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APPLICATION OF A MINIATURE TELEMETRY SYSTEM IN A SMALL GAS TURBINE ENGINE

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ABSTRACT

For the purpose of assessing combustion effects in a small gas turbine engine, there was a requirement to evaluate the rotating temperature and dynamic characteristics of the power turbine rotor module. This assessment required measurements be taken within the engine, during operation up to maximum power, using rotor mounted thermocouples and strain gages. The acquisition of this data necessitated the use of a telemetry system that could be integrated into the existing engine architecture without affecting performance. Due to space constraints, housing of the telemetry module was limited to placement in a hot section. In order to tolerate the high temperature environment, a cooling system was developed as part of the integration effort to maintain telemetry module temperatures within the limit allowed by the electronics. Finite element thermal analysis was used to guide the design of the cooling system. This was to ensure that sufficient airflow was introduced and appropriately distributed to cool the telemetry cavity, and hence electronics, without affecting the performance of the engine. Presented herein is a discussion of the telemetry system, instrumentation design philosophy, cooling system design and verification, and sample of the results acquired through successful execution of the full engine test program.

1. INTRODUCTION

Telemetry systems are used for the measurement of data via sensors located at remote or inaccessible locations. Since its origin in the late 19th century [1, 2] telemetry has become widespread throughout many factions of modern society. It has been applied in a broad range of sectors including, but not limited to, aerospace, biomedical, industrial, infrastructure, meteorological, and military [3]. Strictly speaking, the transmission can be across any medium, be it wireless or physical such as via cable or optical fiber connections. In any instance, the data is being transferred to a location other than that where it is measured. For example, in medicine, patients have been fitted with measurement and transmission devices for diagnosing or monitoring health issues. In other applications, the populations and movements of wildlife have been tracked, and the weather monitored for agricultural and other purposes. Telemetry also provides the ability to remotely monitor data for real time diagnosis and trending.

In recent years, the range of commercially available off the shelf sub-system components for telemetry applications has increased [3]. Capability has also improved with a trend towards digital data transmission. Due to the demand for increased data needs [4], increases in bit rate (or throughput) capability has become a key driver in the development of new technology. Recent improvements in this area have made telemetry more accessible to applications that otherwise would not have been a feasible option. However, applications continue to push the technology to its limit, such that commercially available products are not a feasible option. Nevertheless, a variety of electronic components are available that allow custom systems to be built such that telemetry can be an integral part of a developmental test program. This paper presents one such case. It concerns the development of a miniature telemetry system for the purpose of assessing combustion effects in a small gas turbine engine.

The paper commences with a brief description of the UNIVERS [5] state-of-the-art telemetry system used in the subject application. This is followed by a discussion of the instrumentation design philosophy adopted, and an overview of the integration methodology of the custom-made miniature UNIVERS telemetry system. Included also is a description of the unique cooling system developed to maintain acceptable cavity temperatures for the telemetry electronics. In addition, the supporting thermal, stress and rotor dynamics finite element analyses, undertaken as part of the design integration process, are addressed. Most importantly, the temperature validation testing, performed prior to commencing engine operation with the actual telemetry electronics, is described. Finally, results acquired from the full engine test with the operational telemetry system are presented.

2. STATE OF THE ART

This section provides an overview of the custom telemetry system, instrumentation design philosophy, and associated engine structural modifications that enabled integration of the telemetry module within the existing architecture without compromising engine performance. Specifically addressed are the design changes to the exhaust collector, coupling nut, power turbine shaft and turbine blisks (a single piece turbine wheel casting with airfoils and shroud), and the development of the cooling system.

2.1 INTEGRATED TELEMETRY SYSTEM

The application of telemetry for the measurement of parameters within the core of a gas turbine engine is very complex. It requires an in-depth understanding of gas turbine design, such that the performance characteristics of the engine are not compromised with the modifications necessary to accommodate the telemetry system. For this reason, the UNIVERS digital telemetry system was developed specifically to address the requirements for the extreme application of a gas turbine engine.

The telemetry system utilized for the purpose of this test is a fully modular system, which means that each module operates as a completely stand-alone and independent unit. In addition, the power supply and signal transmission antennae are integrated into each individual module, thus eliminating the need for cross wiring between modules that can introduce reliability and data quality issues. This full modularity was a mandatory requirement for the presented telemetry system, and is a unique design attribute that is the basis for the proven reliability of the system.

The 14 by 14 mm square modules can be configured into systems having from 8 to 440 channels for low and high channel count applications. Each module is designed for a variety of sensors, typically thermocouples and strain gages, to allow a flexible mix of sensor types in groups of 8 channels to be used. A universal interface allows the configuration to be changed simply by replacing the modules via "plug & play" and connecting new sensor wires.

The main functions to be realized inside a telemetry module are shown in Figure 1. The challenge for the subject small gas turbine engine was to provide a solution that could realize up to 64 measurement channels in a very limited space frame of 70 mm diameter. This capacity per diameter is more than double the capacity which can be realized with telemetry systems made from commercial modules. The maximum operating temperature allowed for the UNIVERS system was defined at 250°F (120°C). A flexible configuration of both thermocouple and strain gauge channels in groups of 8 was required, with a sample rate for the dynamic strain gages of 100k samples per second. The thermocouple modules were designed to measure over a range of 0 to 2280°F (0 to 1250°C) with either type K or type N sensors. Figure 2 shows the static antenna and rotating module housing with slots for up to 8 individual telemetry modules; yielding a total capacity of 64 channels. Integration of the telemetry system with the gas turbine engine is described in the following section.

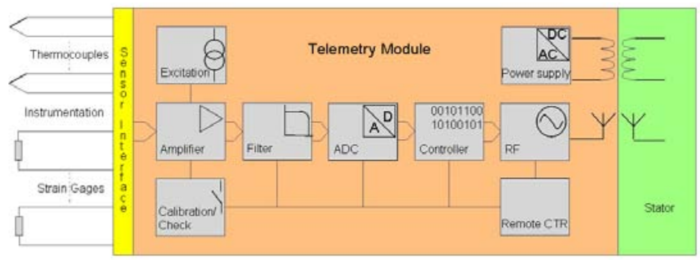


Figure 1. UNIVERS telemetry system functional diagram; ADC – Analog-to-Digital Converter, RF – Radio Frequency Transmitter, CTR - Control.)

Figure 2. UNIVERS telemetry system.

2.2 INSTRUMENTATION DESIGN PHILOSOPHY

The concept of utilizing an integrated telemetry system was driven by the key objective to accurately measure the vibratory stress and transient temperature of a rotating component in a power turbine. However, the engine under consideration is a reverse flow configuration, which renders no external access to the power turbine shafting. Hence, there is no means of externally connecting a conventional slip ring device to acquire data from the instrumentation sensors. One alternative historically used for measuring vibratory stress is a "hot rig," which compromises combustion effects by not including a representative combustor or gasifier turbine module. Although this arrangement will yield an accurate measurement of the blisk response frequencies, it will not necessarily result in accurate vibratory magnitudes due to the approximation of turbulent airflow entering the power turbine. Furthermore, the lack of a representative combustion section significantly compromises the thermal characteristics of the system. Therefore, the only means to accurately capture the required data relied on the ability to integrate a wireless telemetry system in the middle of the engine. At the time this engine was originally developed, the technology available for integrating wireless telemetry systems into such a space was not available. However, recent advances have now made this a feasible alternative. The telemetry module was located in the cavity between the power turbine rotor and exhaust collector that required extensive modification to the engine, and will be discussed later.

The specification of the telemetry system was primarily defined by the data measurement requirements, but was compromised by the limited space available. Although the UNIVERS system offered the smallest and most-capable telemetry electronics available, integrating this into the subject engine involved overcoming several major design challenges; most notably the physical space constraints and high temperature environment of the available cavity. This was made more arduous due to the fact that the power turbine spool was engulfed by an exhaust collector, an awkward weldment of castings and formed sheet metal operating at very high temperature, Figure 3. These constraints limited the number of telemetry modules to 8 thereby limiting the number of available instrumentation channels to 64. In view of this, specific locations for the thermocouples and strain gages needed to be identified such that the data was captured at the points of greatest interest. This was achieved with the support of bench (a laboratory test on a stationary blisk) and historical hot rig data for the strain gage locations.

Strain gage locations were selected from a bench stress distribution test using continuous force excitation on a blisk with a vast array of strain gages applied. Of the full array of strain gages applied, Figure 4a, only locations A, E and H were selected for the engine test. The bench test also confirmed that the blisk responses of interest existed below 16kHz, which was within the 20kHz bandwidth per channel offered by the UNIVERS strain gage module. The selection of strain gage locations also accounted for the fact that the turbine blisks are manufactured with the airfoils grouped in packets, Figure 4b, such that within any given packet the airfoils respond at slightly different frequencies. No redundancy was deemed necessary for the strain gages given that the bench strain gage surveys allow stress values to be determined at redundant or lost strain gage locations by ratioing magnitudes measured from the bench stress distribution.

Thermocouple locations were selected with the aid of a preliminary thermal model. In contrast to the strain gages, it was necessary to apply two thermocouples at each of the 16 selected temperature locations, detailed in Figure 5, to allow for redundancy. The main components of the telemetry system and modified engine components are also illustrated in Figure 5, each being described in further detail throughout the following section.

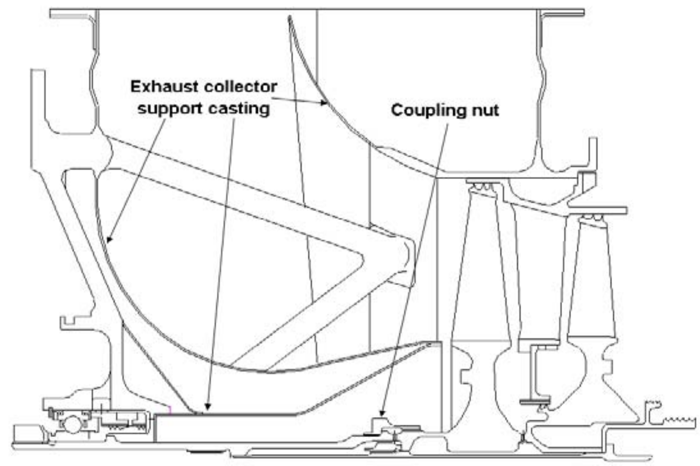


Figure 3. Existing engine configuration.

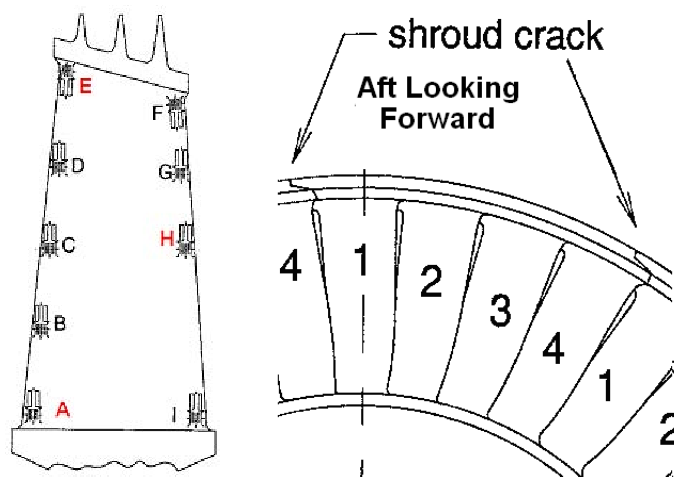


Figure 4. Arrangement of strain gages and blade packets.

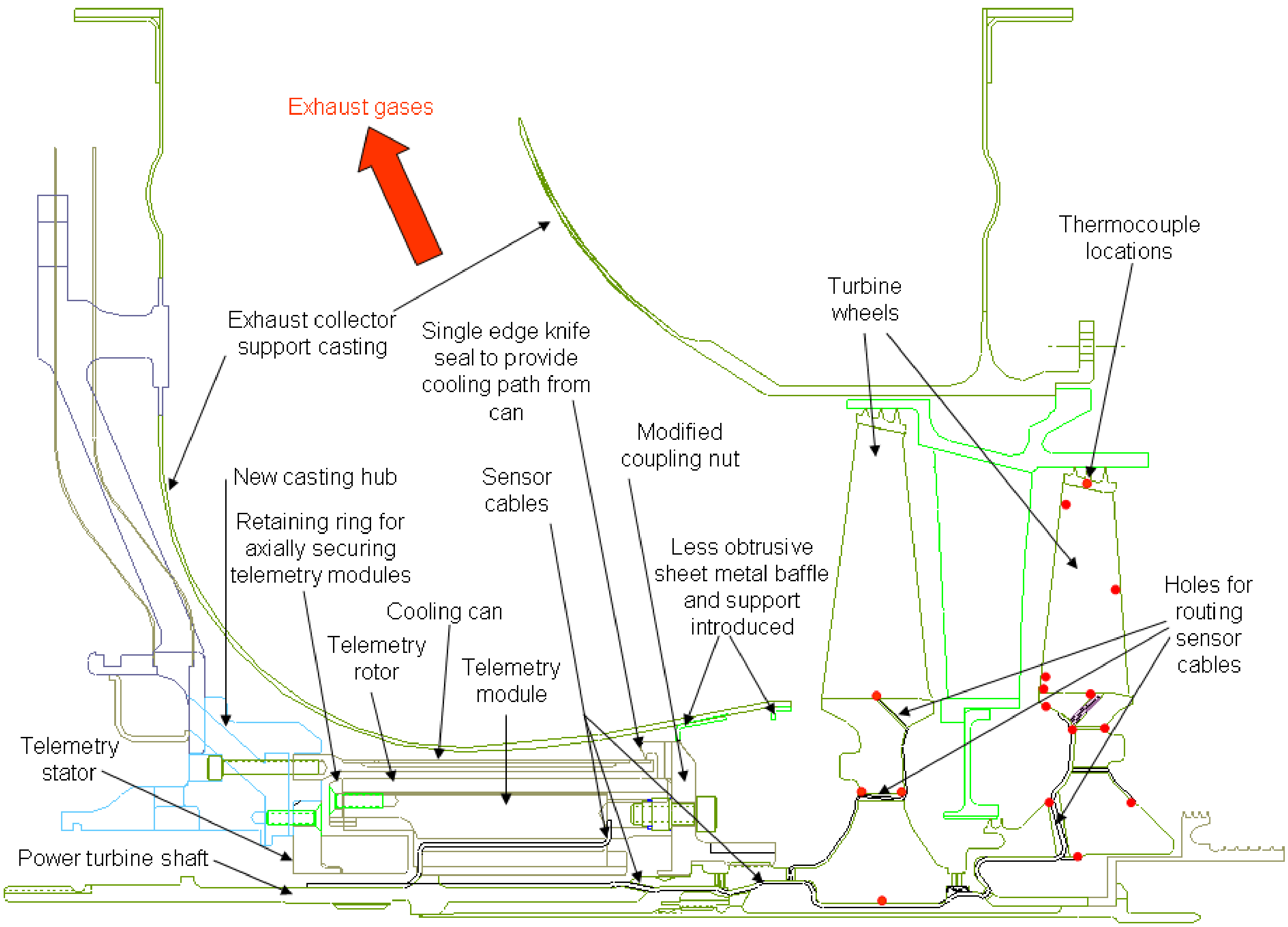


Figure 5. Schematic of the telemetry unit embedded in the turbine; (dots on blisks identify thermocouples.)

2.3 CUSTOM TELEMETRY SYSTEM

After several design concept iterations, it was determined that the best location to position the telemetry module was between the exhaust collector support casting and coupling nut, Figure 3. Locating the electronics in this region required structural changes to the exhaust collector to accommodate the mounting of the telemetry stator while incorporating an in-house designed active cooling system to maintain the temperature within the operating limit of the telemetry electronics, 250°F.

Exhaust Collector

The exhaust collector underwent several key design changes, Figure 6. First, the original casting hub was cut out and replaced by a new hub to which the telemetry stator and cooling can could mount. The new hub also incorporated passages through which cooling air was delivered to the telemetry electronics via a cooling air manifold and delivery tubes. Finally, the original sheet metal supports and heat shields were removed and replaced by a less obtrusive sheet metal baffle and support.

Cooling Can

The cooling can developed specifically for the purpose of limiting the exposure temperature of the telemetry system is shown in Figure 7. This new component was designed to encapsulate the telemetry electronics in a sufficiently cooled volume. It was designed to feed cooling air in a distributed manner (to achieve uniform flow to prevent hot spots) to the outer surface of the telemetry electronic components and was double-walled to minimize the effect of radiant heat from the exhaust collector duct. The cooling can also incorporated a series of bleed holes through which cooling air was dumped to the atmosphere. Figure 8 shows the exhaust collector with the cooling jacket installed, with the cooling air tubes indicated by arrows. These cooling air tubes were connected to a manifold, Figure 9, that fed air via a flow meter and pressure sensor to ensure the desired level of cooling airflow was achieved.

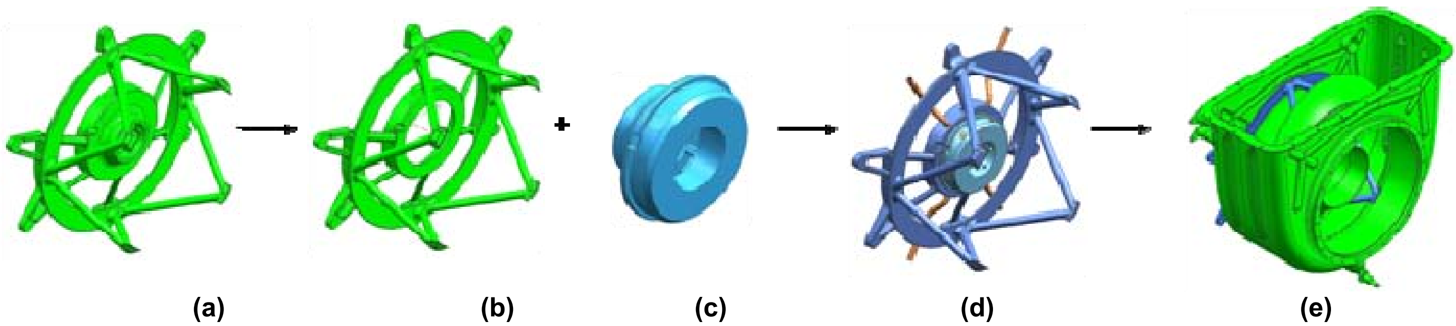


Figure 6. Modification of the exhaust collector; (a) Original configuration; (b) With casting hub cut out; (c) New hub; (d) New configuration with modified hub and cooling air manifold with tubes; (e) Final exhaust assembly.

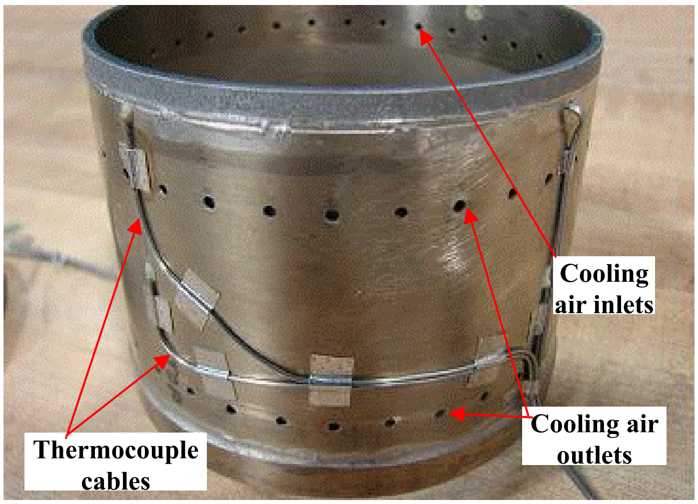


Figure 7. Cooling can developed to limit exposure temperature of the telemetry system.

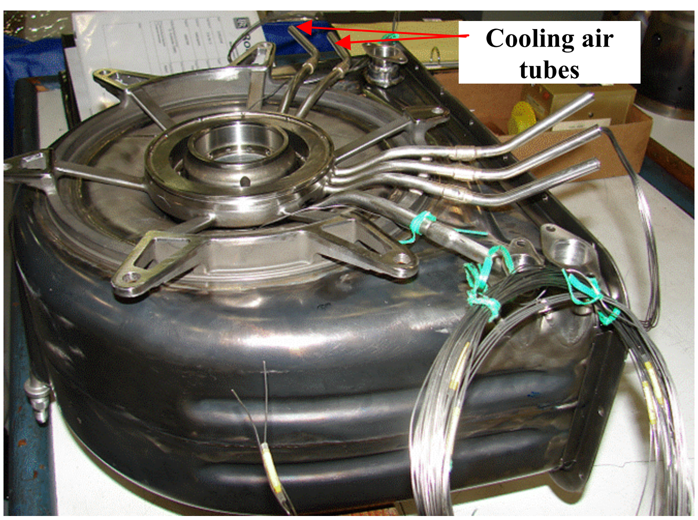


Figure 8. Exhaust collector with cooling jacket installed.

Telemetry Rotor

The conceptual arrangement of the rotating telemetry hardware with the power turbine rotor components is shown in Figure 10. The telemetry rotor was designed to house as many telemetry modules as possible within the space allowed. The telemetry rotor is essentially a can, which also acts as a heat shield for the telemetry electronics. Due to the small radius required to stay within the exhaust collector, the telemetry rotor could only house 8 modules, Figure 11. The aft face of the telemetry rotor, Figure 11a, was slotted to allow the flow of cooling air around the aft side of the rotor. These slots left intermittent pads that bolted to the interfacing nut (coupling nut, Figure 10) to help minimize the conduction of heat from the nut to the telemetry electronics.

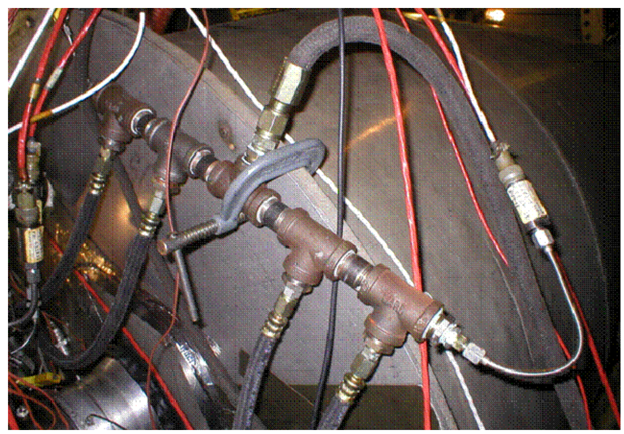


Figure 9. Manifold for cooling air for cooling jacket.

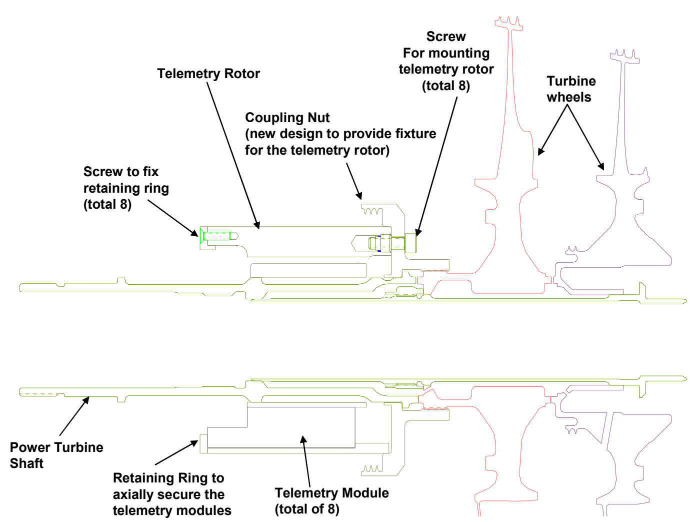
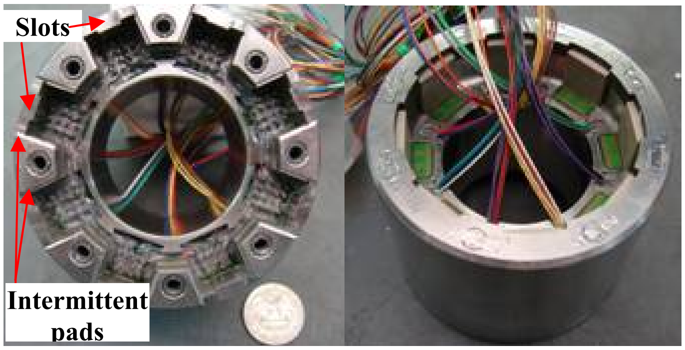


Figure 10. Cross section of integrated telemetry rotor.



(a) (b)

Figure 11. Instrumented telemetry rotor; (a) View of aft face; (b) View of forward face.

Turbine Blisks

The turbine blisks were modified slightly to incorporate feed holes for routing telemetry cables, Figure 12. These modifications were only made in the hub area as directed by analysis, such that blisk integrity and performance were not compromised.

Figure 12. Modified turbine blisk for cable routing.

Power Turbine Shafting

The power turbine shafting was modified to incorporate an intermittent shoulder on which the telemetry rotor would rest. The shoulder was intermittent for two reasons. First, to allow sensor cables to route through it, and second, to touch the telemetry rotor in as few places as possible thereby minimizing the conduction of heat from the power turbine shafting to the telemetry electronics. This shoulder was positioned and shaped in such a way to also serve as a ramp that signal carrying cables could be routed along for transition from the telemetry rotor to the power turbine shaft. In addition, the new shaft incorporated a series of holes through which sensor cables were routed in order to get from the inner diameter of the shaft to the outer diameter. The power turbine rotor, assembled with the turbine blisks and new coupling nut, is shown in Figure 13.

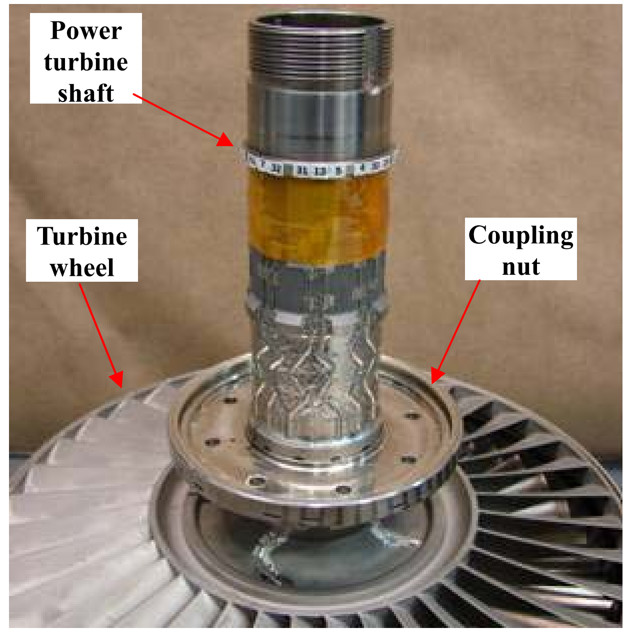


Figure 13. Power turbine shafting assembled with turbine blisks and coupling nut.

Coupling Nut

A new nut was designed to provide the connection between the power turbine and the telemetry rotor. The nut also interfaced with the cooling can via a single-edge knife seal for cooling purposes, Figure 5. Figure 14 shows the telemetry rotor mounted to the coupling nut in its final assembled configuration prior to assembly in the engine.

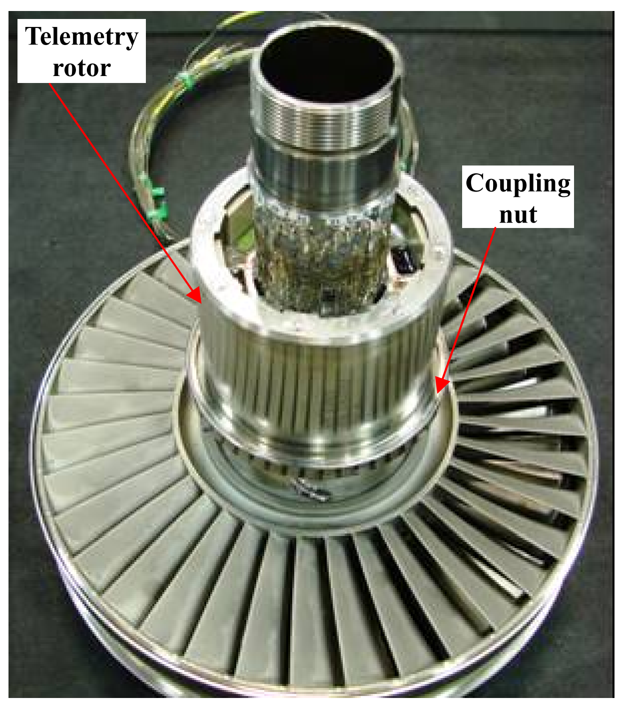


Figure 14. Power turbine shafting assembled with turbine blisks and coupling nut.

2.4 ANALYSIS

To assist with the design of the telemetry rotor and modifications of the existing engine components, a series of analyses were conducted. A brief overview of the rotor dynamics and stress analyses is presented in this section. The thermal analysis is described in Section 3 regarding telemetry system validation.

Rotor Dynamics Analysis

A rotor dynamics analysis was conducted to identify whether the rotor mounted telemetry hardware and other engine modifications influenced either: (1) the location of rotor critical speeds, and (2) the overall system vibration levels. In addition, the analysis helped define the steps to be taken for rotor balancing. The biggest concern was the potential for rubbing of either the dummy or actual telemetry module as the rotor passed through all critical speeds. Figure 15 shows the arrangement of the Rotordyn 2D model used for the analysis [6] showing the displacement locations assessed by simulation. A representative plot of the normalized displacements at the telemetry module, as determined by analysis across the operational speed range of the power turbine rotor, is shown in Figure 16.

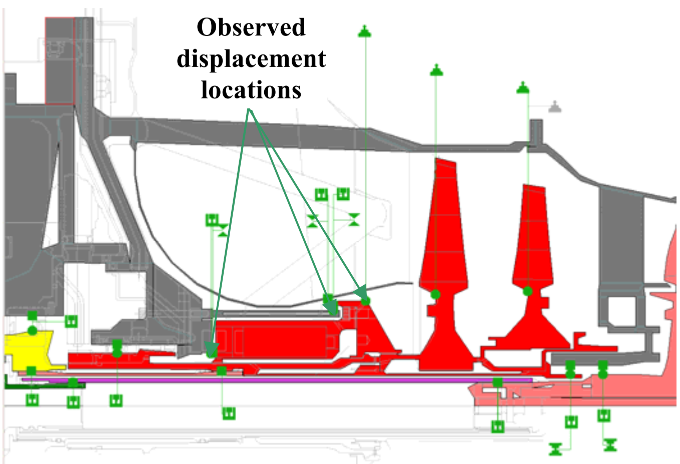


Figure 15. Rotordyn [6] rotor dynamics analytical model.

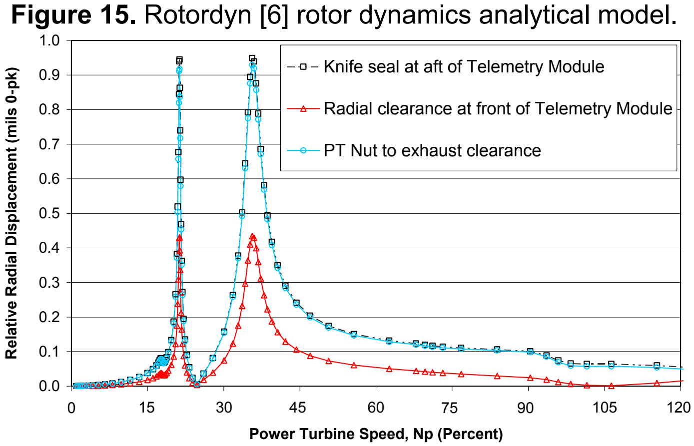


Figure 16. Analytical unbalance response of telemetry rotor module.

Stress Analysis

A stress analysis was conducted to ensure that the holes introduced for routing the telemetry wires did not compromise the structural integrity of the power turbine blisks and shafting. The rotor model used for the analysis is shown in Figure 17.

Figure 17. ANSYS 3D stress analysis model.

This analysis was conducted to ensure there was no risk of a component failure during testing. A stress analysis was also conducted on the cooling can, with particular focus on the features used for radially and circumferentially locating the telemetry module, to ensure that the stresses were well within the capability of the material. The rotor structural model shown in Figure 17 was used to assess stresses up to 115% power turbine speed.

3. VALIDATION OF TELEMETRY EXPOSURE TEMPERATURES

Insufficient cooling of the telemetry system posed the greatest risk to the test program as it could have resulted in failure of the telemetry electronics. This condition would have prevented the collection of the required data, as well as imposed an unacceptable hardware replacement cost and time penalty.

The design of the cooling arrangement was defined by the available space for the cooling can and the means of routing its cooling air in and out of the engine structure. The effectiveness of the initial cooling arrangement was evaluated using a STRATA [7] static 2D thermal model. The output of this analysis verified the cooling system design and was used to establish the required cooling airflow. However, to verify the design, thereby mitigating the high risk associated with insufficient cooling, it was determined that a practice test be undertaken utilizing a dummy rotor in place of the telemetry module. This cooling design verification test also provided valuable insight that was used in a turbine blisk thermal model correlation activity that resulted from the thermal test. The knowledge acquired was subsequently used to develop a real time transient thermal stress model for purposes beyond the scope of this paper. The engine prepared for the practice test utilized much of the same hardware required for the instrumented test. The only difference was that the telemetry electronics were replaced by “dummy” modules. In addition, thermocouples were applied to various static hardware components to monitor and validate key cavity and metal temperatures. These temperatures were of interest to ground and validate the thermal model used to define the requirements of the cooling system to insure that the telemetry electronics would be below the allowed maximum operating temperature. However, of greater interest was the temperature of the dummy modules which, in the absence of the telemetry electronics, could not be measured with rotating thermocouples. Therefore, the dummy modules used in place of the telemetry modules were each populated with a row of thermal dots as shown in Figure 18a. Thermal dots only provide a single pre-defined indication of temperature by changing color permanently once the threshold temperature has been exceeded. Therefore, each module employed a different series of thermal dots with differing threshold levels to offer a scale of graded temperature detection from 190°F to 500°F.

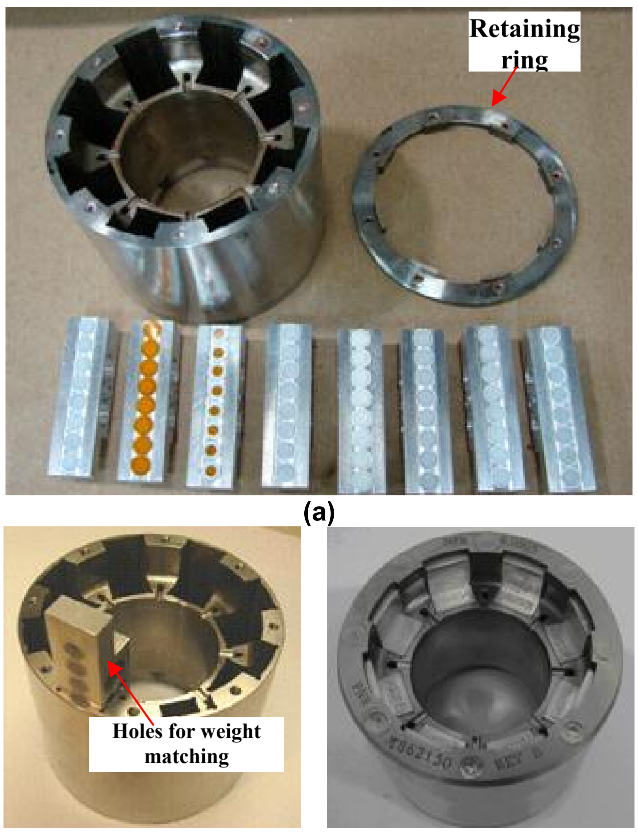


Figure 18. Thermal dots mounted on “dummy” telemetry modules to verify temperature exposure.

Figure 18a also shows an aft view of the cooling can arrangement used to house the rotating telemetry hardware, together with the retaining ring used to secure the modules axially in the can. Figure 18b shows the orientation of the dummy modules, and hence thermal dots, with respect to the can. Figure 18c shows the fully assembled dummy rotor with the retaining ring installed. It should be noted that the dummy modules were weighted equally to match the actual electronic modules. This was achieved by removing metal with a series of holes, as can be viewed in the dummy module shown in Figure 18b.

The telemetry system validation test results were positive. The engine successfully completed an initial check run, then a performance calibration to full power, a thermal simulation cycle consisting of snap transients to and from flight idle and take-off, a typical mission profile test, and power turbine speed sweeps from idle speed to 115% nominal cruise. Throughout the validation test, absolute temperatures were measured on the static side of the cavity using thermocouples. The peak temperatures measured during operation at maximum continuous power are compared to the finite element analysis temperature prediction in Figure 19. The highest temperatures measured in the exhaust cavity during the test were on the outer surface of the turbine module that interfaces with the exhaust collector. This was expected because of the high temperature of the exiting gases through the exhaust collector. The effectiveness of the cooling system is evidenced by the thermal gradient measured across the cooling can, 175°F on the outer surface and 112°F on the inner surface. As can be seen in Figure 19, the thermocouple measurements are in very good agreement with the analysis. Furthermore, the analysis predicted operating cavity temperatures between 108°F and 150°F around the rotating section. This prediction was verified by the thermal dots, which were observed not to have changed color indicating that at no time during the practice test did the telemetry modules exceed 190°F, well within the allowed 250°F continuous operating temperature limit. This test validated and proved that the cooling arrangement was more than adequate to cool the telemetry electronics.

The real telemetry modules produce heat, but this issue was addressed by including built-in temperature sensors in the telemetry modules such that the cooling airflow could be adjusted accordingly during the instrumented testing. However, the excessive use of cooling air flow was limited by the requirement to avoid compromising engine performance.

Table 1 compares engine performance for different test configurations, including the engine prior to it having any modifications (baseline engine). The measured data shown in Table 1 confirms that engine performance was not compromised by incorporating the telemetry module and its cooling system.

Table 1. Comparison of engine performance for each configuration at the same power level (full power).

Engine Configuration	Torque (lb-ft)	Mean Gas Temperature, MGT (°F)	Ambient Temperature (°F)	Power Turbine Speed, Np (rpm)	Gas Generator Speed, Ng (rpm)
Baseline	529	1339	40	32190	50240
Cooling Test	577	1393	62	29479	50954
Thermal Survey	552	1344	63	30844	50696
Stress Survey	565	1333	52	30133	50254

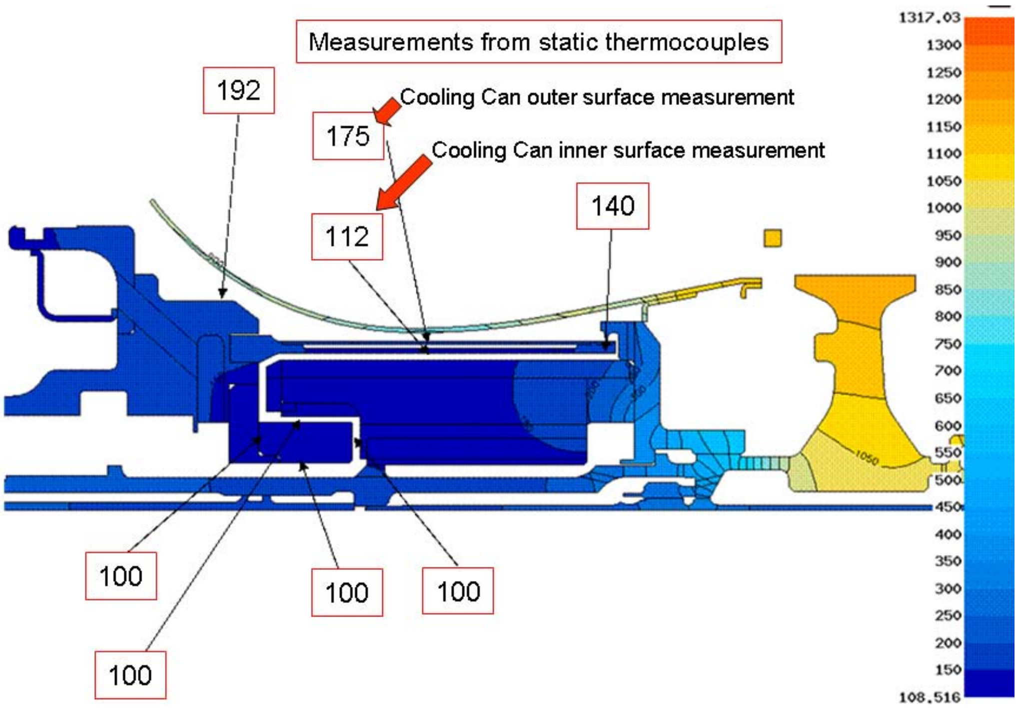


Figure 19. Measured vs. STRATA [7] based predicted telemetry module cavity temperatures at full engine power.

4. TEST RESULTS

The fully instrumented engine with the integrated telemetry system is shown in Figure 20 prior to installation on the test stand. An example of the temperature measurements acquired from the rotating thermocouples via the telemetry system during engine acceleration to full power is shown in Figure 21. The plot shows measurements from two thermocouples mounted on different airfoils at the midspan location and one hub mounted thermocouple together with gas generator speed, Ng, and power turbine speed, Np. This start was undertaken while the engine was still warm from a previous run, which explains why the three thermocouples, mounted in different locations, initially measure different temperatures. As expected, the hub mounted thermocouple measured the highest temperature prior to the run as the hub would retain heat from the previous run longer than the airfoils. Once engine operation commenced, the airfoil metal temperatures converged to similar values very quickly, whereas the change in hub temperature was significantly slower. The thermal stresses induced in the blisks during start up are far greater than at any other point during operation; hence, data capture during engine starts was the main focus of the temperature test. The power turbine speed is observed to settle at 96%, which is within the typical steady state operating range of 95% to 100% depending on specific engine application. The double-humped fluctuation in Np approximately between 45 to 110 seconds is attributed to the control of the dynamometer rig used to load the engine.

The turbine blisk frequency response and associated dynamic stresses, measured via the telemetry system for an engine speed sweep at 500 shp, are given in Figure 22. Due to the packet configuration of the airfoils, there are numerous airfoil responses for any given mode which is why there are several data points in each of the dashed ovals in the top part of Figure 22. This phenomenon does not occur for hub dominant mode responses, in which the data highlighted by the solid ovals is clustered together. The region defined as “low speed transient” represents the speed range passed through as the engine accelerates from ground idle to flight idle. The region defined as “steady-state speed” is the operating region depending on engine application. The region defined as “over speed transient” represents speeds beyond normal operation. The main observation is that no responses occur across the steady-state operating speed range of the engine.

Figure 20. Test engine instrumented prior to installation in the test stand.

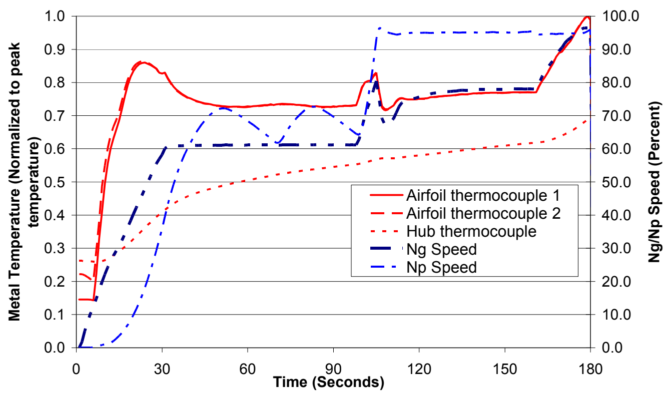


Figure 21. Blisk rotating metal temperature data during acceleration to full power.

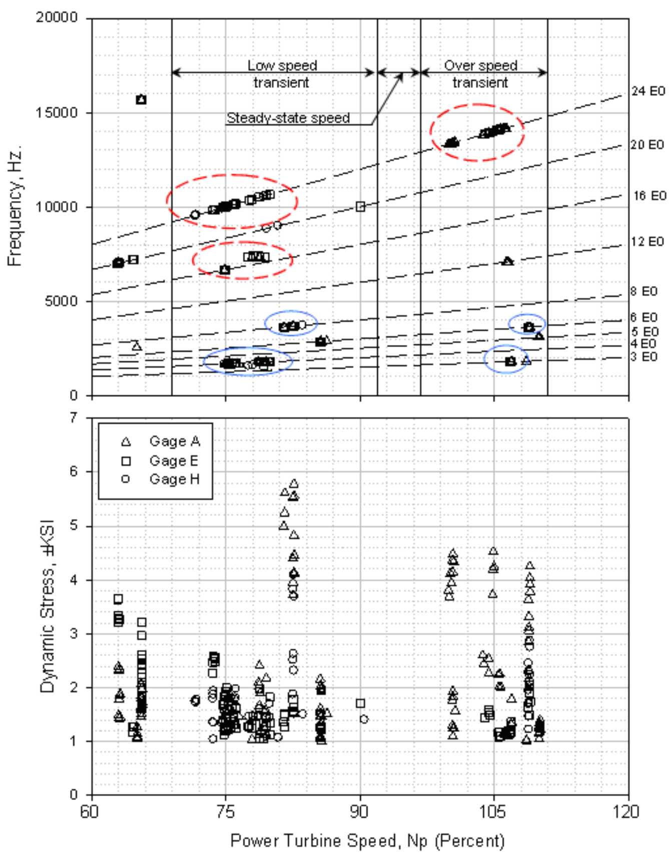


Figure 22. Turbine blisk rotating strain gauge data measured via telemetry system during acceleration to 500 shp; dashed ovals contain airfoil responses, solid ovals contain hub dominant responses. Gages A, E & H correspond to airfoil locations defined in Figure 4a.

Figures 21 and 22 are only two examples of the many successful engine runs, totaling 35 hours operating time, used to capture the transient thermal and vibratory stress characteristics of the power turbine blisks. The telemetry system worked flawlessly throughout the test program, enabling all required data to be captured despite failures of some of the sensors due to normal attrition. Furthermore, no thermocouple measurement positions were lost due to redundant sensors having been incorporated at the time of system integration.

5. CONCLUSIONS

All risks associated with applying a miniature telemetry system in a hot environment in a gas turbine engine were successfully mitigated. This was achieved through appropriate use of thermal and structural analyses during the design phase, and practice testing using a dummy telemetry rotor to assess exposure temperatures. The actual telemetry system worked flawlessly throughout the full engine test program, with key achievements summarized below:

- Engine performance was not compromised by the integration of the telemetry system, as evidenced by maximum engine power (Table 1) being achieved within normal engine operational parameters.
- The telemetry system was successfully operated in a hot environment with the use of a custom designed cooling system.
- All transient thermal and dynamic strain gage data was successfully acquired.
- Thermal data was acquired at a rate sufficient to distinguish the transient characteristics across the turbine blisk that allowed a real time comparison between hub and airfoil temperature gradients.
- The telemetry system provided the high frequency response and resolution characteristics required to capture dynamic strain gage data up to 16kHz.

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