DEVELOPMENT OF A HYBRID-UNISON RING FOR VSV-SYSTEMS FOR NEW HIGH OPR AEROENGINES

Thomas Klauke[1], Dirk Söhner[1], Björn Drees[2], Peter Winkelmann[2], Ronald Klomp-de Boer[3]

[1] Rolls-Royce Deutschland Ltd. & Co. KG, Eschenweg 11, D-15827 Blankenfelde-Mahlow,
[2] Deutsches Zentrum für Luft und Raumfahrt, Institut für Bauweisen- und Konstruktionsforschung, Pfaffenwaldring 38 – 40, D-70569 Stuttgart
[3] National Aerospace Laboratory, Aerospace Vehicles Structures Technology (AVST), Voorsterweg 31, 8316 PR Marknesse, The Netherlands

Summary

Aiming at increasing overall efficiency for future aero engines, the accuracy, robustness and lifetime of the variable stator vane (VSV) system has to be increased. In addition to this, also higher temperatures and pressures due to the increased overall pressure ratio (OPR) have to be considered. In order to achieve these objectives without compromising the weight and cost of the system, the unison ring design (located around the high pressure compressor (HPC) casing, connecting the individual stator vanes with the crankshaft- or bellcrank mechanism) has to be improved in terms of accuracy, temperature and load capability. Within the EU-funded R&T programme E-BREAK (2012 - 2016) a non-conventional VSV unison ring has been further developed by the DLR Stuttgart in order to consider the enhanced requirements. Expert knowledge regarding cost-efficient CFRP-manufacturing from the NLR was incorporated during the design phase of the hybrid unison ring as well as detailed interface requirements from the aero engine manufacturer. The final parts will be manufactured by the NLR in 2015 and tested under realistic, engine-like conditions at the Technical University of Dresden.

1. ABBREVIATIONS AND DEFINITIONS

BMI	bismaleimide
BPR	bypass ratio
CFRP	carbon fibre reinforced plastic
CHUR	composite hybrid unison ring
CTE	Coefficient of thermal expansion
E-BREAK	engine breakthrough components and subsystems
FEA	finite element analysis
HPC	high pressure compressor
LCF	low cycle fatigue
OPR	overall pressure ratio
RTM	resin transfer moulding
TU	technical university
UD	unidirectional
VA-RTM	vacuum infusion resin transfer moulding
VSV	variable stator vane

Hysteresis defines the difference in vane angle of one single vane between an acceleration and deceleration manoeuvre at identical engine speed.

Malscheduling defines the difference in vane angle compared to the demanded vane angle schedule. It consists of two main parts:

- The first component is caused by stagger angle differences due to interface clearances, part tolerances, tightening the lever bolt during module build, etc. and can be measured during engine build. Neglecting minor changings due to thermal expansion during operation, that component can be assumed to be constant.
- The second component is a result of the elastic deformation of the VSV system during operation and clearances between centralisers and casing, which are depending on the thermal condition and the applied operational load.

Positive malscheduling angles are related to more closed vane positions, while negative angles are always describing a more open vane position w.r.t. nominal vane position.

Vane-to-vane variation defines the difference in vane angle between two vanes of one stage. Usually the highest variation around the circumference is of interest.

2. INTRODUCTION

As a result of the growing aeronautic traffic, combined with the expected future rise of oil price, the aero engine industry aims at a development of more efficient products to reduce its CO2 and NOx emissions (see [1]).

Therefore the thermal and propulsive efficiency of aero engines has to be improved by increasing component efficiency and by usage of higher overall pressure ratios and turbine inlet temperatures. As a result of the corresponding increased bypass ratio (BPR), smaller and hotter engine cores will occur for a given amount of thrust.

Thus, the generic tolerances and the appearing wear of the VSV system of a future small core high OPR engine have a more pronounced effect on efficiency and surge margin. Furthermore, the VSV system has to withstand higher aerodynamic and thermal loads caused by the more loaded HPC. Aiming at higher number of life cycles to achieve lower operational costs, the wear rate should be further improved in addition.

Within the EU-funded R&T programme E-BREAK a non-conventional VSV unison ring has been further developed based on previous work from the DLR Stuttgart [2-5] in order to consider these enhanced requirements. Expert knowledge regarding cost-efficient CFRP-manufacturing from the NLR was incorporated during the design phase of the hybrid unison ring as well as detailed interface requirements from the aero engine manufacturer. The final parts will be manufactured by the NLR in 2015 and subsequently tested under realistic, engine-like conditions at the Technical University of Dresden. The design process, the development and the test campaign of that unison ring are summarized within this document.

3. VSV SYSTEM DESCRIPTION

Generally the high pressure compressor (HPC, see Figure 1) of modern aero engine consists of several stages alternating static vanes and rotating blades. In order to optimise the aerodynamic efficiency and to achieve sufficient surge margin, the first stator vane rows have a variable angular position. The VSV system is used to rotate these variable stator vanes in the HPC depending on the aerodynamic speed during the flight. The vane angle in dependence of the engine speed is stated in the so-called VSV-schedule, which is optimised regarding efficiency, vibration excitation and surge margin.

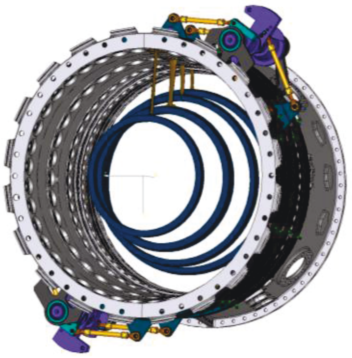

FIG 1. FEA model of a typical HPC VSV system (only 1 vane per stage shown, double actuation system)

The VSV system is moved by one or more hydraulic driven actuators (VSVA) depending on the engine size and design style. The VSVA is connected via tie rods to the crankshaft or bellcrank assembly. Furthermore, the crankshaft system is linked via tie rods to the unison rings, which drives all variable stator vanes of one stage. The VSVs themselves are connected via individual levers to their adjacent unison rings.

The thermal deformation, the structural stiffness of the unison rings and the cold build clearances between centralizer pads (mounted on the unison ring) and casing have an important effect on the precision and operability of VSV system (Figure 2).

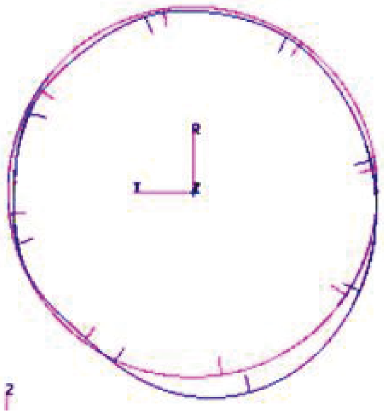

FIG 2. Typical unison ring deformation for a single VSV-actuator design during operation

Also the transient temperature difference between the hot HPC casing and the cooler unison ring next to it (see Figure 3) plays a significant role in terms of VSV accuracy and resulting VSV actuation loads. These clearances are depending on the flight condition and the thermal behaviour of both adjacent parts. The larger the gaps between unison ring centraliser and casing, the higher the vane malscheduling around the circumference and the corresponding effects on efficiency, surge margin and vibration excitation.

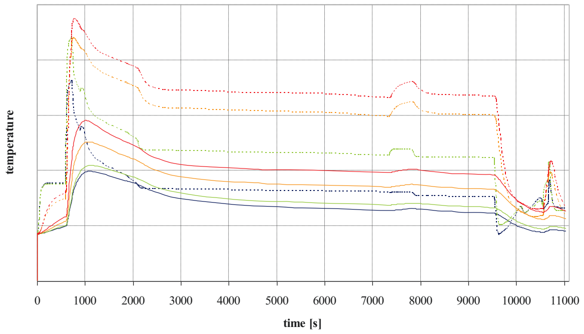

FIG 3. Casing and unison ring temperatures of a 4-stage HPC VSV system during typical flight cycle (dotted lines – casing temperatures, continuous lines – unison ring temperatures)

4. DESIGN INTENT OF THE COMPOSITE HYBRID UNISON RING (CHUR)

The thermal mismatch between generally hotter HPC casing and surrounding cooler unison ring leads to a compromise in the cold build clearance setting for conventional full metal unison ring designs. Hence, a trade-off between VSV high accuracy and low actuation forces at the centraliser sliding pad has to be carried out resulting in higher malscheduling and lower efficiency.

Within former research investigations the so-called Composite Hybrid Unison Ring (CHUR, see Figure 4) was designed by the DLR Stuttgart (Patent # EP0741247, [2] see also [3 - 5]) to minimise the radial interferences to the casing.

The combination of an outer carbon fibre reinforced plastics (CFRP) ring in combination with an aluminium truss generates a thermal expansion behaviour which can be adjusted to the expansion of the compressor casing, where the ring is bedded on. During the heating up of the aero engine the ring deforms from a round to octagonal shape in order to keep the same low clearance level between the HPC casing and the adjacent unsion ring centralisers using a bimetallic-like effect. Due to this design the trade-off between low malscheduling and low actuation forces can be avoided.

FIG 4. Former Composite Hybrid Unison Ring designed by DLR Stuttgart combining composites and metal

5. FURTHER DEVELOPMENT WITHIN E-BREAK

Within E-BREAK the previous CHUR design [2] should be adapted in order to support an application of this design on future high OPR aero engines with increased temperature and load requirements as well as increased vane accuracy demands. Thus, the main activities were focused on the further development regarding:

- improved adaption of thermal growth rates w.r.t. casing expansion rate,
- enhanced operation temperature,
- high load application for future engines,
- improved load introduction (tangential).

While the design and the optimisation of the CHUR has been carried out by the DLR Stuttgart, the CHUR test samples will be manufacturing at the NLR. Finally, the CHUR will be instrumented and tested at the test rig at the Institute for lightweight engineering and polymer technology at the TU Dresden.

6. MATERIAL SELECTION

The composite hybrid unison ring is made of a combination of CFRP ring segments and metal parts.

In order to reduce validation and test costs and to support a fast product introduction, only materials which are already approved by Rolls-Royce were taken into account during the design process. The thermal expansion coefficient (CTE) was also taken into account as the bimetal effect is driven by the CTE difference of the applied materials.

6.1. CFRP - Resin Material

Based on the former mentioned requirement, a high temperature capable bismaleimide (BMI) resin was selected after an assessment and comparison of the available materials. This resin material offers a significantly increased thermal operating range compared to the previously applied epoxy resin.

6.2. CFRP – Carbon Fibre Material

For the same reason a standard, aerospace grade, high tenacity carbon fibre was selected to reinforce the composite structure. This reinforcement fibre material offers the optimum strength/strain-to-weight ratio as well as sufficient temperature capability for the planned application.

6.3. Metal Parts

All metal parts consist of standard aluminium-, steel- and titanium alloys, which are widely used in aerospace applications. Thus, all relevant material property data (e.g. low and high cycle fatigue strength vs. temperature, thermal expansion coefficients) are already available, which allows an accelerated design process without costly and time consuming material testing and validation.

7. MANUFACTURING

7.1. Requirements

Contrary to the commonly applied full metal unison rings, the manufacturing process of hybrid structures as the CHUR is more complex per se. Thus, particular attention was paid to the selection of a cost efficient manufacturing processes in order to achieve total costs in the same level as for the conventional full-metal unsion ring designs, e.g.: tolerances were chosen w.r.t. not only the effect on the component stress but also regarding the manufacturing cost. Furthermore, the general design but also fillet radii and cut out dimensions were optimised in terms of cutting tool availability, processing time and costs.

7.2. Selected Process

As the CHUR consists of different kind of materials, each of them require different kind of manufacturing which have to be selected based on the particularities of the component design. However, also the manufacturing methodology has an effect on the component design.

- The main manufacturing process of the metal parts is standard CNC machining. Water jet cutting could be an option for some components or a combination.

- The main challenge is the cost-effective, accurate manufacturing of the CFRP segments. Due to the chosen design, it follows that unidirectional (UD) carbon fibres are required for the unison ring reinforcement. The preferred manufacturing process for applying UD carbon in an industrial setting is by automated machines, such as filament winding, braiding or automated fibre placement (see Figure 5).

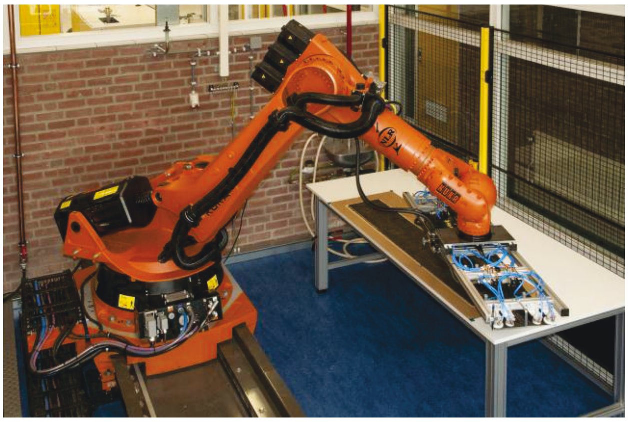

FIG 5. Example of Pick and Place robot at NLR for handling robots

- Filament winding does not provide the required quality and control of hoop direction fibres. Braiding results in a woven pattern which was also not considered to be acceptable. Finally automated fibre placement uses UD fibres and with very accurate control of fibre orientation. However, to this date no UD (dry) fibre tape compatible with BMI resin is available. From the above it follows that for the current task, UD carbon fabric will be applied manually. Automation is still possible in future as industrial setting by using Pick & Place robotics is rapidly increasing in aerospace and automotive composite manufacturing.

- With the demand to use high temperature BMI, resin infusion by a resin transfer moulding (RTM) process is used to manufacture the composite part by default. Basically two approaches are possible; either under high pressure with closed, often steel, high tolerance, double tooling (see Figure 6) or under vacuum with single side tooling and vacuum bagging.

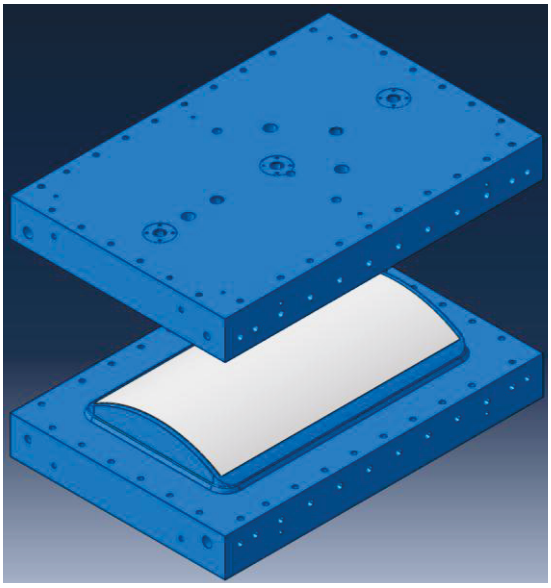

FIG 6. Schematic RTM process of the basic curved panel required for 2 shipsets of CHUR segments

- The second option (see Figure 7) allows a more efficient manufacturing of longer panels from which the segments can be obtained. Also the required tooling can be simplified. Considering the fact, that the CHUR design only requires one side to be smooth - the interface with metal bridge sections - combined with the less expensive tooling, the vacuum infusion (VA-RTM) approach was selected for the manufacture of the CFRP segments.

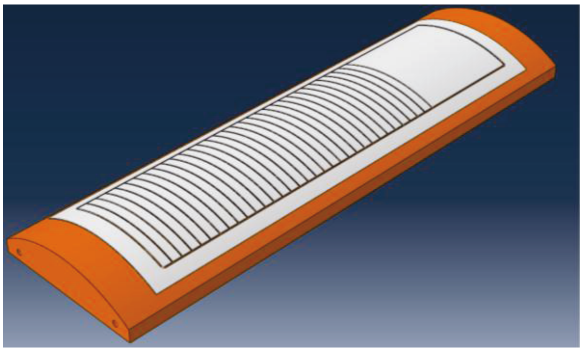

FIG 7. Schematic laminate on tool and CHUR segments for VA-RTM

The initial female moulding prototype is shown in Fig. 8 below. After carrying out initial infusion tests (see Fig. 9), the CFRP segments will be inspected for cavities and dry locations and the dimensions will be measured in order to determine the possible spring back or shrinkage of the part. Additional features for the final infusion process will be added to the female moulding after completion of the initial test phase.

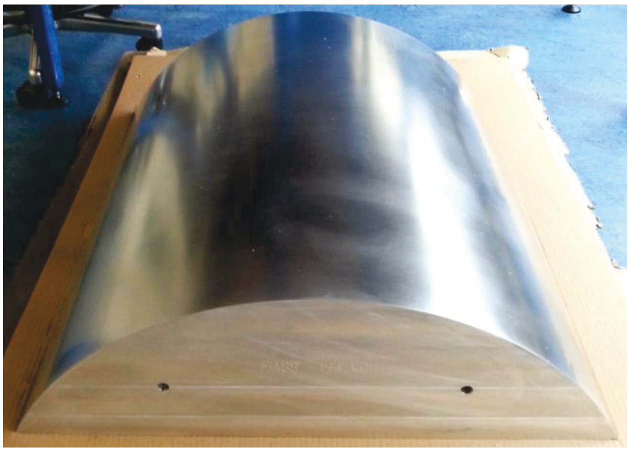

FIG 8. Female mould laminated prototype tool at NLR

FIG 9. First CFRP coupon

8. CHUR DESIGN AND OPTIMIZATION

8.1. Previous Work

The final design of the CHUR based on former development work carried out in a national funded program (reference number 20T9502C, 20T9502D, see Figure 10 and [2]). At this, a concept has been realized and tested on an aero engine respectively on a test rig which uses the combination of different materials to achieve a ring structure with adaptable thermal expansion behaviour. The main focus was the minimisation of malscheduling in conjunction with reduction of weight at competitive costs compared to a conventional metallic ring design.

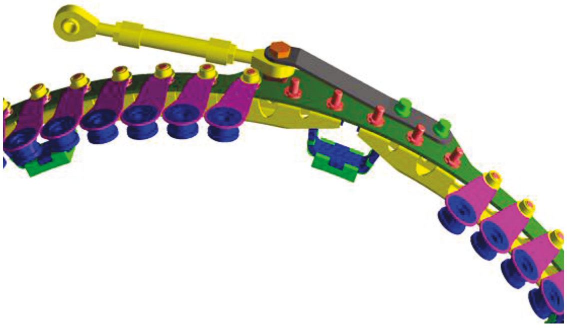

FIG 10. Formerly tested hybrid unison ring variant

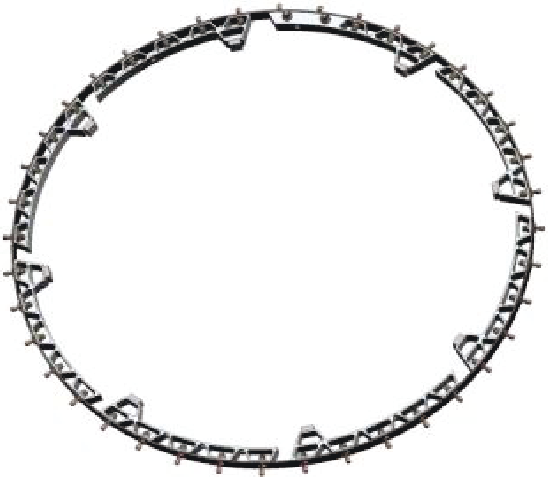

FIG 11. Former composite hybrid unison ring design

The combination of an outer CFRP Ring (see Figure 11) with an underlying aluminium truss generates a thermal expansion behaviour which can be adjusted to the expansion of the adjacent compressor casing, where the ring is bedded on. During the heating-up of the aero engine the unison ring deforms like it is pointed out in the Figure 12 below using a bimetallic effect. At this, the reduced geometrical moment of inertia in the area of the centralizer acts like a virtual joint, avoiding significant stress introduction due heating up the ring as pointed out later on.

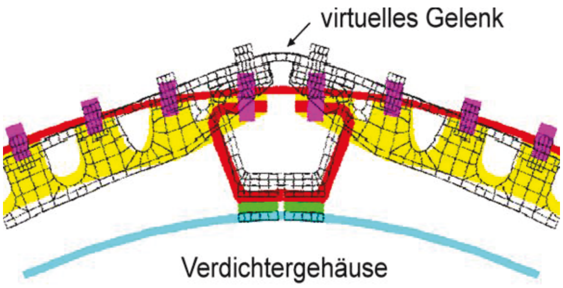

FIG 12. Mechanism to generate thermal expansion of the ring structure

8.2. Initial Concept

At the beginning of the design process different concepts were assessed based on the suggested kind of combination of two materials in the past. Aiming on a better integration of the centralizer in the unison ring, a solution was taken into account were CFRP tubes were integrated in the aluminium truss to take over the support of the ring.

A calculation of that design concept indicates that the thermal deflection of this hybrid system was not sufficient to achieve an increased thermal compatibility to the compressor casing, where the ring is supported on.

Calculations pointed out as well, that the displacement behaviour of the ring is also not desired. The contact area of the centralizer has to be tangential to the compressor casing. Further calculations confirmed that the ring should be preferably supported at a single line orientated along the direction of the engine centre line. As this was not completely convertible, the ongoing design was going to find a compromise. The basic design for the centralizer was seen in a kind of V-arrangement.

8.3. Truss Beam Optimization

A topology optimization was carried out to find the optimum truss geometry. A thermal compatibility, which is equivalent to the maximum of the achievable bi-metallic effect for the ring with the highest temperature loading, was the target function for the optimization. On the other hand the tangential deformation under circumferential loads should be minimized in order to achieve the lowest possible vane malscheduling.
The design space was restricted as constrain for the topology optimization considering the adjacent components of the compressor module and the remaining CHUR parts (Figure 13). In a first step 2D-calculations (plane stress) were carried out followed by 3D-calculations, which were later on used to generate optimised 3D-geometries for further calculations of the ring.
The finite elements were weighted concerning their contribution to reach the optimisation target within the calculation (see Figure 14). Finally the red coloured elements disclose the optimized structure. A transfer of the resulting lattice structure into a 3D geometry model was used for further optimization.

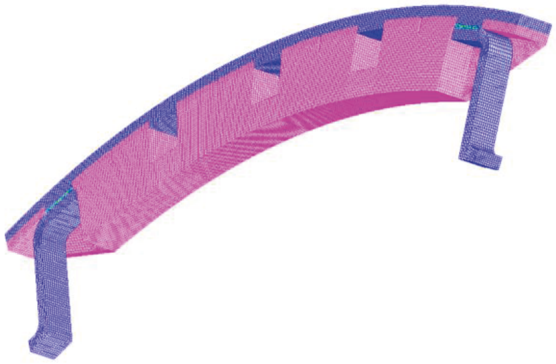

FIG 13. Definition of design space for the topology optimisation

FIG 14. Weighted Elements as results of the topology optimization

Before examining the complete ring structure the stresses were calculated and further optimization was carried out regarding a single segment with a combination of temperature loads and circumferential forces representing the highest loaded substructure nearby the load introduction. Maximum allowable material strength data for low cycle fatigue (LCF) and ultimate load cases for the chosen materials were taken into account during the design process.

The main driver in material selection was, beside a high strength at the required temperatures, their contribution to the thermal expansion behaviour. The truss and the ring materials were selected for maximum difference in CTE, maximizing the bimetal effect.
The thermal expansion of the centralizer reduces the radial thermal expansion of the assembly, asking for a low CTE for the centralizer. CFRP was skipped due to strength issues in the prior development (low out-of plane strength). Invar material was considered as an alternative, but the available strength is too low for this application, so titanium was selected as a strength driven alternative.

In general, it can be stated, that several material combinations are possible for the ring depending on the application and the desired properties. A large difference in the coefficients of thermal expansion is necessary, whereby the material with the lower CTE should be applied in the ring structure. The overall thermal deflection of the CHUR can be adjusted by modifying the height of the truss or the distance between the supports. A light weight structure can be achieved using a combination of CFRP and aluminium.
The thermal induced stresses and actuation loads, which were calculated using finite element analysis (FEA), are of main interest with respect to the hybrid structure (Figure 15).

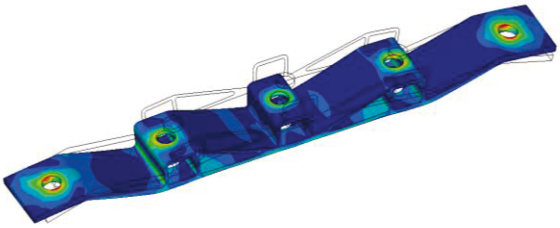

FIG 15. Stresses of aluminium truss during normal operation

High stresses occur especially at the outer bolts of the aluminium truss and the CFRP ring respectively as expected as these bolts have to transfer the tangential forces from the aluminium trusses to the CFRP ring and back to the next truss. As the tangential forces are almost completely transferred by the aluminium due to the load path, these bolts have to transfer the complete load, resulting in high bearing loads. That interface is also tested using simplified coupons to verify the design experimentally (see also Chapter 10).

8.4. Centraliser – Ring – Truss Interface

During the progress of the design, the zone around the centralizer was identified as most critical and limiting for maximum loads. Main reasons for the high stress levels are the implementation of the virtual joint and the bolt loads. Therefore different modifications were investigated as pointed out in Figure 16. The modification of the centralizer and its integration in the design is accompanied by a reduced cross section of the outer ring to decrease the geometrical moment of inertia.

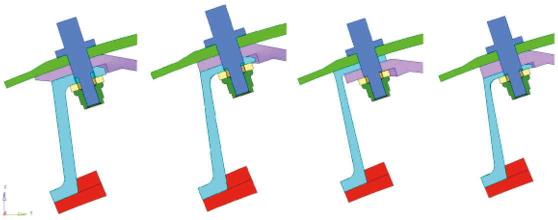

FIG 16. Local design optimization

Within all these calculations several boundary conditions are implemented in the finite element model:

- Contact definition between all material transition areas,
- Isotropic/anisotropic material behaviour,
- Pre stress in bolted joints,
- Friction between materials.

8.5. Full Ring Analysis

After final optimization of the single segment, the complete ring was investigated in detail including the load introduction feature. Here two different versions were taken into account. The first one comprises a single actuator which transfers the tangential load at a single position into the ring, while a second one uses two opposed actuators.

The calculations pointed out that the angle of attack of the tie-rod, which transfers the load into the unison ring needs to be chosen carefully. Small deviation from the optimum would cause high bending loads within the structure.

For further stress reduction the positions of the load introduction were modified compared to the original CHUR. The load introduction was moved as close as possible to the line of action defined by the lever pins using the available design space.

As expected the calculations confirmed, that the 2-actuator-system leads to a significant reduction of actuator force and reaction forces of the centralizers due to the reduced contact pressure between compressor casing and unison ring centralisers.

8.6. Actuation Accuracy – Vane Malscheduling

Vane malscheduling is reducing the compressor efficiency, increases fuel burn and rotor and stator vane excitation. Thus, the reduction of vane malscheduling level is a major requirement especially for high-efficiency small core-size future aero engines.

Beside the vane malscheduling due to the clearances between CHUR centralizer and HPC casing, the circumferential displacement due to thermal expansion and normal operating loads is also contributing to the total vane malscheduling.

Vane malscheduling is generally evaluated based on the tangential displacements of the pins at the centre position of the levers ball heads. Figure 17 shows the resulting displacements of the CHUR for a single actuator configuration and normal operating loads as an example. The vane malscheduling was significantly reduced for all load cases (normal operation and surge) compared to a conventional full metal solution as a result of the stiff CFRP band.

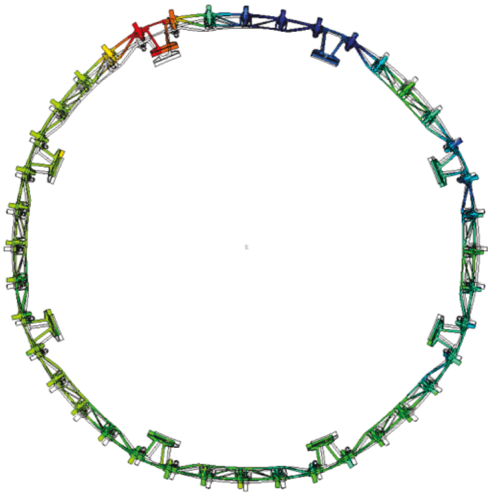

FIG 17. CHUR deformation, 1-actuator set-up, normal operational load

8.7. Buckling Analysis

As an outcome of the FEA small regions were identified where compression load in the ring is dominating. Especially for this situation a buckling analysis has been carried out in order to calculate the remaining reserve factors against buckling. While a non-linear calculation did not converge in combination with the contact analysis, a simplified linear buckling analysis was carried out to determine the bifurcation points regarding the three first buckling modes (Figure 18).

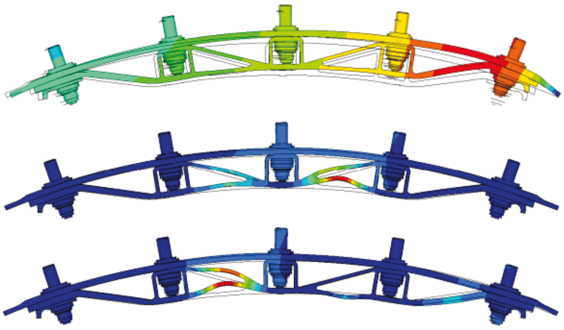

FIG 18. Calculated buckling modes (mode 1 at the top, middle: mode 2, bottom: mode 3)

The resulting buckling factors are all >2 for the investigated modes, which proofs the chosen CHUR design.

9. FULL ASSEMBLY DESIGN

The available design space at the compressor module was additional limiting factor, which has to be considered during the whole design phase. The given interfaces with the adjacent parts like the HPC casing, the crankshaft and the vane lever were taken into account in order to avoid clashes with other components during the actuation of the VSV system.

The final CHUR structure in combination with the complete HPC module was modelled using a full assembly mock-up to visualise the given design space restraints due to the compressor casing and the adjacent VSV stage.

Here, the integrated multifunctional pins have to be mentioned in particular, which contribute to the weight reduction of the unison ring system. They combine the truss and the ring segments as well as they are used for the load transfer from the vane lever to the unison ring. Additionally they are used to join the segments respectively the ring segments among each other.

Within the development work the load introduction was revised and especially adapted to the foreseen test rig application, representing the VSV mechanism of a state of the art two-spool aero engine. This kind of load introduction is in good accordance to the intended tangential load introduction, what is the optimum solution avoiding secondary bending moments in the CHUR component.

The proposed CHUR also avoids the usage of special bridging pieces like they are used in the conventional metallic design. Thus the overall weight of the unison ring assembly could be reduced by ~40% compared to the conventional full-metal design.

10. TEST CAMPAIGN

Different tests are planned in order to validate the assumed material properties of the laminate, the predicted strength of the components and the stiffness and thermal behaviour of the full CHUR assembly:

10.1. Coupon tests

At first experimental investigations using simplified plane specimens were carried out in order to quantify the effect of the low glass fibre content in the UD carbon fabric (see Figure 19 and 20). At this, notched plane specimens were loaded by tensile and alternating loads to determine the maximum allowable bearing load (→ ultimate load) and to proof that the worst case operational bearing load can be withstand for the defined life time (→ LCF test).

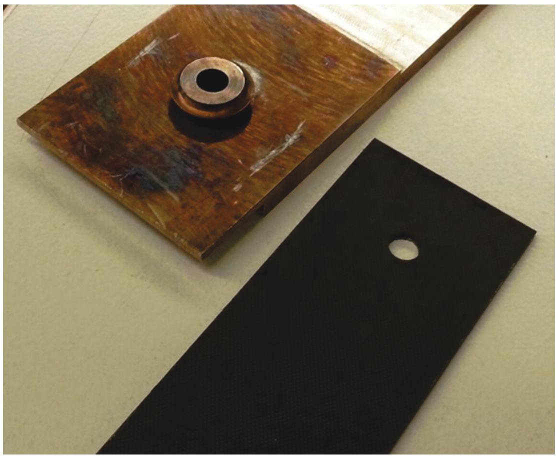

FIG 19. Test Specimen of CHUR for tensile and LCF testing at NLR

FIG 20. LCF testing of plane test coupon at NLR

10.2. Full assembly VSV rig test

The experimental validation of the full CHUR assembly will take place on the multistage VSV rig at the TU Dresden lab. At this, different kind of loads (worst case normal operation load at steady and transient conditions, surge loads) will be applied at single and double actuator configuration in order to validate the former made numerical prediction. The resulting vane malscheduling around the circumference will be measured using vane angle resolvers. Strain gauges are applied to measure the component stresses due to the VSV actuation.

11. SUMMARY AND CONCLUSION

Aiming at increasing overall efficiency for future aero engines, the accuracy, robustness and lifetime of the variable stator vane system has to be increased. In addition to this, also higher temperatures and pressures due to the increased overall pressure ratio have to be considered.

Within the EU-funded R&T programme E-BREAK (2012-2016) a non-conventional VSV unison ring has been further developed by the DLR Stuttgart in order to consider the enhanced requirements, which is described in detail within this paper.

Expert knowledge regarding cost-efficient CFRP-manufacturing from the NLR was incorporated during the complete design phase of the hybrid unison ring as well as detailed interface requirements from the aero engine manufacturer Rolls-Royce Deutschland Ltd & Co. KG.

An overall weight reduction of ~40% compared to the current full metal unison ring design was achieved by the combination of CFRP and lightweight aluminium alloys. Furthermore the adapted thermal expansion behaviour and the stiffer design itself led to an improved vane scheduling accuracy, which ends up in lower fuel burn, higher surge margin and less vibration excitation of the adjacent rotor blades.

Test parts will be manufactured by the NLR in 2015 and subsequently tested under realistic, engine-like conditions at the institute for lightweight constructions and polymer technology at Technical University of Dresden.

12. ACKNOWLEDGEMENT

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