SIXTH FRAMEWORK PROGRAMME
PRIORITY [4]
[AERONAUTICS & SPACE]

Contract for:

SPECIFIC TARGETED RESEARCH OR INNOVATION PROJECT

FINAL PROJECT REPORT

CONTRACT N° : 030889

PROJECT N° : AST5-CT-2006-030889

ACRONYM : PREMECCY

TITLE : Predictive Methods for Combined Cycle Fatigue in Gas Turbine Blades

PROJECT CO-ORDINATOR : Rolls-Royce plc, UK

PARTNERS :

RRD	Rolls-Royce Deutschland Ltd & Co KG	Germany
ITP	Industria De Turbo Propulsores S.A	Spain
TM	Turbomeca	France
SN	Snecma	France
Avio	Avio S.P.A	Italy
MTU	MTU Aero Engines GmbH	Germany
SIE-UK	Seimens Industrial Turbomachinery Ltd	UK
VAC	Volvo Aero Corporation	Sweden
TECNALIA	Fundacion Tecnalia Research & Innovation	Spain
TUD	Technische Universitat Dresden	Germany
ARMINES	Association pour la Recherche et le Developpement des Methodes et Processus Industriels	France
CRSA	Centrale Recherche S.A.	France
IPM	Institute of Physics of Materials, Academy of Sciences of the Czech Republic	Czech Republic
PoliMi	Politechnico di Milano	Italy

PROJECT START DATE 1st June 2006

DURATION 66 Months

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Project Summary

Introduction

The modern gas turbine is a complex machine, the design and development of which takes many months and costs millions of Euros. The European gas turbine manufacturing industry is under pressure to minimise the resources required to bring a new design to market, due to global competitive pressure and increasing customer expectations.

Accurate design and prediction tools are key to success in this process. The PREMECCY project identifies the field of rotor blade Combined Cycle Fatigue (CCF) as an area where there are shortcomings in the existing industry standard design and prediction tools, and thus where significant benefits can be achieved. Rotor blade CCF accounts for up to 40% of the total number of issues that arise during an engine development programme and a similar proportion of in-service problems.

The primary objective of the PREMECCY project is to develop new and improved CCF prediction methods for use in the design process. These will reduce the number of development and in-service CCF problems thereby reducing the time and cost required to develop a new engine and reducing the operating costs once in service. They will also enable the design of lighter, more efficient blades, reducing engine SFC.

In order to develop the new prediction methods the project has generated high quality material test data. Advanced specimens and testing methods that are mechanically, geometrically and environmentally representative of operating conditions have been used to support the verification activities.

Partners Involved

The PREMECCY project is made up of a consortium of fifteen partners, including nine major European gas turbine manufacturers, one specialist SME and five world-class research facilities. The complimentary expertise and experience of the consortium represents an optimised resource with which to achieve the project's challenging objectives. The partners include:

1	Rolls-Royce plc (Coordinator)	RR
2	Rolls-Royce Deutschland Ltd & Co KG	RRD
3	Industria de Turbo Propulsores, S.A.	ITP
4	Turbomeca	TM
5	Snecma	SN
6	Avio S.p.A.	AVIO
7	MTU Aero Engines GmbH	MTU
8	Siemens Industrial Turbines	SIE-UK
9	Volvo Aero Corporation	VAC
10	Fundacion Tecnalia Research & Innovation	TECNALIA
11	Technische Universität Dresden	TUD
12	Association pour la Recherche et le Dévelopement des Méthodes et Processus Industriels	ARMINES
13	Centrale Recherche S.A.	CRSA
14	Institute of Physics of Materials, Academy of Sciences of the Czech Republic	IPM
15	Politecnico di Milano	PoliMi

Project Objectives

Gas turbine rotor blades are subjected to very high levels of stress and temperature during each engine operating cycle. Superimposed upon this quasi-steady state condition, the blades also endure vibrational stresses induced by the local perturbations in gas pressure through which they travel. These vibration levels tend to be most pronounced when a blade or rotor natural frequency coincides with an excitation frequency thus leading to resonance. From a purely mechanical point of view, it is therefore desirable to design rotating components and engine architecture so that such resonances do not occur within the operating speed range of the engine. However, the reality is that such a goal is impossible without massive compromise to other aspects of the engine design and hence its operability. Thus modern gas turbine blades are designed to withstand, rather than avoid, the stresses generated in a resonant condition during normal operation.

The assurance of adequate High Cycle Fatigue (HCF) margin of a rotor blade is a critical part of the overall design process. Moreover, it is important to ensure that the blade integrity and life remain acceptable when the influence of HCF is superimposed onto other damage mechanisms such as Low Cycle Fatigue (LCF) and creep that are inevitable in the gas turbine environment. This superposition of HCF with other damage mechanisms is generically termed Combined Cycle Fatigue (CCF).

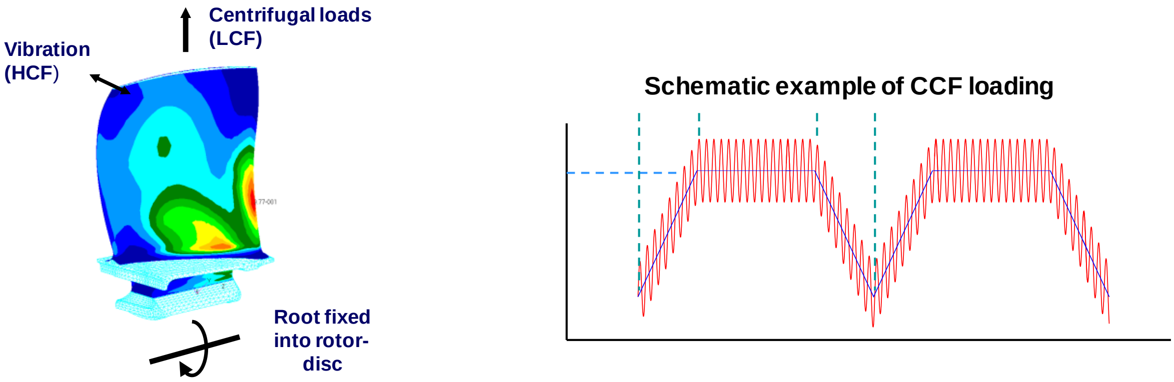

Figure 1 – a) Schematic view showing Vibratory and Centrifugal Loads acting on a rotor blade (left) b) Schematic example of CCF loading (right)

The current industry standard assessment of HCF integrity at the component design stage is based on the Goodman or modified Goodman (range-mean) approach. Specimens are tested at a range of min:max load ratios (known as R ratios) to produce a Goodman or range-mean diagram which shows the material capability in terms of any combination of alternating stress and steady stress.

A standard load range-mean diagram is generated by uniaxial testing, that is to say, both the alternating and steady load applied are aligned with the specimen axis. Thus the specimen is not tested in a true vibrational mode but through the application of a controlled off-resonant cyclic load. This type of testing is not truly representative of the resonant condition the component. This is because, at resonance, the alternating stresses are related to the response of the mode-shape and thus tend to be complex in distribution. In addition to these shortcomings, the industrial design process tends to assess the effect of HCF in isolation from other damage mechanisms that occur during operation. Most approaches neglect any other damage directly, utilising an empirically derived safety margin to ensure integrity. The blades designed this way are sufficiently robust; however, using this approach there is ample possibility that the blades are over-designed relative to their operational requirements.

The primary objective of the PREMECCY project is to understand the impact of LCF on HCF strength and develop new and improved CCF prediction methods for use in the design process. In order to facilitate the generation of improved prediction methods, the project has generated high quality material test data. Advanced specimens and testing methods that are mechanically, geometrically and environmentally representative of operating conditions have been used to support the verification activities.

Project Execution

The fundamental aim of the PREMECCY project is to deliver new and improved Combined Cycle Fatigue prediction tools for use in the industrial design of Gas Turbine blades. This has been performed through a programme of material characterisation and advanced specimen testing that represents a technological step forwards in its own right in conjunction with advanced development of life prediction methods. The project is divided into seven distinct Work Packages (WP), including:

- WP1: Specimen design
- WP2: Specimen procurement
- WP3: Material testing and characterisation on conventional specimens
- WP4: Advanced specimen testing
- WP5: Lifing and predictive methods development
- WP6: Dissemination and exploitation
- WP7: Project management

Conventional Specimen Testing

A comprehensive program of conventional specimen tests has been performed to characterise the behaviour of the three gas-turbine materials under investigation: TI6242, IN713LC and CMSX-4. More than 800 conventional specimens have been tested as part of this project.

The results from the conventional specimen testing have directly supported the development of new lifing methods as part of WP5.

Advanced Specimen Design, Test Commissioning and Execution

Advanced blade-like specimens in all three materials have undergone a detailed design and analysis process. The objective was to test blade-like specimens at conditions closer to gas turbine blade operating conditions. It was therefore necessary to design specimens with a critical zone representative of typical blade geometries and test them on-resonance, at a frequency close to engine order resonant crossings and at temperatures representative of in-engine working conditions.

In a CCF rig the alternating load is generated by resonating the specimen through an independent exciter mounted perpendicular to the specimen major axis. The steady tensile load is applied in the usual way. Figure 2 shows a schematic view of a CCF rig and Figure 3 shows one of the CCF rigs developed as part of PREMECCY.

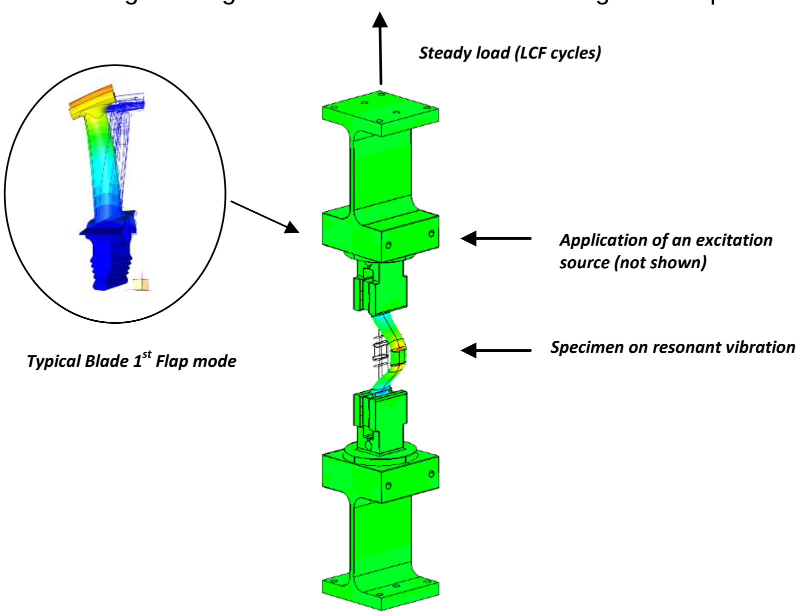

Figure 2 - Schematic view showing a blade-like specimen test (right) simulating a rotor blade under resonant vibration of its first flexural mode (left)

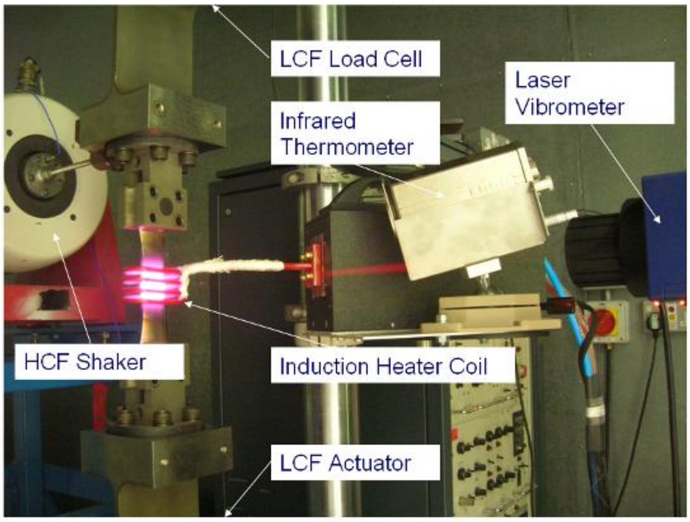

Figure 3 – Combined Cycle Fatigue rig

The test rig validation activities included static and dynamic calibration and thermal profiling. Figures 4 and 5 illustrate some of the calibration activities carried over during the project.

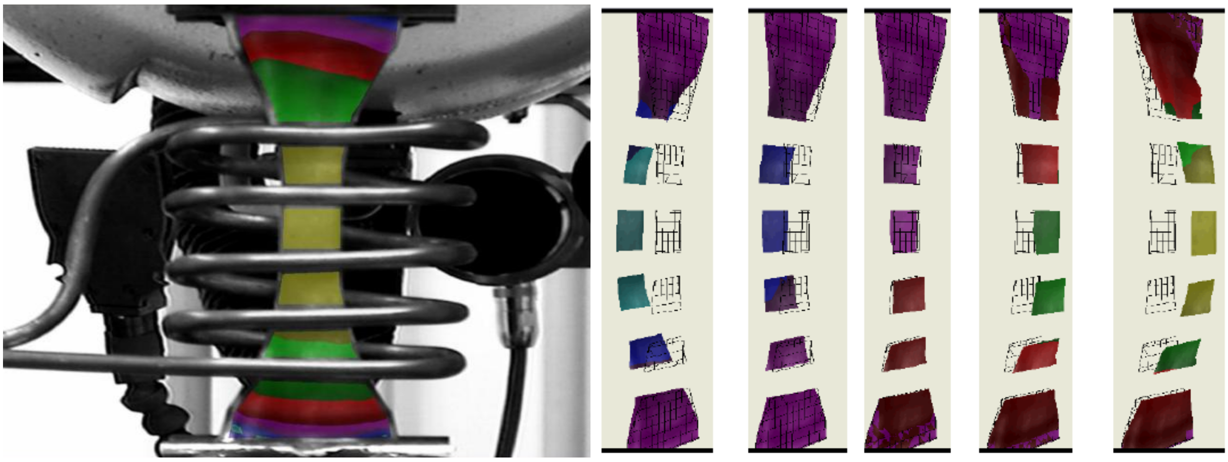

Figure 4 - Qualitative plots of the mode shape tested in one of the CCF rigs

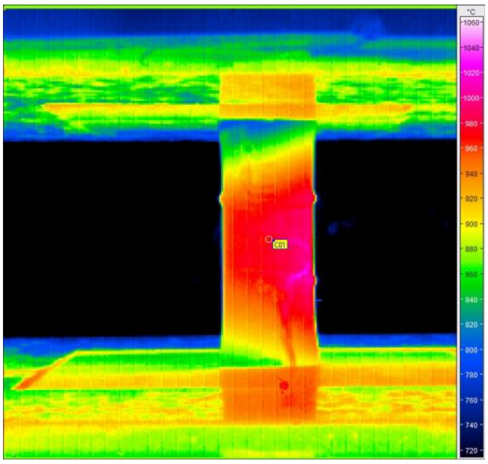

Figure 5 - Thermographical picture obtained from the hot gas CCF rig

The commissioning of the advanced CCF test rigs and validation of testing conditions, presented a great number of challenges. However, the quality of the test data was extremely satisfactory, capturing phenomena affecting the behaviour of conventional lab specimens differently to real engine components (e.g. frequency effects).

The CCF test results of various test series show that the HCF fatigue strength can be reduced due to superimposed LCF cycles.

Development of Lifing and Prediction Methods

The scope of the methods developed as part of PREMECCY range from improved engineering lifing methods based on linear elastic calculations up to advanced simulation techniques considering deformation modelling techniques, such as Chaboche and Chailetaud modelling, or time homogenization methods for superposing HCF and LCF.

The prediction methods based on simple engineering approaches (linear elastic calculations) are based on the results obtained from the conventional testing. These testing results are the basis for the life assessment of real engine components, which can be quite complex in geometry and loading conditions, with three dimensional stress/strain distributions.

In the case of PREMECCY, with regard to the simple engineering approaches, the results obtained from the conventional testing were immediately used to define the loading conditions for the advanced specimen testing. As a project result, the prediction based on the results from conventional testing, did underestimate the strength of the advanced specimens. This shows that the simple engineering methods can be conservative and can potentially lead to overdesigned components.

The prediction methods based on the moderate approaches including nonlinearities are more able to consider additional effects. Models based on fracture mechanics do allow a qualitative description of the material behaviour for CCF, including the influence of LCF cycles.

Promising results from the academic methods can be shown for simple components such as lab specimens, but the application for a real engine component, including validation and certification, is still challenging. This is the character of a research project and the academic approaches highlight to the industrial partners what should be further investigated and what the requirements are to make these methods and simulation techniques applicable for daily use.

Use and impact

The PREMECCY project has characterised the behaviour of three gas turbine alloys under Combined Cycle Fatigue loading conditions, which has advanced the knowledge of the material behaviour in operational conditions representative of a gas turbine engine.

The CCF test results of various test series indicate that under certain conditions the HCF fatigue strength can be reduced due to superimposed LCF cycles. The advanced test results generated within PREMECCY provide a good basis to estimate the CCF effect for various materials and test conditions. This will provide an immediate benefit to the industry.

The PREMECCY project has provided industrial partners with access to state of the art methodologies, closer to the physics of the material behaviour and which do show the potentials for future life cycle assessment methods. Promising results can be shown for simple components such as lab specimens, but the application for a real engine component, including validation and certification, is still challenging.

In addition to this, a large number of publications have been developed as part of the PREMECCY project, contributing to the dissemination of the knowledge gained during the project. For detailed information on the results obtained as part of PREMECCY, it is recommended to consult the publications provided in the following section.

Dissemination

Within the time frame of the PREMECCY project, PoliMI organised the 11th International Conference on the Mechanical Behaviour of Materials (Como, Italy, 5-9 June 2011). This is one of the oldest conference series in the mechanics of materials field having taken place regularly every 4 years since its first edition in 1971 held in Kyoto, Japan).

During this conference, a special session dedicated to the topic “Combined High- and Low-Cycle Fatigue” took place (Tuesday 6 June 2011, session chair: M. Filippini – Politecnico di Milano), during which partners presented their research work carried out within the PREMECCY project, greatly enhancing the visibility of the PREMECCY consortium within the international scientific community.

A list of these publications generated as part of the PREMECCY project is provided next:

1. *Effect of combined cycle fatigue on Ti6242 fatigue strength.* L.Mendia; Estensoro, F.J.; Mary, C.; Vogel, F. Procedia Engineering vol. 10 2011. p. 1809-1814. DOI: 10.1016 /j.proeng.2011.04.301. ISSN: 1877-7058.
2. Weser, Swen; Gampe, Uwe; Raddatz, Mario; Parchem, Roland; Lukas, Petr. *Advanced Experimental and Analytical Investigations on Combined Cycle Fatigue (CCF) of Conventional Cast and Single-Crystal Gas Turbine Blades.* Vancouver: 2011. ASME Turbo Expo 2011. paper GT2011-45171.
3. Thiele, Marcus; Weser, Swen; Gampe, Uwe; Parchem, Roland; Forest, Samuel *Advancement of Experimental Methods and Cailletaud Material Model for Life Prediction of Gas Turbine Blades exposed to Combined Cycle Fatigue.* Copenhagen: 2012. ASME Turbo Expo 2012. paper GT2012-68452.
4. O. Aslan, S. Forest, *Crack growth modelling in single crystals based on higher order continua,* Computational Materials Science, vol. 45, pp. 756--761, 2009. doi:10.1016/j.commatsci.2008.09.016
5. O. Aslan, S. Quilici and S. Forest, *Numerical Modeling of Fatigue Crack Growth in Single Crystals Based on Microdamage Theory* , International Journal of Damage Mechanics, vol. 20, pp. 681-705, 2011. doi:10.1177/1056789510395738
6. O. Aslan, N.M. Cordero, A. Gaubert, S. Forest, *Micromorphic approach to single crystal plasticity and damage* , International Journal of Engineering Science, vol. 49, pp. 1311--1325, 2011. doi:10.1016/j.ijengsci.2011.03.008
7. Forest, S. and Aslan, O., *Microdamage modelling of crack propagation in single crystals, Multiscale effects in fatigue of metals*, Euromech Colloquium 505, Paris, France, July 7--9 2010, edited by E. Charkaluk and A. Constantinescu, Springer, 2011.
8. O. Aslan, S. Forest, *The micromorphic versus phase field approach to gradient plasticity and damage with application to cracking in metal single crystals*. In Multiscale Methods in Computational Mechanics, edited by René de Borst and Ekkehard Ramm, Lecture Notes in Applied and Computational Mechanics 55, Springer, pp. 135-154, 2011.
9. D. Aubry and G. Puel, *CCF modelling with use of a two-timescale homogenization model*, Fatigue 2010 - International Fatigue Conference, Procedia Engineering, 2, p. 787-796, 2010.
10. D. Aubry and G. Puel, *Two-timescale homogenization method for the modeling of material fatigue*, WCCM9 - 9th World Congress on Computational Mechanics, IOP Conference Series: Materials Science and Engineering, 10, 012113, 2010.
11. G. Puel and D. Aubry, *Méthode d'homogénéisation temporelle : application à la simulation numérique de la fatigue*, 10e Colloque National en Calcul des Structures, 2011.
12. G. Puel and D. Aubry, *Time-homogenization method: application to fatigue*, ENOC 2011 - 7th European Nonlinear Dynamics Conference, 2011.
13. G. Puel and D. Aubry, *Material fatigue simulation using a periodic time homogenization method*, European Journal of Computational Mechanics, 2012 (to appear).
14. Filippini, M., 2011. “Notched *Fatigue Strength of Single Crystals at High Temperature*.” Procedia Engineering, Vol. 10: pp. 3787–3792. doi:10.1016/j.proeng.2011.04.618

15. Filippini, M., 2011. "*Creep-Fatigue at High Temperature of Notched Single Crystal Superalloys*." Journal of ASTM International Vol. 8, No. 6, doi:10.1520/JAI103735.

16. L. Kunz, P. Lukas and R. Konecna, Combined cycle fatigue of Ni-base superalloy, Key Engineering Materials vol. 465, pp. 523-526, 2011. doi:10.4028/www.sientific.net/KEM.465.523.

Appendix – Acronyms

- CCF Combined Cycle Fatigue
- FE Finite Element
- HCF High Cycle Fatigue
- LCF Low Cycle Fatigue
- PREMECCY PREdictive Methods for Combined Cycle fatigue
- SFC Specific Fuel Consumption
- SME Small or Medium Enterprise
- WP Work Package