which seek to achieve these goals, a number of particularly innovative technologies are explored, one of which - the Smart Aero-engine - is the topic of the MAGFLY project.

The main objectives of the research project MAGFLY was the development of a technology for Smart Aero-Engines based on the use of Active Magnetic Bearings (AMBs). These 'mechatronic' bearings offer considerable potential benefits:

- to reduce the engine's weight;
- to lower the friction losses;
- to avoid wear in the bearings;
- to eliminate lubricating oil systems;
- to reduce emissions;
- to reduce fire hazards and
- to increase the operating speeds and performance as well.

Furthermore, these bearings make it possible to control the engine's mechanical behaviour with respect to vibrations, noise, and fatigue-inducing stresses and last, but not least, the inherent Smart Machine Technology (SMT) allows improved monitoring, diagnosis, prognosis and correction capabilities based on extended software developments.

AMBs are already used successfully in machine tool spindles, medium-size turbo machines and other rotating machinery applications.

In the first year of working the main focus was to develop designs and design rules for load sharing bearings and high temperature magnetic bearings. In parallel the modifications and designing of test rigs were carried out, respectively.

These developments and information regarding load share bearings and magnetic bearings were used to establish new and modified methods and software to build up a whole system model and a whole system design environment to run numerical calculations. Finally the manufacturing of the test rigs was started and the tests were initiated.

The MAGFLY project has been very successful in bringing together the leading members of Europe's turbomachinery and AMB technology research community, assembled from universities, national research establishment and industry. This unique composition made it possible to make best use of the various strengths assembled within the project group, so that through the co-ordinated experimental, analytical and numerical effort and investigation it was possible to achieve the ambitious goals of the MAGFLY project

A number of setbacks occurred in the course of the project, mostly related to failures in the experimental equipment. These technical issues being typical for advanced research and test activities were resolved by the respective partners with speed and initiative supported by the flexibility of the consortium to rearrange the project schedule.

In this context, the flexibility of the scientific officer on behalf of the European Commission in granting an extension to the project life span is much appreciated since it eventually allowed the consortium to achieve all relevant objectives.

The table below shows the target, the progress and status of the MagFly project.

< Summary from the Final Technical report see [1]>

	TARGET	Status at	Progress in MAGFLY	Status at	Priority Developments
		2001	2001-06	2006	2007 on
1 Stop-or-Go criteria (to meet specified minimum levels)					
1.1 Temperature Range	Development and validation of high temperature active magnetic bearing		Selection of coil and core material of high temperature AMBs; Realization and validation of five axis AMB running at high temperatures.	Characteristics of high temperature material validated; first five-axis AMB running at over 500° celsius	Improvement of fill-factor and production process of high temperature AMBs
	AMB running permanently in a temperature range up to 200°C	Actual: due to oil supply and cooling the max temperature in the bearing chambers are limited to below 185°C (oil cooking, oil fire etc)		Target fulfilled. AMBs even running up to 550°C for more than 600 h.	Increasing the life of high temperature rigs the heat insulation of hot bearing chambers can be reduced (weight reduction)
1.2 Backup Bearing	Develop combined load share and emergency mechanical bearing, improve design prediction, establish high temp capability	Experience only in relation to emergency bearing. Temperature limit of 200 deg C. Basic analysis only	Developed new analysis methods, established materials capable of reaching 500 deg C, established concept for load sharing and emergency operation		To feedback data from rigs to confirm analysis results, to further test behaviour of combined load and emergency concept.
	Oil-free, mechanical bearing (i) to cover loss of AMB (ii) to load share with AMBs at high amplitudes		Develop simulation tools for BackupBrg; develop test rig to evaluate; design, build and test prototype	Effective macro model available for Backupbrg dynamic behaviour	More detailed model to describe internal Backup brg behaviour.
	Capability to define mechanical parameters of bearings and support assuring acceptable rotor behaviour during backup bearing contact, optimal controllers for load sharing	Practical experience available, not much knowledge on properties of corrugated ribbons, some strategies for load sharing controller	Modelling and measurement procedures for soft mount elements for backup bearings, new control strategies for load sharing	FE model of corrugated ribbons for computing stiffness (not fully validated), influence of mechanical parameters defined by simulation, impact controller (not validated on project test rigs)	Validation of controller concepts on test rig representing an aero engine, experimental assessment of spring-damper elements
	Important to have reliable backup bearings		Develop nonlinear modelling capability to include backupbrg in whole engine model	Prediciton capability for assembly with backupbrg included. Partially validated	Further development of models/predictions and validation in complete test rig
1.3 Heavy Landing Capacity	AMB capable to carry at least 1 g load due to unexpected manoeuvres, heavy landing in combination with load share bearings (short time)		Design of AMBs to carry 1g load	Demonstration using virtual test rigs of the ability to predict performance under normal and abnormal operation	Increasing the capability of AMBs to higher g-loads (short time) by use of load-sharing bearings
1.4 Control for flexible rotor and flexible support structure	AMB controller able to handle flexible support structure	No experience		Ability to pass through resonance range with feed forward control, above resonances FFC minimises vibration	AMB controller: Combination of flexible rotor and flexible support structure
	Capability to design and implement (model based) controllers enabling the passing through flexible support modes	No experience	Controller design on the machine (measurement based, not model based)	Passing through at least three flexible support modes shown on project test rig	Use developed models to design controllers, validation of controllers
	Capability to define support flexibility, and controllers to accommodate	No experience	Modelling procedure to include support flexibility in whole machine model; test rig to validate models	Modelling method developed; test rig constructed but not extensively used; validation not completed	Complete series of validation tests on Rig 5.2; develop flexibility classification procedure; validate controller performance
2 Tradeable Criteria (to be optimised/maximised)					
2.1 Weight	MINIMISE				
2.2 Reliability	MAXIMISE				
2.3 Efficiency	MAXIMISE				
2.4 Life	MAXIMISE				
2.5 SMART capabilities	Capability to diagnose the state of the rotating part, interrogate the state of the rotating parts with the magnetic bearings				
	Efficient use of AMBs, take advantages of all additional benefits (by-products)	System observation (crack detection)	on-line balancing tool, data collection and exchange possibilities	on-line balancing tool and data collection and exchange possibilities are developed and tested	further increase of system efficiency
2.6 Cost	MINIMISE				
2.7 Maintainability	MAXIMISE				
2.8 Force Capability	MAXIMISE				
2.9 Noise	MINIMISE				

The Partners

Objectives of the project

The key (socio-economic) objective of this project has been to strengthen the competitiveness of the European aero engine industry by ensuring sustainable market growth under consideration of environmental and safety issues. Future aircraft gas turbine engines must provide increasing cycle performance at reduced weight in order to minimise fuel consumption and consequently reduce emissions of greenhouse gases.

Today's aero-engines are designed with mechanical bearing systems, which consist of ball or roller bearings, often supported by squeeze film dampers. All over the world, but particularly in the United States and in Europe, there is a drive towards greater efficiency with the *'More Electric Aircraft'* and *'More Electric Engines'* programmes and the prognosis is that future aero-engines will increasingly incorporate mechatronic systems.

One of the steps in this direction is to substitute the current mechanical bearing system by **Active Magnetic Bearings** (AMBs). This substitution offers the prospect of several advantages, specifically:

- more compact and efficient engine design;
- significant reduction in weight;
- lower friction losses, and hence increased efficiency;
- ultra-low wear in the bearings;
- reduced fire hazard (no oil in the engine);
- longer maintenance intervals;
- lower direct operating and lifetime costs;
- higher speeds and performance;
- control and reduction of vibrations, noise and stresses;
- improved monitoring, diagnosis, prognosis and correction capabilities in the sense of SMART Machine Technology (**SMART** is used here in its original context of: **S**elf-**M**onitoring, **A**nalysis and **R**eporting **T**echnology)

Active Magnetic Bearings, supporting a rotor without any contact by using actively controlled magnetic field forces, have already been in use in a number of industrial areas, e.g. in stationary turbo-machinery (compressors, expanders, small gas turbines and pumps), in machine tool spindles (milling and grinding spindles) and other fields of application (centrifuges, flywheels, rotors in ultra-high vacuum).

The MAGFLY project designed AMBs for aero-engines, developed load-sharing bearings and the design and demonstration of AMBs for high-temperature environments, up to 600^{o} C. The integrated dynamic modelling of the rotor, AMBs, load-sharing bearings, support housing and casing, enable the designer to optimise the AMB size and performance. The modelling tools are finally packaged in a user-friendly format for industrial design assessment.

In addition to these mechanical developments, the project explored the use of AMBs as diagnostic tools which offers new possibilities for future aero-engine design based on SMART machine technology.

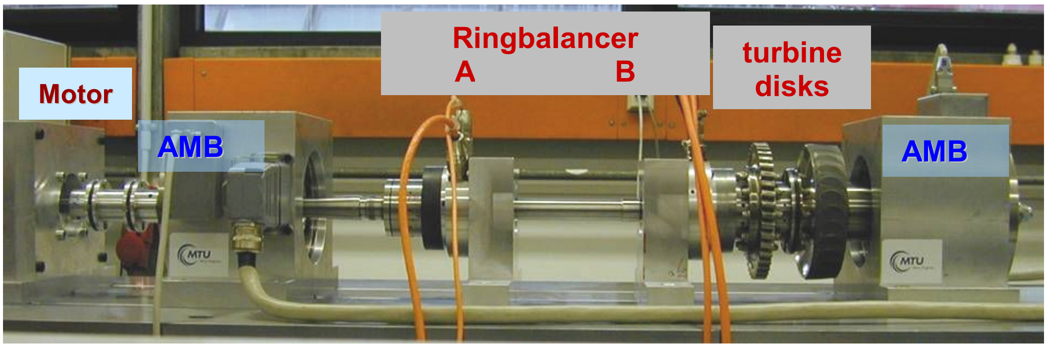
Scientific and Technical Description of the Results

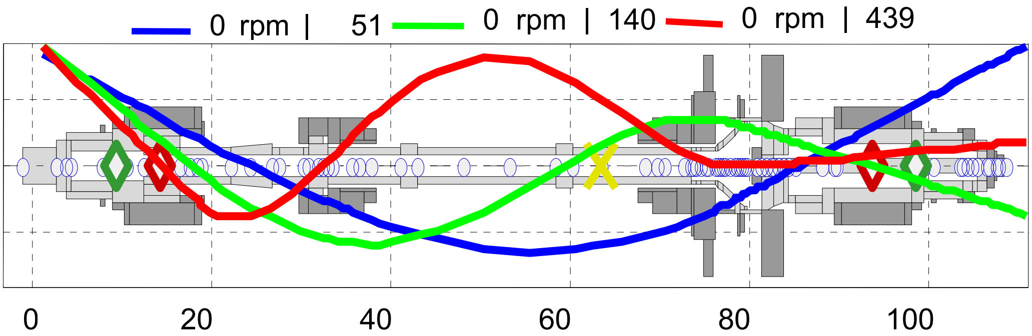
The central thrust of this research project was to secure the future development possibilities of SMART aero-engines with active magnetic bearings. In order to realise such complex and highly sophisticated mechatronic systems as will be required to achieve this goal, different problems have to be solved by means of extensive research work.
First of all, a ***new generation of Active Magnetic Bearing*** were designed for this high-tech application: **WP1**. This process includes the design of a load-sharing bearing. Besides the magnetic bearing itself each bearing needs an auxiliary bearing (usually a roller bearing), in order to support the rotor in an emergency case (failure of an AMB) and during standstill. However, the additional auxiliary bearing should also support the magnetic bearing in overload conditions, e.g. in the case of heavy landings, high-speed manoeuvres and unbalanced blade conditions (transient conditions). Numerical and experimental tools are available for evaluating the design of potential load-sharing bearings. They have been developed in a former EU-project [2, 3] by ICSTM and TUD. As an additional result the geometric dimensions of the AMB bearing are provided.

If the AMBs can operate at higher temperatures than conventional designs, they can be placed much closer in to the hot regions of the engine, resulting in greater freedom in the overall architecture of the engine. Therefore, another objective of this first workpackage is to design an AMB with high-temperature resistant materials with an emphasis on cost and volume reduction, long-term performance and controllability. A high-temperature rig is available for this investigation, also from a previous EU project. [2]

Workpackage WP2 deals with the ***Whole System Modelling***. The development of an overall model for the SMART aero-engine with AMBs is a basic requirement for an optimal design of the whole mechatronic system. This model, usually based on Finite Elements, has to include all major mechanical components: casing, bearing supports, auxiliary bearings and the rotor with respect to their dynamic behaviour. In addition, for a complete model, the mechatronic components like actuators (magnetic bearings), amplifiers and sensors must also be included. Finally, the "intelligent" part of the system - a digital controller with refined control laws which is responsible for the stability and performance of the mechatronic system – must also be incorporated. This controller integrates the different components into an optimised control circuit. The complete modelling procedure has to be made available as a user-friendly, fast and reliable modelling tool for commercial applications in the field of aero-engine design using mechatronic components.

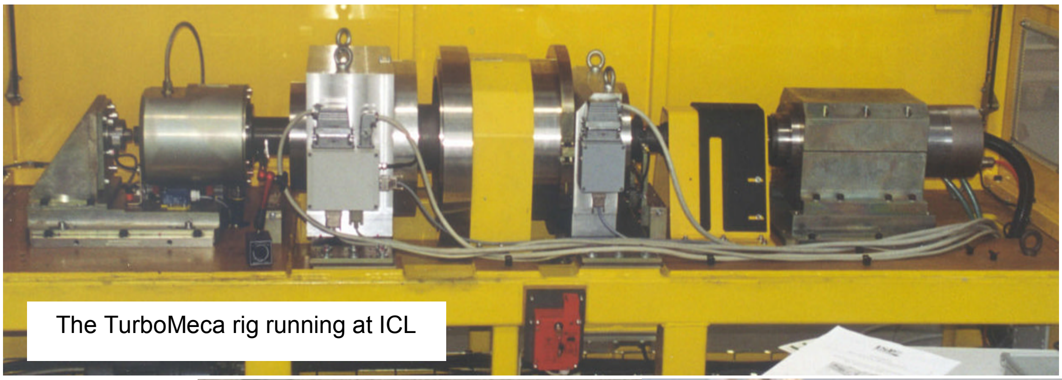
The ***Whole Engine Mechanical and Electrical Design*** was treated in **workpackage WP3**. The modelling tools from WP2 are used for this task in order to simulate the whole system and to evaluate the dynamic behaviour with respect to performance, control, stability, vibration, noise, stresses and life expectancy. Based on these simulation results, a design optimisation is performed with respect to a robust



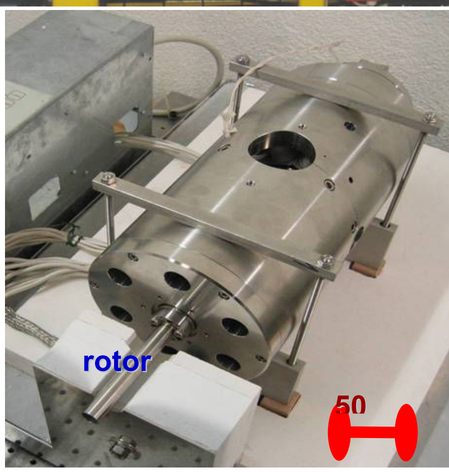


Rig 1 (MTU) running at TU Darmstadt

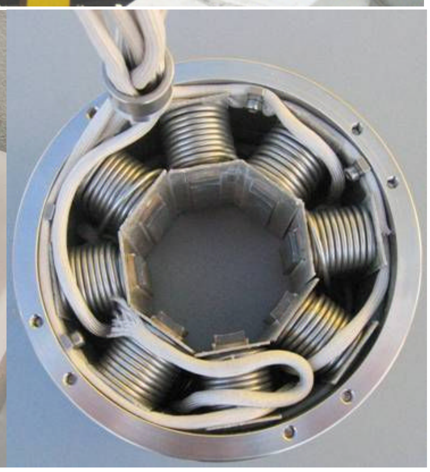
Mode Shapes (calculated, free-free)



The TurboMeca rig running at ICL



High-temperature rig running EPFL, the walls of the furnace are dismounted



high temperature magnetic bearing

design and reduced damage sensitivity (damage tolerant system). Besides the mechanical robustness, all the mechatronic components have to be included. These are important for the engines function and performance, on the one hand, and for the smart features of the aero-engines, treated in WP4, on the other.

The primary aim of **workpackage WP4** was the development of a ***SMART Machine Technology for Aero-engines***, which guarantees an optimal engine condition with respect to higher performance and comfort (efficiency, vibration and noise) and higher reliability (reaction to failures, robust operation, long maintenance intervals).

The basic concept of an aero-engine with magnetic bearings offers already a variety of advantages compared with conventional engines: detailed observation of the process by integrated sensors, data processing and on-line control via a microprocessor. However, there is much more potential in a fully mechatronic system and further technical and economical benefits for the process can be achieved with respect to higher performance, comfort and reliability, if more intelligence could be added to the aero-engine system by well suited software and hardware components. Although the project is not intended to implement all of the above mentioned goals and to achieve a full mechatronic system, it will certainly make a significant advance towards this goal.

Workpackage WP5 was concentrated on ***Test Rig Demonstrations*** of the various developments from WP1-4. Two complete-system test rigs are run in TUD's and ICSTM's labs. The operation of the rotating systems in Active Magnetic Bearings was tested with respect to the dynamic systems behaviour. The rigs will be equipped with all mechatronic hardware components (actuators, sensors, amplifiers) and connected to the Smart Machine Management system, also the monitoring, diagnosis, prognosis and correction features are investigated. The hot rig was running at EPFL.

Results and Conclusions

The MagFly project has completed all of its contractual objectives, deliverables and milestones. The continued initiative and dedication of the project partners have reached significant advances in the understanding of active magnetic bearings in engine like rigs. The interaction of high quality experimental work with advanced research on active magnetic bearings in combination with rotordynamics, supported by the experience and feed-back from the industrial partners, has led to an extremely fruitful collaboration amongst the project partners.

During initial commissioning of rig 2 at the company ISP in France an unexpected crash happened and the rig experienced severe damaged. An extension of in total 15 month was thus requested and consequently granted by the European Commission through the Scientific Officer. Within this extended time frame, it was possible to rebuild rig 2 and to conclude the planned experiments.

In the above table the targets of the MagFly project are listed and compared with the status at the start of the project, the progress during the life time of the project and the status at the end of the project.

It is distinguished between "stop-or-go" and tradeable criteria.

Areas of application of active magnetic bearings including the SMART-technology are industrial gas turbines, gas turbines in ships, and each kind of test rigs.
The application to aero engines needs further basic generic research. Entry into service will be in a decade or even beyond.

In summary, the MagFly project has been successful in the achievement of its goals and objectives.

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