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ADVANCED EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS ON COMBINED CYCLE FATIGUE (CCF) OF CONVENTIONAL CAST AND SINGLE-CRYSTAL GAS TURBINE BLADES

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ABSTRACT

Rotor blades are the highest thermal-mechanical loaded components of gas turbines. Their service life is limited by interaction of creep, low cycle fatigue (LCF), high cycle fatigue (HCF) and surface attack. Because assurance of adequate HCF strength of the rotor blade is an important issue of the blade design the European project PREMECCY has been started by the European aircraft engine manufacturers and research institutes to enhance the predictive methods for combined cycle fatigue (CCF), as a superposition of HCF and LCF.

Although today's predictive methods ensure safe blade design, there are certain shortcomings of assessing fatigue life with Haigh or "modified Goodman diagrams", such as isolated HCF assessment as well as uni-axial and off-resonant testing. HCF and LCF are considered without taking into account their interaction.

PREMECCY is aimed to deliver new and improved CCF prediction methods for exploitation in the industrial design process. Beside development of predictive methods the authors are involved in the design and testing of advanced specimens representing rotor blade features. In this connection the paper presents a novel test specimen type and a unique hot gas rig for CCF feature test at mechanical and ambient representative conditions.

NOMENCLATURE

LP, IP, HP	Low pressure, intermediate pressure, high pressure
ΔK	Stress intensity range
ΔK_{HCF}	Threshold of stress intensity range for HCF
N	Number of cycles
N_{HCF}	Number of HCF cycles
N_{LCF}	Number of LCF cycles
Q	Quality factor
R	Stress ratio of a cycle (min/max)
R-M	Range-mean
σ_a	Stress amplitude
σ_m	Mean stress
T	Temperature
T_s	Absolute melting temperature of the material

INTRODUCTION

Gas turbine blades dispose of limited service life. Four major damage mechanisms can be identified:

- **Creep:** Time dependent viscoplastic deformation of the material under the influence of stresses that are below the yield strength at temperatures $T > 0{,}4\ T_s$
- **Low Cycle Fatigue (LCF):** Fatigue at low frequencies and high amplitudes (number of cycle to failure below 10^4)

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- **High Cycle Fatigue (HCF):** Fatigue at high frequencies, low amplitudes (number of cycles to failure above 10^4)
- **Surface Attack:** Oxidation, hot gas corrosion which necessitates protective coatings

While all of these damage mechanisms must be regarded during the design process of gas turbine blades, this paper only addresses the fatigue behaviour. Conventional cast and single-crystal gas turbine blade materials are investigated. State of the art of HCF life assessment during the design process of gas turbine blades is a modified Goodman approach. Normally a Haigh diagram, generally called range-mean (R-M) diagram, is used to obtain allowable mean σ_m and alternating stresses σ_a for a given fatigue limit.

The methodology of generation of the database for these Haigh diagrams has several shortcomings. Two major shortcomings have been reported in [1]. These are the neglected statistically distributed initial damage like rogue flaws or inclusions but mainly the accumulation of in-service damage by LCF. While the first issue can be handled by the method of damage tolerant design, which assumes an initial damage during design to avoid potential failures due to occasionally appearing defects, the second issue usually is treated within the context of fracture mechanics [1, 2]. As a result of those studies for a combination of HCF and LCF loadings, commonly called combined cycle fatigue (CCF) two different material behaviours can be distinguished. The first behaviour predicts that either LCF or HCF itself affect the crack-growth rate for CCF, while the second behaviour describes an accelerated growth-rate for ΔK below the HCF threshold ΔK_{HCF}, which consequently leads to a potential non-conservative design.

In contrast to fracture mechanical approaches for predicting CCF strength, the most common tool for assessing HCF fatigue strength during the design process, is still the Haigh diagram. Besides the two major shortcomings of the Haigh diagram which are initial defects and in-service damage e.g. in form of LCF leading to CCF, there are also several less obvious disadvantages and uncertainties concerning the generation of them. These are primarily a result of the kind of excitation causing the damage while disregarding the actual position of HCF damage, which is commonly in the case of a gas turbine blade the fillet radius between the blade and the platform and the shank radius at the blade root (FIGURE 1).

- R-M diagrams are usually generated by performing uni-axial tests. The applied alternating and steady stresses are aligned with the specimen's axis. This is in contradiction to the real excitation of turbine blades leading to multi-axial load cases with a mean stress (tension) induced by centrifugal loads and an alternating stress (bending) by aerodynamic loads, caused by rotor-stator interaction. In accordance to [3] the loading has to be considered in the same way like geometric notches influencing the decay of the stress gradient.
- The specimen is not tested in a vibration mode representing the reality, but by cyclic load-controlled off-resonant tension tests. Although at resonance the alternating stresses are related to the response mode-shape, which can be a flap or torsional mode and thus is complex in distribution.
- One of the widely used standards for conducting force controlled constant amplitude axial fatigue tests ASTM E 466-07 is suggesting a test frequency within a range of 10^{-2} Hz to 10^{2} Hz, while the typical engine-orders for flap modes are in the order of 10^3 Hz. Thus the creep influence within the HCF test results following the standard at elevated temperatures is significantly stronger than in the case of a frequency close to reality.
- The isothermal test condition results in uncertainties due to the temperature gradient in a real component, which has an influence on the distribution of the mean stress. This gradient cannot be neglected in particular for cooled components such as turbine blades.
- Currently there are no specific models for cubic anisotropic materials, due to a lack of understanding of cubic anisotropic HCF behaviour.
- The stress/ strain response stays in the elastic range of the material.
- Uncertainties of the stress concentration factor of notched specimen considered in the Haigh diagram can have a significant influence on life prediction.

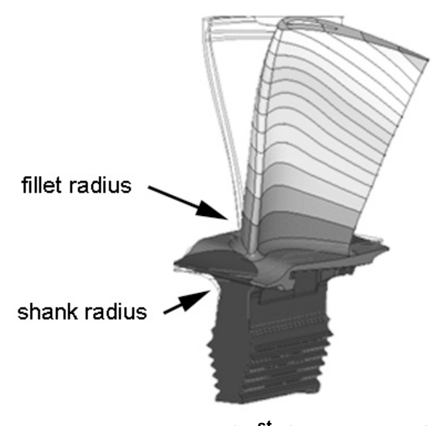

FIGURE 1. Displacements of 1st flap mode of a turbine blade showing CCF life limiting areas (Courtesy of Rolls-Royce plc)

Nevertheless, the Goodman method has been used for more than a century and is undoubtedly a valuable tool for the mechanical design engineer. However, the demand for ever more powerful, efficient, reliable and safe gas turbines has lead to a high complexity of rotor blade design. This leads to a state of affairs where the number of variables associated with the

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true component HCF integrity in the engine environment outnumber those considered at the design phase. To increase this number of variables during the generation of R-M diagrams for the design process and to enhance the predictive methods for combined cycle fatigue (CCF) as a superposition of HCF and LCF the European aircraft engine manufactures and research institutes started the European project PREMECCY [4].

THE PREMECCY PROJECT

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. These issues cost the industry Millions in both maintenance and redesign costs. Thus 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 keys to success in this process. All industrial partners are in a position to exploit the resulting methodologies within their existing design processes. The consortium consists of 9 European gas turbine manufacturers, with Rolls-Royce plc as coordinator, 1 SME and 5 research institutions. The complimentary expertise and experience of the consortium represents an excellent resource to achieve the challenging objectives.

Objectives

PREMECCY is aimed to deliver new and improved CCF prediction tools for exploitation in the industrial design process. The following working programme was specified to achieve the project objectives:

1. Designing advanced test specimens, geometrically representative for rotor blade critical features
2. Defining and executing a matrix of traditional lab tests to fully characterise the materials in question
3. Modifying existing test rigs to allow CCF testing of advanced specimens at mechanically and environmentally representative conditions
4. Defining and executing a matrix of advanced specimen tests to explore the effect of a range of CCF mechanisms on life
5. Developing new and enhanced CCF prediction methods and tools based on existing deformation models and using the characterisation and advanced test data generated within the test matrices

Dresden University of Technology (TUD) is involved in specimen design, methodology development and CCF feature tests. For these tests TUD's hot gas rig has been upgraded and is now ready for tests with loading conditions close to reality of gas turbine blades. The necessary modifications and features of this rig and experiences from commissioning tests will be presented in detail in the following.

Materials Selection

A wide range of advanced alloys is used within the gas turbine, particularly in areas of high loading and/or temperature. It would not be feasible to incorporate all of these materials in an advanced testing and methods development programme such as this. The selection of materials for inclusion in the PREMECCY test matrices is therefore critical to maximise the data and methods exploitation. In conference, the PREMECCY partners have identified and agreed upon three key materials to be the subject of this programme. These three alloys are representative of three broader material groups thus expanding the potential methods exploitation across families of materials rather than being specific to each single material. The materials selected are:

- **Titanium 6.2.4.2 (Ti6242):** A high temperature wrought titanium alloy typically used in IP and HP compressor rotor and stator components
- **Inconel 713LC (IN713):** A high temperature conventionally-cast (CC) low-carbon nickel-base alloy typically used in LP turbine blade and vanes and finding application in HP compressors due to increasing temperature and pressure requirements
- **CMSX-4:** A very high temperature cast single crystal (SX) nickel-base alloy typically used in HP and IP turbine blades and vanes

Specimen Design

In order to fully investigate the identified influencing parameters on CCF, advanced specimen design and mechanical testing methods are required. A significant package of work has been devoted to the design of test specimens. Unlike conventional cylindrical or rectangular cross-section HCF test specimens, PREMECCY adopts the aerofoil-like working section that was shown to be effective already in the RAMGT - Robust Airfoils in Gas Turbine Engines project [5]. Such geometry is considerably more representative of the real engine components of interest to all partners. Detailed design, including the definition of critical features for investigation such as stress concentrations, is carried out using the latest design and finite element analysis (FEA) techniques. Test experience gathered in RAMGT enables to minimise technical risks. For example, difficulty in achieving uniform or repeatable specimen temperature distribution during RAMGT testing was attributed to the length of the specimen. Thus in this programme specimens will be shorter, to ensure improved heating characteristics without compromising any other features of the design.

Material Testing

Conventional HCF tests are uni-axial, applying both the steady and alternating loads along the major axis of the specimen. The reality of gas turbine rotor blade resonance is that the alternating loads are typically generated by a flap or

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torsional mode-shape resonance. The resulting alternating stress field is considerably more complex than that generated in the conventional test. In addition, the frequency of alternating load application of a usual test machine is low, typically less than 100 Hz, compared with in-engine blade frequencies, which are normally between 100 Hz – 10 kHz. This low frequency testing can result in pessimistic test results, particularly at high temperatures, due to the unrealistic high dwell times. In order to carry out a representative test more advanced test conditions are required.

Achieving a representative CCF test under laboratory conditions is particularly challenging. To resonate a tension loaded specimen at amplitudes sufficient to cause failure requires novel test rig design. The addition of further variables, such as complex geometries and high temperatures is an even greater challenge. However, the ability to test more complex specimen geometry and load cycles has already been demonstrated in the RAMGT project.

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.

Methods Development

The PREMECCY test programme will deliver a large amount of material data as basis for enhancement of the predictive methods. A key feature of the methods development work package within PREMECCY is the alliance of research and industrial partners. The research institutions will focus primarily on developing advanced models of the material behaviour at a microscopic level. Several research partners have considerable expertise in this field and the test results generated within this project offers a significant opportunity for the advancement of their knowledge. The industrial partners will identify which of these modelling approaches has the most potential for application at the component level. Based on this they will develop advanced engineering approaches that can be applied in the design process and that will offer improvements in both accuracy and timescale compared with existing design capabilities. These improvements will have a major impact downstream of the design process through the reduced incidence of HCF and CCF issues in development and service and the improved efficiency of the blade design.

In summary, this programme has the following scientific and technological objectives:

1. To design advanced, aerofoil-like test specimens incorporating features identified as being critical to CCF behaviour
2. To fully characterise the HCF and CCF behaviour of two gas turbine blade materials and one compressor blade material
3. To modify and enhance existing HCF and CCF test rig capability
4. To complete a matrix of CCF tests, using advanced test specimens, that are mechanically and environmentally representative of gas turbine operation
5. To develop and verify enhanced engineering lifing and prediction methodologies for HCF and CCF in gas turbine blades
6. To develop and verify advanced models for the physical behaviour of gas turbine materials under the influence of HCF and CCF

DESIGN OF CCF FEATURE TESTS IN HOT GAS ENVIRONMENT

The design of an advanced material test comprises two major aspects that cannot be regarded in isolation from each other. On the one hand there is a test machine, which is restricted in its capabilities, and on the other hand there is the specimen, which has to be designed to satisfy the restrictions of the test machine and to represent the desired feature of interest.

During the RAMGT project existing standard tensile test machines had been upgraded with an electrodynamic shaker, a heating device (furnaces and induction heaters), a laser proximity probe and control software to perform CCF tests on blade like specimens. The key components of those CCF rigs (tensile test machine, shaker, laser probe, heating device) are used within the PREMECCY project as well and therefore give hard restrictions to the major test conditions and specimen dimensions. The main restrictions of the CCF test rigs for the advanced specimen design are:

- Maximum achievable tensile force
- Maximum achievable shaker power
- Maximum achievable shaker frequency
- Maximum load train/ specimen length
- Maximum oven height (furnace, coil)

In context of control circuit and specimen design it is also important to decide which load regime for advanced CCF tests is feasible. The general CCF load regime to be used is shown in the top row of FIGURE 2. It comprises an LCF cycle with dwell during that HCF cycles with the resonant frequency of the specimen are superimposed. The LCF loading times are free of HCF cycles. It was decided to design the advanced specimens for a frequency range of the first flap mode of 1 kHz to 2 kHz to target the typical fatigue limit of HCF ($N_{HCF} = 10^7$). Due to the performance of the control circuit and the inertia of the vibrating system, which are limiting the minimum LCF dwell time, the number of LCF cycles is restricted. With the knowledge of the RAMGT tests it could be shown that the minimum LCF dwell time is approximately four seconds, while one second of those four seconds is used to stabilize the amplitude of the superimposed HCF cycles. This unfortunately leads to a low number of LCF cycles of averaged $N_{LCF} \approx 1667$ for a pure CCF load regime.

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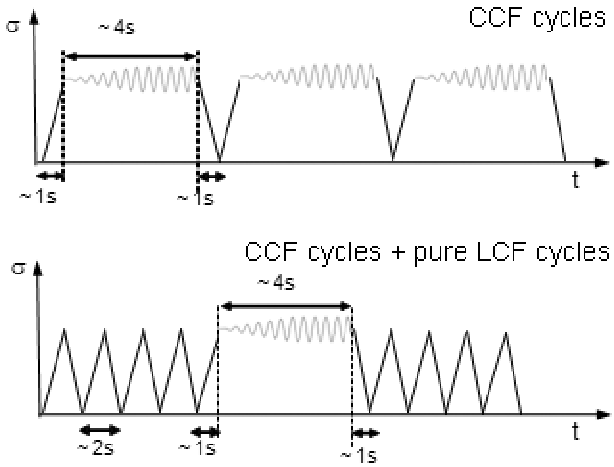

FIGURE 2. Load regimes for advanced CCF testing

To meet the target of approx. $N_{LCF} \approx 10^4$ it was agreed to insert an adequate number of pure LCF cycles without dwell in between the CCF cycles. The resulting load regime is shown in the bottom row of FIGURE 2.

Differences of Hot Gas Rig to Other Advanced CCF Test Rig

The hot gas rig of TUD [6], which cannot be regarded as a standard test rig, had to be upgraded to fulfil at least the specified requirements to perform the advanced validation tests. As already mentioned the distinctive feature of this rig is its capability to perform tests in a hot gas environment with a maximum hot gas temperature of 1250 °C. It is designed for stationary and cyclic thermal loading (TMF, thermal mechanical fatigue), capable to test inner air-cooled components, with superimposed stationary or cyclic mechanical loadings (LCF, HCF, CCF). Actually not all of its features are needed for PREMECCY.

The basic layout is shown as top view in FIGURE 3. Natural gas is burned and set into circulation in a horizontal plane by a radial hot gas ventilator, while the test rig is not pressurized. The length of the test-section is 500 mm in flow direction and the cross-section is 300 mm x 400 mm. The specimen arranged inside this test-section has to be adapted to a load frame that is lifted up from ground and mounted to the hot gas rig. Thus relative movement between the specimen and the test section is suppressed. To adjust the maximum flow velocity for the minimum cross-section the flow channel can be modified in any way with segments of high temperature concrete, so that velocities of 60 ms^{-1} are achievable.

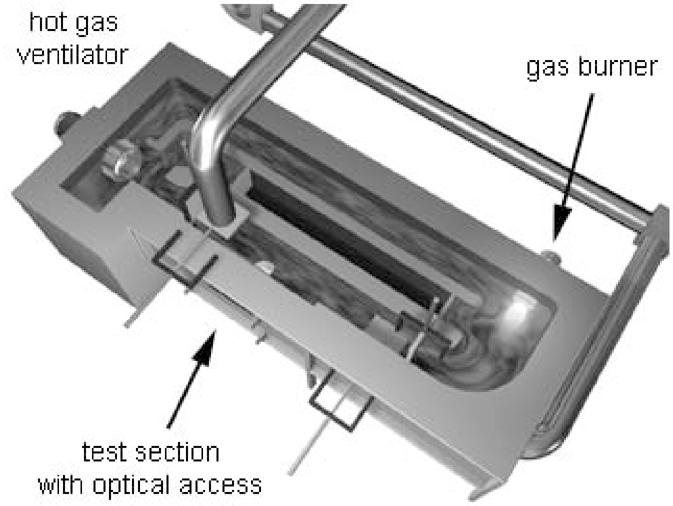

FIGURE 3. Top view of hot gas rig for advanced CCF validation testing

Load Train

The RAMGT load train comprised two leaf springs, that are needed to allow the specimen to bend, and two clamping devices that are attached to the leaf springs to hold the specimen in between. It was decided to change the clamping system due to damping and alignment issues. The basic design idea was to use a central pin to hold the total axial force needed to apply LCF loads in addition with four smaller bolts to minimize the damping of the load train by increasing the surface contact stiffness of clamping device and specimen. FIGURE 4 presents the modified load train for CCF testing within the hot gas rig with the actuators and sensors.

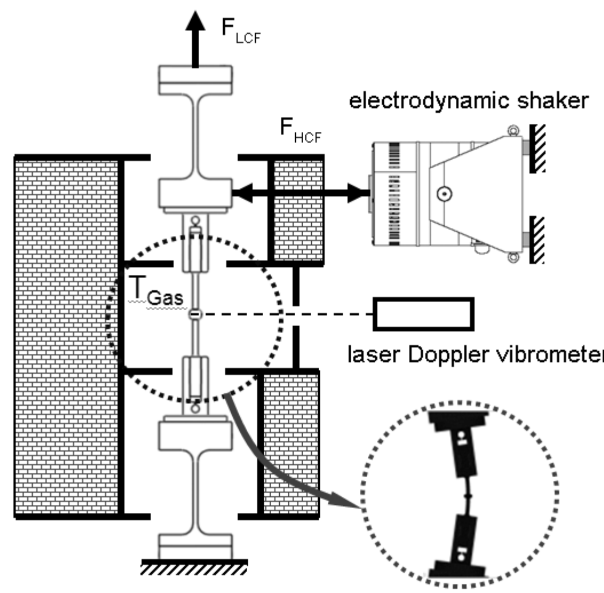

FIGURE 4. Schematic stream-wise view of the modified load train for CCF testing, actuators and the laser vibrometer

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With this configuration it is possible to apply a non-uni-axial CCF load to the specimen by generating a LCF load with servo-hydraulic actuators in a classical manner and a HCF load with an electrodynamic shaker that is perpendicular to that. To adapt the RAMGT load train to the load frame of the hot gas rig the following major modifications had to be realised:

- Installation of a 100 kN servo-hydraulic actuator in conjunction with a hydraulic power unit and a control system (used for LCF loading)
- Installation of a 489 N electrodynamic shaker in conjunction with its power amplifier and cooler
- Installation of a laser vibrometer for a contactless measurement of the vibration velocity, displacements and frequencies
- Redesign of the flow path geometry, due to shaker drive rod coupling to the load train
- Installation of a multi-channel DAQ (data acquisition) hardware for monitoring hot gas rig status parameters and measuring temperature fields with dummy specimen
- Design of a special ceramic insulation assembly for the upper leaf spring due to decreased insulation thickness

Specimen Design

The specimen has to represent a blade feature, which is most relevant for CCF damage. The fillet radius between the turbine blade and the platform is exposed to high tensile loads during the takeoff phase of the flight cycle and to high bending loads especially in first flap mode (cp. FIGURE 1). The basic ideas for the advanced blade-like specimen design in context with the rig capabilities and a constrained maximum length for single-crystal specimen of 230 mm, due to the capabilities of the foundry, can be summarised as follows (FIGURE 5):

- Representing the fillet radius between turbine blade and platform in a mid-chord position
- Representing the turbine blade by an elliptical cross-section of the specimen (due to hot gas flow mandatory for hot gas rig)
- Introducing a central lumped mass around the elliptical blade, which is beneficial to
    - bring the design feature (fillet radius) close to the symmetry plane of the specimen and therefore relieves the complexity of temperature control for the radiation and induction heaters compared to a feature located close to the clamping region of the specimen
    - influence the mode-shape of the first flap mode by adding a kind of oscillating weight
- Cropping the lumped mass along the leading and trailing edges to concentrate the maximum tensile stress and the maximum bending stress at the mid-chord position
- Using a tapered design in two symmetry planes to decrease the stresses towards the clamping region

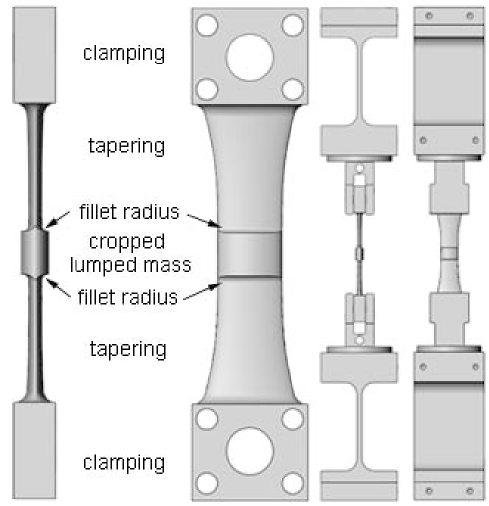

FIGURE 5. Advanced specimen design and load train assembly

There were three main design goals for the advanced specimen. Thus the fatigue testing is going to follow the standard staircase method, by this means of a constant R-ratio, it is of great importance to keep this R-ratio constant in the region of maximum tensile and bending stresses to guarantee a minimum scatter of data perpendicular to the line of constant R-ratio in the Haigh diagram. Ignoring this fact would lead to test results of an unknown R-ratio, e.g. in the case of a torsional misalignment. On the other hand the area of the region in the fillet radius (test feature) first reaching the fatigue limit should be minimized to maximize the chance that this spot is actually within the region of constant R-ratio. Besides it had ensured that the other components of the load train do not fail before the specimen. As a third design goal the specimen should be used for two different materials, the isotropic material IN713LC and the cubic anisotropic single-crystal CMSX-4. While the focus was on reaching an optimum for CMSX-4, IN713LC with its very different Young's modulus could be handled too.

Conducting a parameter study for the advanced specimen design implies the execution of three major tasks that had to be carried out with elastic FE calculations:

1. Static FE calculation to obtain the stresses caused by the axial load for LCF cycling
2. Pre-stressed modal analysis to obtain the stresses caused by the dynamic load for HCF cycling (by scaling the eigen-solution to the fatigue limit of the desired R-ratio), the mode-shape and the eigenfrequency of this mode-shape

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3. Forced response analysis with an assumption of the damping values to keep the constraint of the maximum shaker force within the limit

Exemplary results of tensile and bending stresses for CMSX-4 at constant material temperature of 950 °C, 40 kN axial load and an R-ratio of R = 0.7 are presented in FIGURE 6.

Besides the CCF stress situation the modal analysis and the forced response analysis can be used to keep the following design goals:

- Keeping the specimen’s eigenfrequency of the mode-shape that is representing the first flap mode between 1 kHz and 2 kHz (cp. FIGURE 7)
- Ensuring that the frequency of neighbour modes are either far enough from the design frequency or not excitable with the current load train topology (cp. FIGURE 8)
- Adhering the limit of the shaker capability, with means of keeping the reachable HCF amplitudes in a useful margin

As another example for the design study FIGURE 7 shows the scaled design mode-shape of the advanced specimen of CMSX-4 and the load train for 950 °C and 40 kN axial load. It turns out that the lumped mass of the specimen participates the most for this mode-shape (1st flap mode) and that the load train itself is not exposed to large deformations and therefore stresses, which is compulsory for the load train endurance.

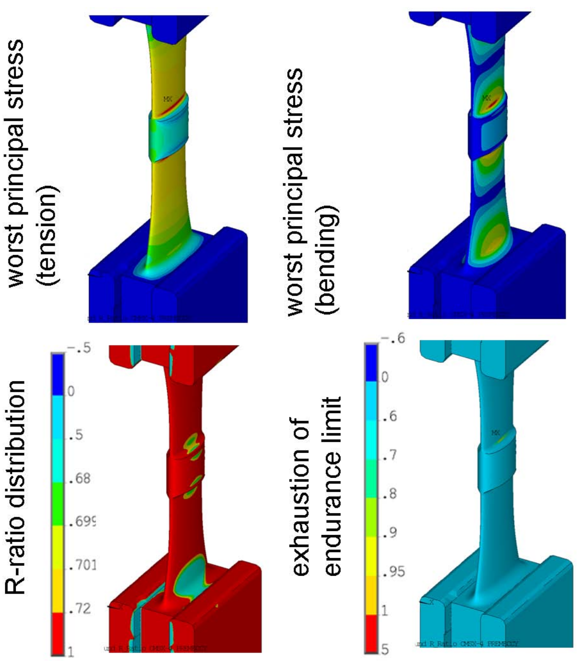

FIGURE 6. Stresses, R-ratio and exhaustion of endurance limit for CMSX-4 at uniform 950 °C, 40 kN axial load and R = 0.7

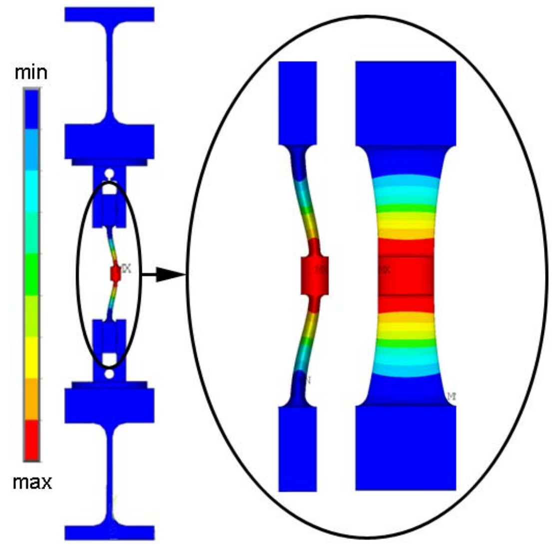

FIGURE 7. Displacements of mode-shape of advanced specimen of CMSX-4 at uniform temperature of 950 °C and 50 kN axial load

FIGURE 8 shows the result of two modal-analyses carried out to find the safety margin to excite really the first flap mode of the specimen instead of any other. This is important as in reality the load train has a temperature distribution with about 950 °C in the fillet area and room temperature at the outward ends of the leaf springs. The eigenfrequency will be in between the two data points shown for each mode (cp. section Commissioning Tests). The data points show clearly that the spacing of more than 200 Hz to the neighbour modes is large enough to assure a safe operation of the first flap mode.

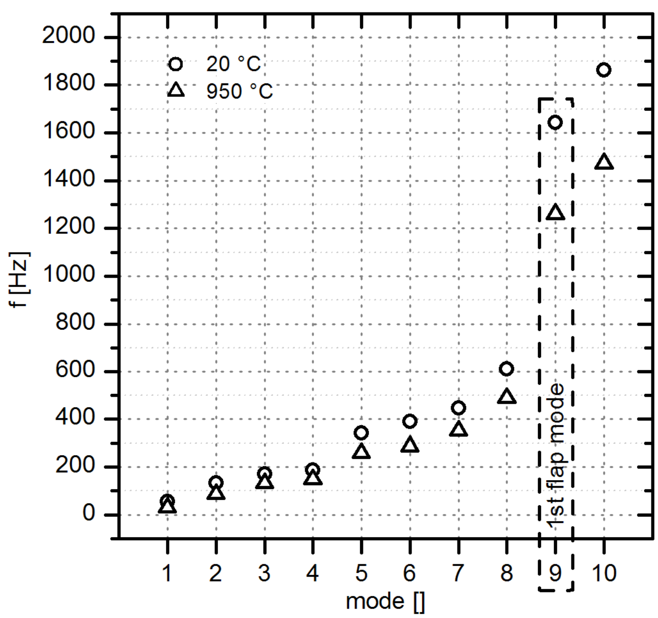

FIGURE 8. Eigenfrequencies of the 50 kN pre-stressed load train with CMSX-4 specimen at uniform temperatures of 20 °C and 950 °C

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COMMISSIONING TESTS

After upgrading the hot gas rig for CCF testing a number of commissioning tests have been conducted to validate theoretical results and to ensure reproducibility of testing:

- Performing a static alignment
- Measuring temperature distribution for the specimen and the load train
- Detecting eigenfrequencies for the designed advanced specimen for different temperatures and axial loads
- Qualitatively check of the specimen's mode-shape
- Evaluating the damping coefficient of the specimens frequency response

Static Alignment

ASTM E 1012-05 was used to determine the residual percentage bending of the advanced specimen attached to the load train of the hot gas rig. As result the static alignment for the hot gas rig is within the project limit of 5% for static loads larger than 20 kN (cp. FIGURE 9). Because axial load for CCF testing will be in the order of 40 kN to 60 kN this alignment meets the requirements.

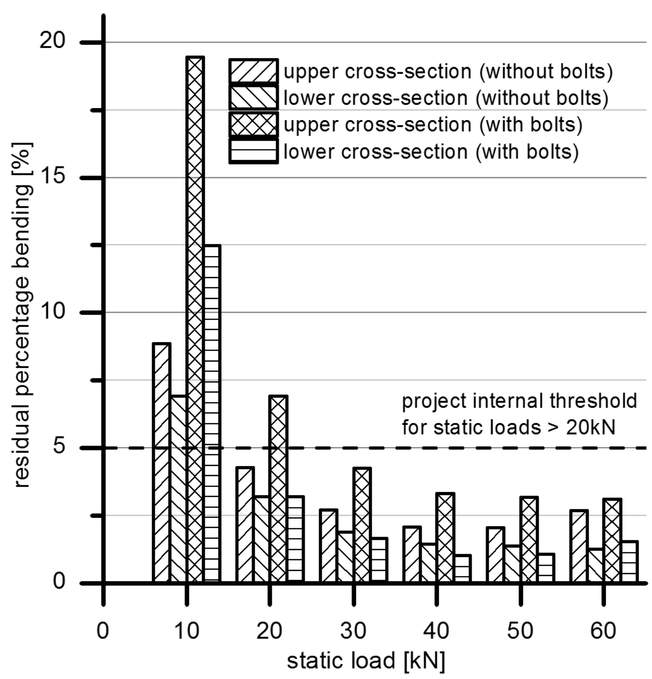

FIGURE 9. Residual bending after static alignment according to ASTM E 1012-05

An FE calculation showed that the misalignment of the hot gas rig for an axial load of 50 kN compared to the perfect aligned load train is leading to a difference of the worst principal stresses of 4 MPa at nominal levels of the stresses two orders higher and thus can be neglected.

Temperature Field Measurement and Analysis

While the other test rigs within PREMECCY are heated by radiation or induction heating the hot gas rig is convectively heated by combustion gas. The conventional heating systems are known to produce a relatively uniform temperature within the specimen's cross-section, while there is always a minor temperature gradient along the axis of the specimen. By controlling the heating system, which in most cases consists of three channels, unintentional temperature gradients caused by unsteady cross-section changes or buoyancy effects can be minimized to achieve uniform conditions for the specimen.

In contrast, a convective heating enables tests closer to the reality of the turbine. Of course, the aim is a non-uniform temperature distribution, by a temperature field reflecting that of a real component. Thus TUD is performing the validation testing, which is thought to validate the methodology used to predict the CCF fatigue limit for the advanced specimen under non-uniform temperature loading with data that was obtained by the advanced testing on laboratory CCF test rigs.

Because of the complex temperature distribution caused by the fluid flow, a CMSX-4 dummy specimen with the shape of the advanced specimen has been equipped with 9 type K surface attached thermocouples and 3 type K internal thermocouples. They have been distributed in a way to get a clear picture of the stream-wise temperature gradients and those perpendicular to that direction, along the load train axis.

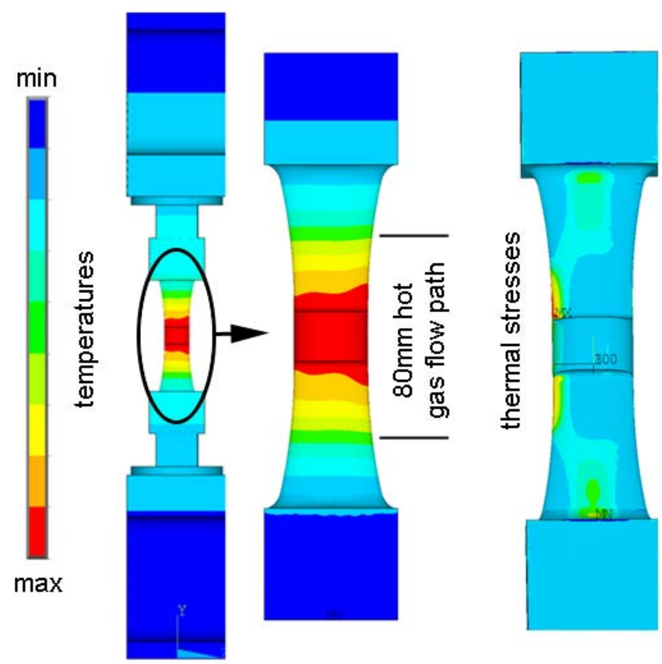

FIGURE 10. Temperatures for CMSX-4 advanced specimen at 950 °C (fillet radius) in the hot gas rig (left) and corresponding thermal stresses (right)

In any case, the thermal induced stresses of the specimen tested in the hot gas rig are higher than those of conventional heating. While in the case of almost uniform temperature

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conditions it is sufficient to perform a static elastic FE calculation with matched and mapped temperatures, it is recommended to perform a separate thermal analysis for non-uniform temperature conditions. To obtain the necessary boundary conditions from the discrete results of the thermocouples, it was assumed that the temperature gradient, as the reason for thermal induced stresses, can be reproduced by a set of continuous quadratic functions. This was done for two directions and extrapolated to the surface of the advanced specimen. FIGURE 10 shows the temperature field of the CMSX-4 advanced specimen at 950 °C with the measured temperature distribution. Further the distribution of the thermal stresses is the basis for the adjustment of the non-uniform temperature test conditions in the hot gas rig.

Excitation of high-cycle vibrations

Key component for excitation of high-cycle vibrations is the shaker, which has to be integrated in the hot gas rig. The commissioning test for high-cycle excitation is aimed to measure the eigenfrequency of the advanced specimen as function of temperature and static load and to investigate the damping in the system. Due to thermal insulation of the hot gas rig the shaker drive rod is ten times longer than the rods of the other, i.e. induction heated test rigs of PREMECCY. Commissioning tests have to prove that the achievable displacement amplitudes as a function of temperature level and axial loading are on an acceptable level. A more powerful shaker could not be adapted due to dimensional and mass restrictions of the load frame.

To obtain the necessary data a hot test run was performed similar to those for the temperature field, with a CMSX-4 dummy specimen. In that case the hot gas rig was equipped with the required hardware needed to perform CCF tests. The eigenfrequency of the specimen was identified by a sinusoidal sweep for a varying axial load on three temperature levels (FIGURE 11). In a second step the maximum lateral displacement of the advanced specimen's lumped mass for each eigenfrequency was determined.

FIGURE 11 shows linear characteristics of the eigenfrequencies with increasing load as expected. The eigenfrequency at room temperature for 50 kN axial load fits to the calculated frequency of mode 9 in FIGURE 8. While the measured eigenfrequency at 950 °C and 50 kN is right in between the calculated isothermal cases for mode 9 in FIGURE 8. That is feasible since the axial temperature distribution of the load train is within the range of 20 °C to 950 °C in the fillet radius.

During the design phase of the advanced specimen a quality factor of Q = 1000, derived by the half-power method, was used. For damping of the load train of the hot gas rig for an axial load of 5 kN a quality factor of Q = 908. Thus the design is based on a reliable value.

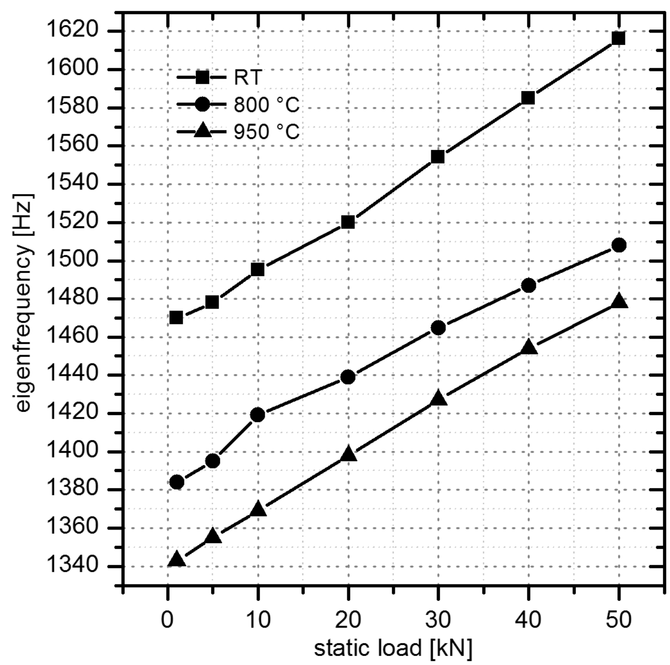

FIGURE 11. Eigenfrequencies for advanced specimen of CMSX-4 in the hot gas rig for different static loads

Mode-Shape

Since the laser Doppler vibrometer is directed to the centre of the lumped mass and that the modal analysis showed a maximum displacement of the lumped mass for the desired first flap mode, it is assumed that this mode can be detected by seeking the maximum amplitude of the displacement signal of the laser Doppler vibrometer within a specified frequency range. But as it is a single-point vibrometer there is no evidence for the shape of the mode with this procedure.

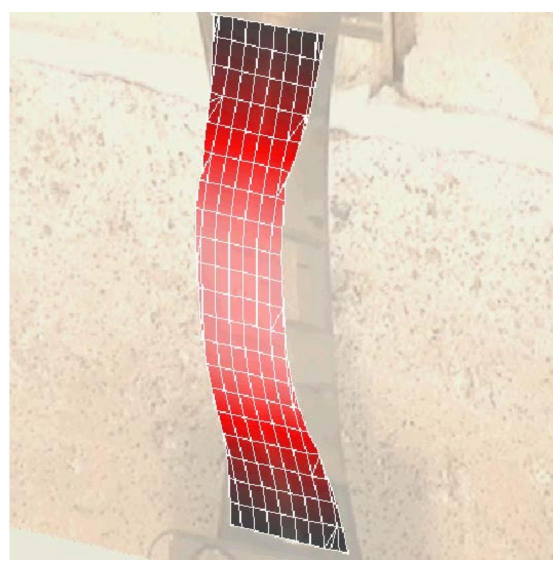

FIGURE 12. Qualitative results of the mode-shape of the 1st flap mode of the advanced specimen at room temperature (background shows the initial shape)

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Therefore the mode-shape was qualitatively checked at room temperature with a laser scanning vibrometer, which is capable to determine operational deflection shapes of eigen-modes. The result of the measurement is shown in FIGURE 12. which is in good accordance with the result of the modal analysis presented in FIGURE 7. In a next step the quantitative dynamic alignment has to be carried out to validate the strains of the dynamic FE analysis.

PRELIMINARY RESULTS AND DISCUSSION

The characterization of the three materials on laboratory level is completed. As an excerpt selected results of HCF and CCF tests of notched (cp. FIGURE 13) and smooth specimens for CMSX-4 in [001] direction shall finally be presented. They have been carried out in laboratories of project partners to determine the 10^7 fatigue limit by using the standard staircase method with at least 10 samples per test condition.

HCF and CCF test results of plain CMSX-4 specimen at 750 °C and 950 °C for R-ratios of R = 0, R = 0.6 and R = 0.8 show no clear evidence for the examined conditions that CCF cycling is more damaging than HCF cycling. Rather there is even a positive effect of CCF cycling compared to HCF cycling for high R-ratios (R > 0.8). A similar picture was already shown by Forrest [7]. Data points on the mean stress axis for R = 1 are derived from creep data in that manner that the creep time is the product of the reciprocal test frequency and the number of cycles to failure, thus this point is consistent with the fatigue data.

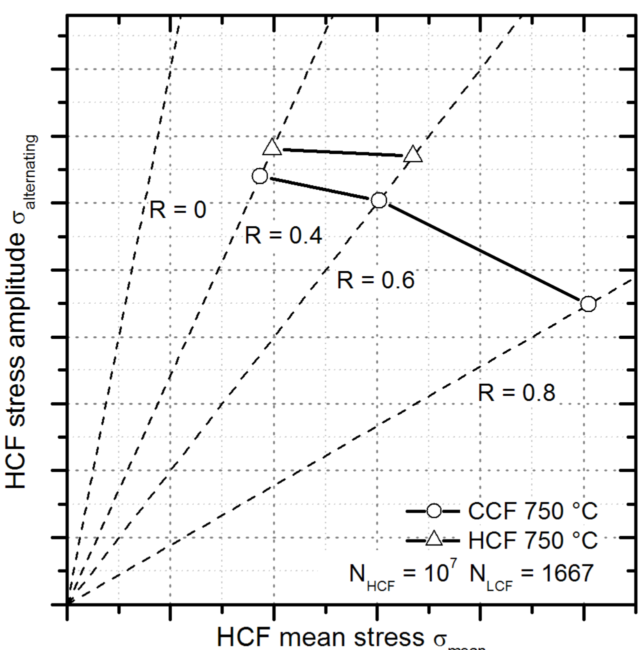

FIGURE 13. $N_{HCF} = 10^7$ and $N_{LCF} = 1667$ Fatigue limit of HCF and CCF cycling for CMSX-4 notched specimen ($k_t = 2.15$) in [001] direction at 750 °C [Institute of Physics of Materials (IPM)]

HCF and CCF test results of notched CMSX-4 specimens shown in FIGURE 13 have been generated on the very same machine of the Institute of Physics of Materials (IPM). Thus the scatter due to different laboratories can be neglected. Although these tests show that CCF cycling is more damaging than HCF cycling, the effect is small and within the scatter of the material itself.

However, the CCF test rig of IPM has a LCF dwell time of 60 s and a HCF frequency of 100 Hz. This results in relatively low number of LCF cycles ($N_{LCF} = 1667$). The CCF effect is expected to be more distinctive for larger N_{LCF}.

The Commissioning tests of TUD's hot gas rig upgraded for CCF testing have been completed successfully. Furthermore the first HCF demonstration test of an advanced specimen of CMSX-4 (950 °C, R = 0.8) has been successfully finished in the hot gas rig. Although the loads were beyond those for 10^7 fatigue limit to explore the test rig capabilities, the test has shown that the crack initiation location and the number of cycles to failure are in accordance with the FEA results.

Validation test campaign will start next. The current test matrix schedules 8 HCF/ CCF tests as shown in TABLE 1.

TABLE 1. Validation test matrix

material	number of tests HCF / CCF	temperature of test fillet	R-ratio
CMSX-4	2 / 2	950 °C	0.8
IN713LC	2 / 2	800 °C	0.8

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