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A NOVEL APPROACH TO LOW EMISSION COMBUSTION RIG TESTING

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Abstract

Future engine programmes are facing significant challenges with demanding development schedules and ambitious technical performance requirements. In addition, a new Rolls-Royce generation of rich burn - quick quench - lean burn (RQL) low emission combustor is in development to reduce NOx emissions by more than 30% compared to current in-service technology of BR700 engines. These stringent emission targets require the introduction of latest combustor technologies with fast quenching jet air mixing accompanied by advanced cooling designs. To mature these new technologies they have to be validated on rig level before their implementation within an engine development programme.

Hence a novel, accelerated approach for combustion rig testing has been developed. This utilised advanced preliminary design and CFD tools for the definition of the combustor subsystem and fast-make innovative design and manufacturing techniques for the make of the rig hardware, which had never been attempted before within Rolls-Royce for this type of application. The main purpose was to provide a process for fast manufacturing a full annular prototype combustor, which allows fast turn-around times of combustor hardware and testing of multiple configurations upfront any engine development programmes providing valuable, early test data. The advantage of the new approach is to enable early testing and hence down-selecting between different low emission combustor and component standards assessing key combustor attributes and risks. This represents a significant step towards a "right-first-time" combustor design into future products.

Full Annular (FANN) rig testing is a standard used to evaluate the aero-thermal performance of the combustor and to understand, amongst others, gaseous and particulate emissions, thermo-acoustic characteristics, combustor exit temperature traverse and combustor liner temperatures. FANN rig tests are frequently undertaken for new engine development programmes, but typically testing occurs late within the engine development programme due to extended lead times of conventional combustor manufacturing, causing significant risks to the programme not meeting customer or legislative requirements.

Additive Layer Manufacturing (DLD) is an emerging technology of significant interest to Rolls-Royce and offers many opportunities for improving product competitiveness and lead-times. The Rolls-Royce Deutschland combustor team have been at the forefront of this technology advancement over recent years and therefore decided to fully exploit the lead-time reductions offered by both designing and manufacturing the rig combustor with DLD.

Due to the limited physical size of the available DLD machines, the combustor could not be fully 3D printed in one operation, so it was split into 8 sectors, which were printed individually and then laser welded using an automated operation.

The total lead time for the DLD combustor make was 3.5 months which corresponds to a 70% reduction compared to a conventionally made combustor with a typical lead time of 18 months. This was achieved through close cross-functional working with suppliers using a series of manufacturing trials for DLD and welding and a "design for DLD" approach.

The first fast make combustor - for whose design a patent has been granted - together with a new rig was designed, manufactured, and delivered to test, based on the novel approach, according to schedule. Multiple low emission full annular combustor configurations have been tested delivering precious data to enable a substantiated combustor standard down select.

Part of the work to be presented has been supported through the Lufo IV programme FetMaTec (20T0903A) and the Lufo V programme EmKoTec (20T1313) enabling more efficient combustion testing in the future.

1. INTRODUCTION

Although significant improvements have been made in the field of combustion modelling capabilities, the development of low emission combustion technologies will require substantial experimental and validation efforts to meet future legislative requirements for gaseous and particulate emissions. In general, new aero-engine technologies have to be validated before they can be introduced into a new product. Since a validation on engine level requires a demonstrator engine and thus a significant level of investment, testing to a technology readiness level of 5 to 6 are preferably done on rig level. For combustion technology development this final demonstration on component level corresponds to full annular (FANN) combustor testing, with combustor hardware being close or possibly identical to engine hardware standard. The typical lead time for the design and make of a combustor rig is 18 months, the lead time for a new combustion chamber is 24 month (6 months design + 18 months manufacturing using conventional manufacturing methods).

If a new combustor shall be validated for an engine program, the combustor rig shall run ideally significantly ahead of the first engine. With the above described standard approach this is not achievable, since rig and engine will run in parallel.

For this reason a new approach has been developed which will deliver rig combustion test data much faster than with the standard approach. The combustor manufacturing lead time is reduced from 18 to 3.5 months and the total lead time from 24 to 8 months. With this new approach within a year a new combustor can be tested on an existing rig.

To achieve this, the additive layer manufacturing technology of direct laser depositioning (DLD) has been chosen to make the combustor hardware, for this a dedicated design for manufacturing has been developed.

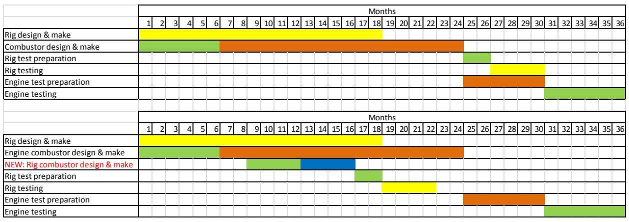

FIGURE 1: Schedule

2. DESIGN PROCESS

The overall intent was to get an aerodynamic representative component in drastically reduced time scales and optimize the combustor design for a new aero-engine by as early as possible altitude and high pressure combustor rig testing. Hence the component design need a certain level of flexibility regarding cowl shape, mixing port diameter and port position. In order to meet the very challenging time scales, a true design for manufacture was required and the manufacturing engineer of the suppliers for the DLD parts, the weld engineer as well as the fixture designer for the laser welding step were integral parts of the project team right from the start of the concept design. The design solution also needed to be robust enough to ensure a high level of integrity for a limited number of tests with very limited stress optimization and largely unknown temperature distribution on the part. Every step was cautiously taken with this target in mind. First, a suitable alloy needed to be selected. After carefully evaluation of all available options, the decision was made to use C263 despite its limited temperature capability because of its high deposition rate in the DLD process, its good weldability & machinability and its high yield level in case of overload, as a forgiving mechanical behaviour was preferred over a higher strength but more brittle response.

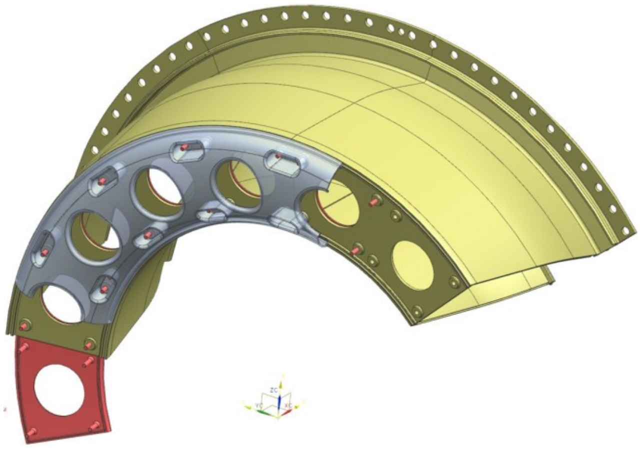

FIGURE 2: Overall concept

As the currently available DLD machines are not large enough to make this size of combustor in one piece, several approaches were studied in order to split the combustor in more manageable pieces and on how to joint them together. In series production the focus would be to fill the powder bed as tightly as possible with small and rather flat sections of the combustor liner. This approach would also lead to the fact, that some portion of the combustor would only be supported via at least one weld seam. But the tight schedule did not allow for build/weld/test trials in order to understand lifing of laser weld seams between DLD parts. Hence the design solution needed to work without detailed weld seam lifing and the decision was made to focus on U-shaped segments comprising the outer combustor wall including the mounting flange, the combustor base plate and the combustor inner barrel in a single DLD part, see Figure 2, which are welded together to generate a full ring, but each segment would be fixed individually on the outer flange and could not become loose (damaging downstream components during test) in case of weld seam failures under mechanical load, but it would only cause an increase in air leakage.

In order to achieve the requested flexibility regarding cowl shape, heat shield cooling and mixing port size and position, these parts are not integrated in the DLD part for the sector but kept as separate items. The studs of the heat shield are used to fix also the cowl segment in place. Mixing port inserts are spot welded in place, see Figure 3.

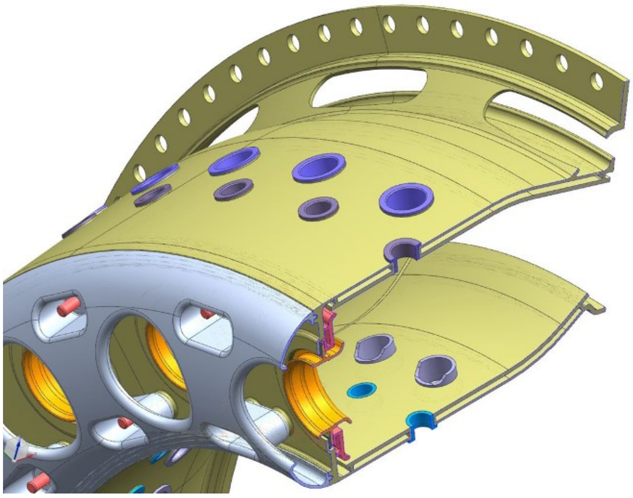

FIGURE 3: Mixing port inserts

Based on this set of decisions, the concept got further refined. First, a set of potential shapes of the sector edge and hence the weld seam were developed: Straight and pure axial half way between the fuel spray nozzles to avoid a direct flame interaction with the seam; straight but with a circumferential slant to pass between mixing ports (opposing slants on inner and outer barrel to follow the swirl of the fuel spray nozzle to protect the weld seam even further); curved in a kind of S shape to start straight axial but curve around the mixing ports. It turned out during trials that the accuracy straight out of the DLD process is not good enough for a weld seam with acceptable metallurgical quality. This triggered a machining operation to prepare the weld faces. Discussion with the weld engineer and the fixture designer led to the insight, that some level of adjustment would most likely be required on the prototypes in order to set a homogeneous weld gap of for example 0,15±0,05mm all around. The only shape that allows some level of adjustments is the straight split line in the axial-radial plane between segments, as all the other shapes interlock when assembled to a full ring, which looks advantages at first glance and might be a good solution for series production with tight process control, but negates any kind of adjustability for the prototypes.

The dual wall structure represents a cast tile mounted via studs onto a sheet metal cold skin generating an impingement-effusion cooling scheme for maximum effectiveness. In the DLD combustor, both skins are actually generated together as one piece. The expected level of leakage between the separate parts in the engine design was reintroduced by a series of properly sized holes in the DLD one-piece design, see also Figure 4. Also the flow disturbance of the studs and washer protruding into the annuli above and below the combustor in the engine was represented in the DLD design by fake studs in order to achieve a representative inflow condition for the mixing ports, see Figure 4.

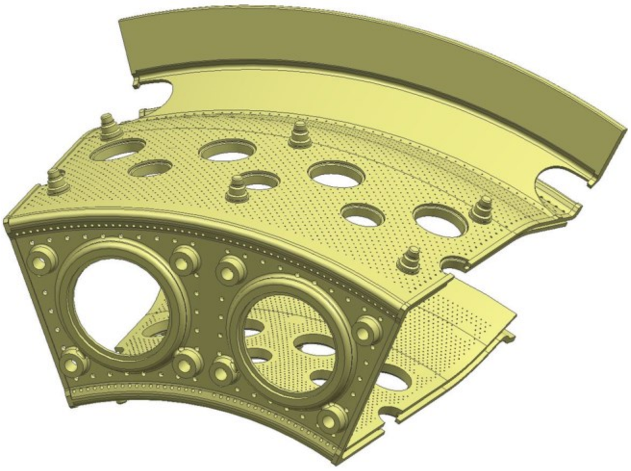

FIGURE 4: DLD segment geometry

The fake studs also connect the hot and the cold skin at a representative position and generate a disturbance in the effusion cooling pattern on the combustor hot side, reducing locally the cooling effectiveness in the DLD combustor in a representative manner, despite the fact that the generative manufacturing of the part would allow to design against this impact, but this was not the aim in the reported exercise. Oversized openings for the mixing port inserts, see Figure 4, allow a couple of millimeter adjustment of the port position by asymmetrically drilled inserts or a moderate enlargement of the port diameter. Port inserts being flush on the hot side can be exchanged by inserts with a tubular extension on the hot side, so called chutes. Experiments can be defined first in a rainbow style for medium pressure testing for emissions and later exchanged with the selected style for altitude relight testing, where a rainbow arrangement delivers difficult to interpret results.

During the initial welding trials, it became clear, that laser welding two skins at the same time could not be developed to the required quality standard in the available time frame. Also welding a solid wall of full thickness of the dual wall design with good metallurgy turned out to be difficult with the available equipment and would require more development time. As solution to this dilemma, it was agreed with the supply chain just to weld the cold skin and to cool the cavity between the two skins above the weld seam with a small amount of cooling air, sized to represent the leakage between tile and liner in the conventional design, see Figure 5. A gap between the edges of the hot skin would allow the laser beam to pass through during welding and the cooling air to escape out of the cavity during operation in addition to the accommodation of the thermal expansion of the hot skin.

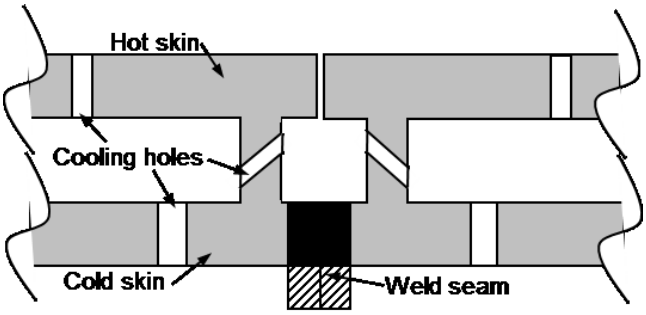

FIGURE 5: Weld seam design [1]

Also visible in Figure 5 is the integral weld filler (hashed area), which is generated as feature on the DLD geometry in order to fill the small weld gap with material for minimum overall shrinkage [1]. The remains of the weld filler are dressed flush with the weld seam (black area in Figure 5).

This parallel development of the design concept and the related manufacturing process took around four months. With now all details of the solution being developed and agreed with the supply chain, the detailed design of the eight individual segments to make a full ring was carried out in the following four months using updated performance and air system data and all the inputs from DLD supplier, welding engineer, fixture designer and machining experts.

3. MAKE PROCESS

To have any chance to deliver parts in 30% of the conventional lead time, the decision was made early on to focus on additive manufacturing, specifically on direct metal laser sintering (DMLS) or direct laser depositioning (DLD), where the part is generated on a flat baseplate using a thin layer of powder, which is selectively melted where a layer needs to be put on the part. After that, the baseplate is lowered by a small amount and then recoated with powder. By repeating this step many times, the part is grown on the baseplate. Some finishing steps need to follow, like separation from the baseplate, removal of the support structure, heat treatment and grit blasting.

An important step in order to achieve reliable results was to acquire a sufficient amount of powder in order to make the welding trial pieces, flow check parts and combustor segment trial builds and 16 segments for two combustors. This way differences in metallurgy, weldability and powder driven build results of small, but through-flow determining features could be excluded.

With the basic DLD parameter set being fixed, a total of 144 weld trial pieces where generated in order to cover most of the features found on the combustor segment concept like constant and gradually changing wall thicknesses, Y-branches and 90° bends. These flat representations were used for weld trial with the identical robotic arm, see Figure 7, selected for the joining process of the combustor segments into a full ring, see Figure 8, in exactly the same orientation during this step. These trials were also used to determine the initial width and height of the integral weld filler, as wire feed of the weld filler was difficult to realize, especially while welding the inner barrel of the combustor.

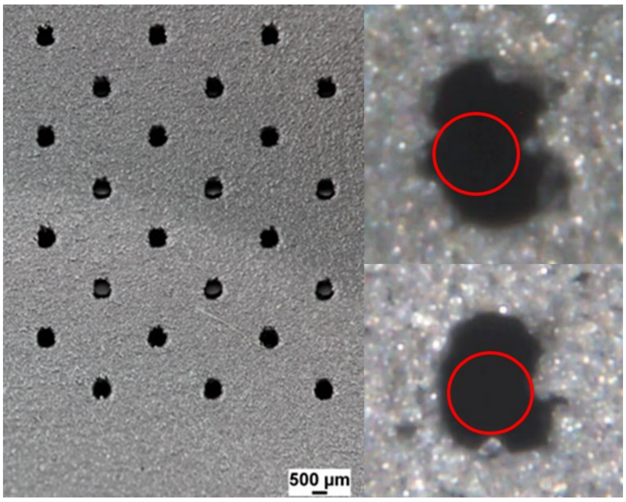

FIGURE 6: Cooling holes by DLD

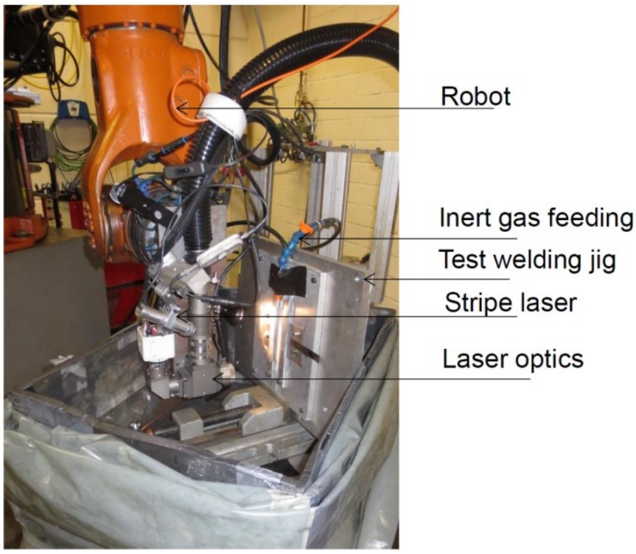

FIGURE 7: Welding trials on coupons (photo courtesy PHOTON Laser Engineering)

Also a lot of flow check pieces were generated in exactly the intended build orientation and inspected using pin check, optical inspection and flow check.

As a solid pin only detects the largest inscribed circle into a hole (see Figure 6) and repeated checks indicated steadily increasing diameters, this method was soon discontinued. Only optical inspection and calculation of the ragged hole inlet area prove to have a strong correlation with the flow check results. When this correlation was established for a specific DLD machine, the parameter set got fixed and is used since then. The next level was to step up from coupons to segments. Preliminary trial segments were generated and inspected by structured light for their shape and flow checked. The deviation in shape was used to drive the support structure design. With a fixed DLD parameter set and DLD machine, the flow was found to be consistent with the expectation.

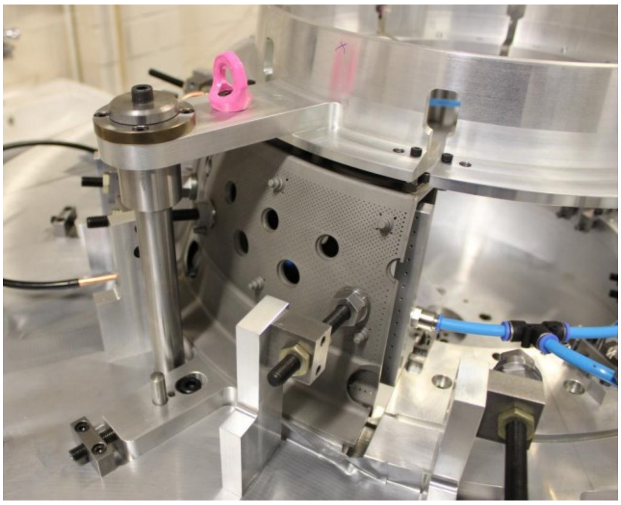

FIGURE 8: Welding jig for combustor (photo courtesy PHOTON Laser Engineering)

FIGURE 9: DLD combustor (courtesy PHOTON Laser Engineering)

To reduce the number of required trials, only one segment was made at a time and cut apart after full inspection in order to weld the outer edges of the halves from the same segment to each other. This step was carried out by the aforementioned 5-axis robot. So the weld set-up and also the weld program was applied to the trial pieces and got verified by these trials. The weld line of the segment was inspected by cut-ups and micrographs to establish the absence of pores and the presents of the intended micro structure. Specific findings on the segment weld trials were fed back into the weld program of the robot.

The detailed make process development described above was carried out in parallel to the refinement of the design concept. After finalizing the detailed design, the pure manufacturing time was again a period of four months or just eight months from new air distribution and final mixing port size to an instrumented metal part ready for testing, see Figure 9.

4. FULL ANNULAR TESTING

Usually a suite of full annular tests is performed on different rigs in different facilities to measure, determine and analyse the different performance parameters of the combustion system. To perform these tests, two dedicated full annular rigs are designed and made for each combustor size.

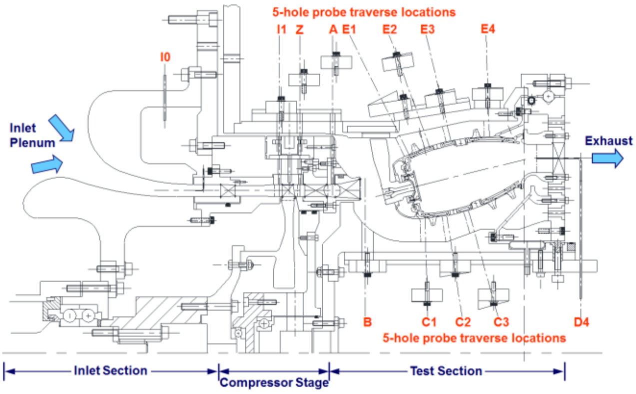

FIGURE 10: Cross-section of Loughborough Perspex rig (sketch courtesy Loughborough University)

One rig (Figure 10) is for atmospheric cold flow testing and the second rig is for hot combustion testing up to full engine pressure P30 and entry temperature T30, shown in Figure 11. Both rigs can be equipped with the fast make combustor described in the chapters before and depicted in Figure 9.

The testing performed includes:

- Full annular cold flow tests in a flow bench at Loughborough University to determine the pressure losses and mass flow of the individual features of the combustor can such as mixing ports and cooling holes.
- Full annular cold flow tests in the perspex rig shown in Figure 12 at Loughborough

University to determine the detailed flow field of the pre-diffuser, of the combustor external flow passages (annuli) and inside the combustion chamber including pressure loss, velocity field and turbulence levels.

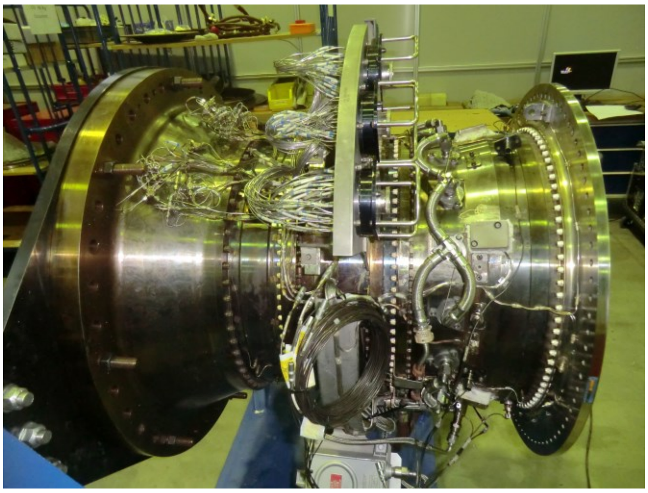

FIGURE 11: Full annular combustor rig (P30 = 40bar)

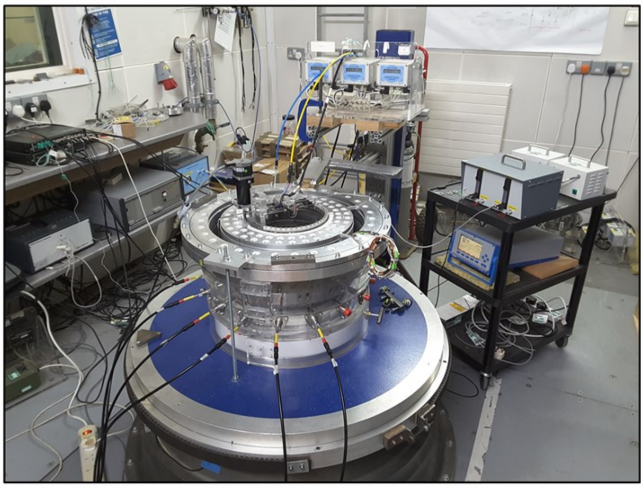

FIGURE 12: Full annular Perspex rig in Loughborough University test cell (photo courtesy Loughborough University)

- Full annular hot combustion tests in the C06 test facility in Derby or the HBK5 test facility at DLR Cologne (Figure 13) using the rig shown in Figure 11 to measure the temperature distribution inside and outside the combustor using thermal paint, to measure the combustor exit temperature traverse, to measure the combustor emissions which are NOx, CO, UHC and smoke using a rotating emissions sampling probe which traverses the full circumference downstream the combustor exit (Figure 14).
- Full annular hot combustion tests in the C06 test facility in Derby or the HBK5 test facility at DLR Cologne to identify the thermo-acoustic characteristics of the combustor at low and high power, i.e. combustor rumble.

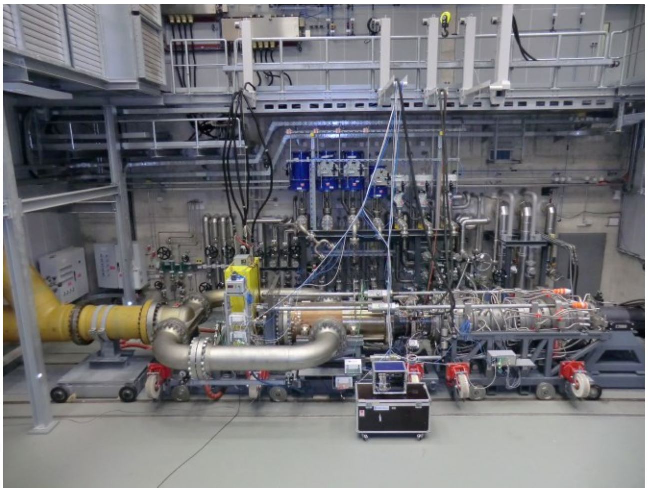

FIGURE 13: Full annular combustor rig in HBK5 test facility at DLR Cologne

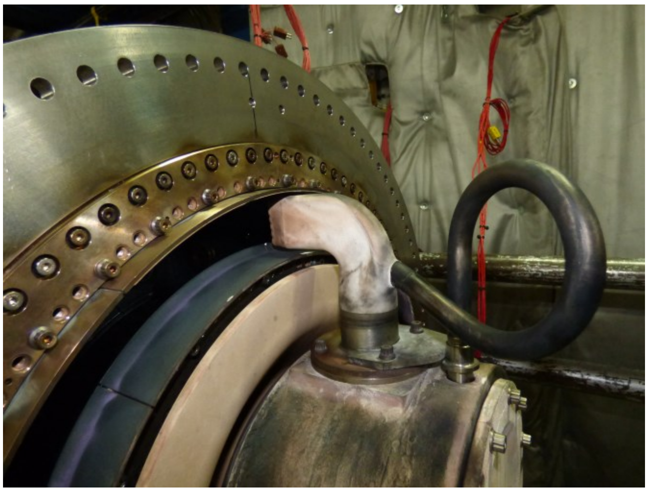

FIGURE 14: Emission sampling probe installed at the combustor exit

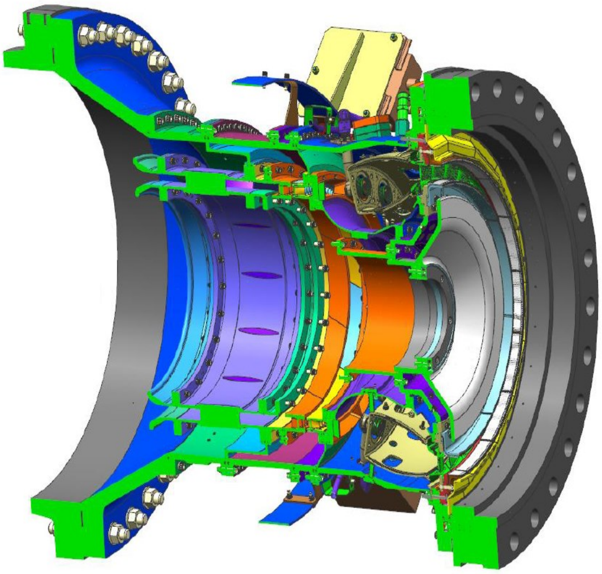

FIGURE 15: Full annular combustor rig with HPT NGVs installed

- Full annular hot combustion tests in the C06 test facility in Derby or the HBK5 test facility at DLR Cologne with downstream high power turbine nozzle guide vanes (Figure 15) to validate the turbine cooling design using thermal paint on the nozzle guide vanes and platforms.

- Full annular altitude relight testing at the altitude test facility of the Institut für Luftfahrtantriebe (ILA) at the University of Stuttgart to measure the combustor relight capability and combustion efficiency at sub-atmospheric conditions (Figure 16).

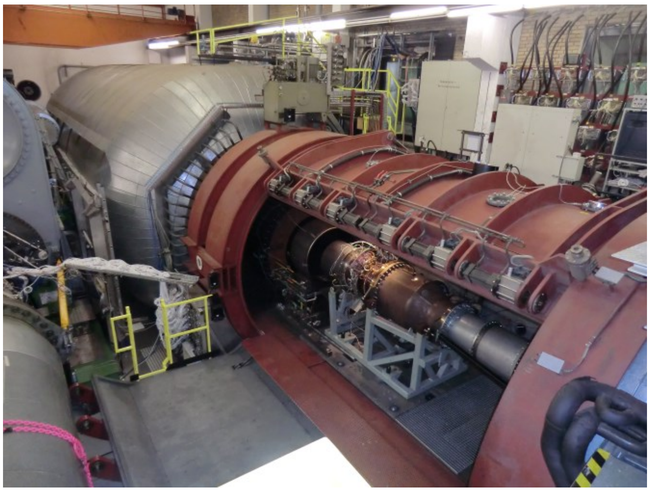

FIGURE 16: Full annular combustor rig in sub-atmospheric test facility at ILA Stuttgart

5. SUMMARY AND CONCLUSIONS

Demanding schedules and challenging technical performance requirements of new engine programmes motivated the development of a novel approach for combustion rig testing. This utilised innovative design and fast-make additive layer manufacturing techniques (DLD) for the make of the rig hardware. Due to the limited physical size of the available DLD machines, the combustor could not be fully 3D printed in one operation, so it was split into 8 sectors, which were printed individually and then laser welded using an automated operation. The total lead time for the DLD combustor make was 3.5 months which corresponds to a 70% reduction compared to a conventionally made combustor with a typical lead time of 18 months. The first fast make combustor - for whose design a patent has been granted - was designed, manufactured, and delivered to test, based on the novel approach, according to schedule. Multiple low emission full annular combustor configurations have already been tested delivering precious data to enable a substantiated combustor standard down select. Further tests are planned to support in a very cost effective way engine development programmes as well as the development of future proof lean and rich burn combustion systems in the framework of German R&T programmes such as Lufo V Emkoval (20T1516).

6. ACKNOWLEDGMENTS

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7. NOMENCLATURE

BMWI	Bundesministerium für Wirtschaft und Energie
DLD	Direct Laser Depositioning
DMLS	Direct Metal Laser Sintering
HPT	High pressure turbine
ILA	Institut für Luftfahrtantriebe
Lufo	Luftfahrtforschungsprogramm
NGV	Nozzle guide vane
P30	Combustor entry pressure
R&T	Research and Technology
T30	Combustor entry temperature

8. LITERATURE

[1] C. CLEMEN, M. GERENDAS, E. EBEL, P. PENZ: “GASTURBINENBRENNKAMMER SOWIE VERFAHREN ZU DEREN HERSTELLUNG”, EP2871418B1