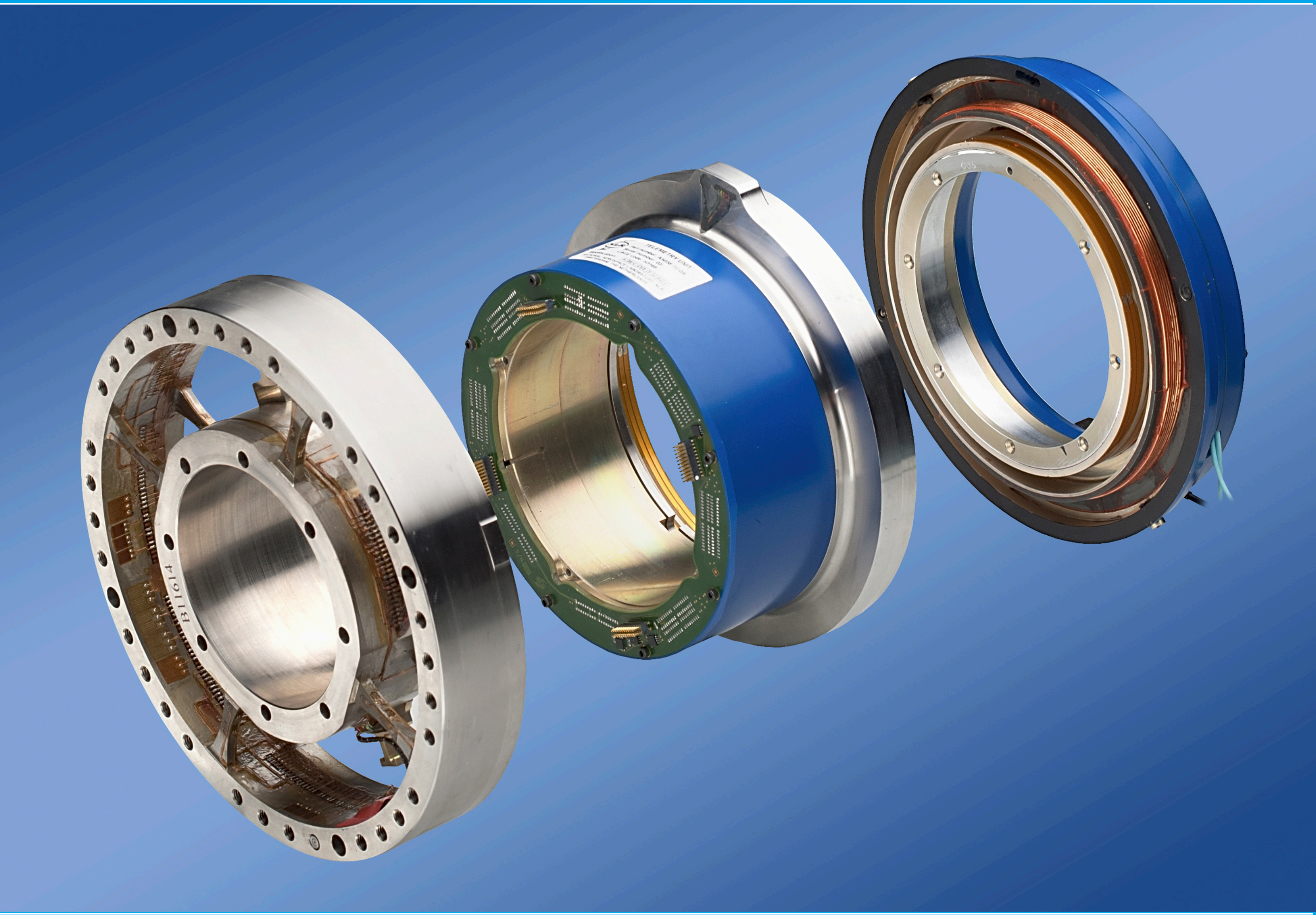
A Contactless Telemetry System for a Contra-Rotating Open Rotor Test Campaign

NLR-TP-2015-172 - May 2015



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EXECUTIVE SUMMARY

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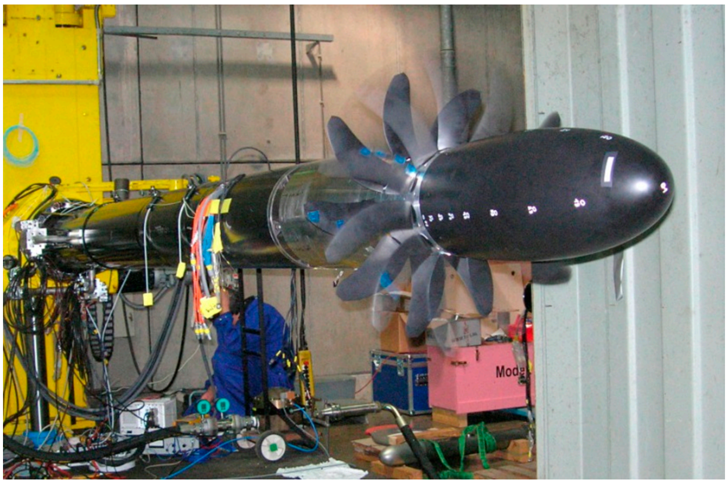

Description of work

Within the Clean Sky European program Airbus and its partners conducted a series of wind tunnel tests to experimentally investigate the aero-acoustic performance of a CROR-powered aircraft on a T-tail baseline at low speed and a scale of 1/7. For this purpose, NLR developed an extensive instrumentation system. This instrumentation system was required to perform highly synchronised measurements of several hundred acoustic and mechanical parameters.

Custom design and manufacture of a dedicated telemetry sub-system was needed to enable measurements in the rotating domain at a rotational speed of up to 8,400 RPM. In view of the limited reliability and life of slip ring assemblies at these high rotational speeds and the high data rate needed, the decision was

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This report is based on a paper presented at the NATO STO symposium on Test Cell and Controls Instrumentation and EHM Technologies for Military Air, Land and Sea Turbine Engines, AVT-229-RSY-030, Rzeszów, Poland, April 21, 2015.

taken to develop a contactless method of transferring electrical power and measurement data between the stator and the rotor parts.

This paper discusses the requirements for and the design of the sample-synchronous instrumentation system and highlights the design challenges found in the rotating telemetry system. Finally, the system's performance during the 750-hour measurement campaign is briefly discussed.

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Abstract

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Content

Abbreviations

Acronym	Description
1P	Once per revolution
ADC	Analogue-to-Digital Converter
CROR	Contra-Rotating Open Rotor
DC	Direct Current
DNW	German-Dutch Wind Tunnels
FEC	Front-End Computer
FPGA	Field-Programmable Gate Array
IDMS	In-flow Dynamic Measurement System
kB	Kilobyte
kSPS	Kilosamples per second
LLF	Large Low-speed Facility
Mb, MB	Megabit, Megabyte
MDMS	Model Dynamic Measurement System
MIS	Model Instrumentation System
NLR	National Aerospace Laboratory NLR, the Netherlands
PCI	Peripheral Component Interconnect
PXI	PCI eXtensions for Instrumentation
RPM	Revolutions per minute
TCP/IP	Transmission Control Protocol (TCP) and the Internet Protocol (IP)

1 Introduction

Investigations on Contra-Rotating Open Rotor (CROR) engines have been carried out as early as the 1980s. Problems with vibration and noise as well as dropping oil prices put a halt to those activities at the time. Today, potential savings in fuel consumption and advances in material engineering and aerodynamics have led to renewed interest in this kind of propulsion.

A CROR has two series-mounted rotors which rotate in opposite directions coaxially. The purpose of the second rotor is to undo the rotating motion of the air originating from the first rotor. In addition, the propulsion efficiency of a CROR is high due to its high bypass ratio. However, the integration into an airframe is challenging regarding masses, aerodynamics, noise and vibration. CROR rotor noise is a particular concern during take-off and landing.

Therefore in 2012, within Clean Sky, a European Joint Technology Initiative, Airbus and its partners conducted a series of wind tunnel tests at the large low-speed facility of the German-Dutch Wind Tunnels (DNW-LLF) in Marknesse, the Netherlands. The step-by-step research conducted is intended to lead to introduction of CROR propulsion on passenger aircraft. A first step in the development is theoretical work; the second step consists of validation through wind tunnel measurements. Test aim is to achieve deeper understanding of the aerodynamic and acoustic aspects of the CROR concept in low-speed conditions.

2 Model and Sensor configuration

The CROR concept aircraft wind tunnel model is a complete aircraft scale 1:7 with two air-powered engines. For these engines, with a maximum rotational speed of 8400 RPM, Airbus designed and built the air motors. NLR designed and produced the composite propeller blades, hubs, 6-component rotating strain balances and related telemetry. Apart from propeller blades for the Airbus model, propeller blades were also designed and built for other engine manufacturers.

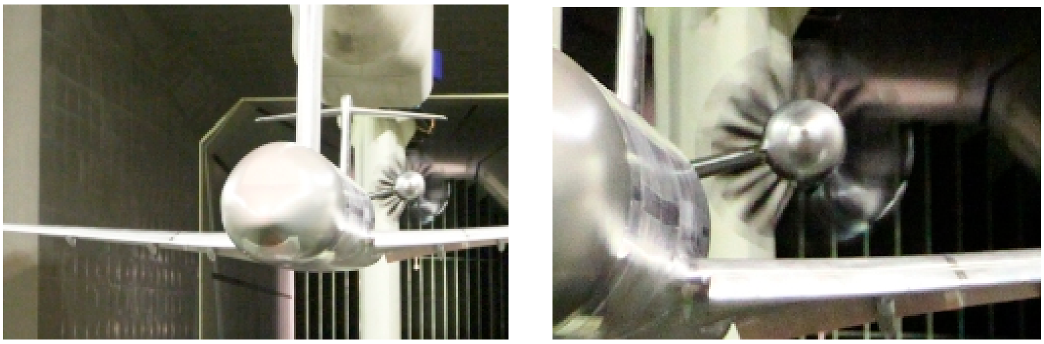

Figure 1. CROR engine mounted on a concept aircraft model.

Each engine contained two RSBs and two identical telemetry units, one for each propeller hub. The set-up enabled relatively easy conversion between a pusher and a tractor configuration of the engine.

For the acoustic tests, the model was surrounded by large numbers of microphones placed at various distances. The model itself, and a number of rotor blades, are also equipped with microphones and pressure transducers for making acoustic measurements and profiling the pressure distribution across the model and the wings. Rotor forces and moments were also continuously measured for each rotor.

3 Test Campaign

The DNW Large Low-Speed Facility (LLF) was selected for executing the low-speed range test campaign. It was launched in April 2012 and comprised three test programs. Depending on the program, an isolated CROR test set-up or a complete concept aircraft model was used.

The first test program was performed with one engine in the LLF open test section. The second test, handling quality, took place on the complete model (aircraft plus engines) in the closed test section. The third test was executed with the complete model in the 'open space' section for noise investigation. Measurements were made during approximately 750 hours and resulted in many terabytes of data for subsequent analysis. The campaign was successfully concluded in January 2013.

4 Model Instrumentation System

NLR developed the mechanical and acoustic measurement system with components both in and outside the CROR model.

4.1 Instrumentation system requirements

The following major requirements applied to the instrumentation system:

- 80 microphone channels, 152 pressure channels, 32 strain gauge channels, 12 temperature channels
- Excitation power outputs for the pressure transducers and strain gauges
- 16-bit resolution and 10 kilosamples per second (kSPS) for the strain gauge and temperature channels
- 24-bit resolution and 100 / 200 kSPS for the pressure and microphone channels
- Maximum timing divergence between all channels: 1 µs
- Telemetry units: Support operation up to 8,400 RPM. Local acceleration: $5.5 \cdot 10^4$ m/s^2.

4.2 System overview

The instrumentation system requirements called for the development of a dedicated acoustic and rotor force Model Instrumentation System (MIS). The main reason for this was the strict requirement to provide highly synchronous data of all acoustic sensors and the rotor forces. All sound pressures in relation to the angular positions of the rotating propellers needed to be measured with a mutual timing error of less than 1 µs. The MIS comprises the entire chain of data acquisition, pre-processing, monitoring and registration. A Control and Display Computer provides the test specialists with a real-time display of measurement data and allows for monitoring of critical parameters.

The system's acoustic sensors consist of microphones and pressure transducers. Microphones are used in the so-called In-flow Dynamic Measurement System (IDMS). This system measures 48 microphones mounted on a traversing rake system measuring in the flow. The microphones and pressure transducers inside the model itself are measured by the Model Dynamic Measurement System (MDMS), for a total number of 144 sensors. Both the IDMS and MDMS rely largely on standard measurement equipment.

Sensors in the propeller blades are also part of this acoustic measurement system. For each of the 4 rotors, a total of 10 pressure sensors are mounted in two blades, adding another 40 acoustic sensors to the system. The four Telemetry Units (TU) were custom designed for measuring and digitizing the sensor signals for forces, temperatures and the blade pressure sensors in the rotating domain. The measured data of the TU is transferred in a contactless manner from the rotating part to the fixed part of the TU and then to the Front-End Computer (FEC) using standard point-to-point 100 Mb/s FO Ethernet hardware. The Telemetry Units are discussed in detail in chapter 5.

A high-level overview of the MIS is shown in the block diagram below.

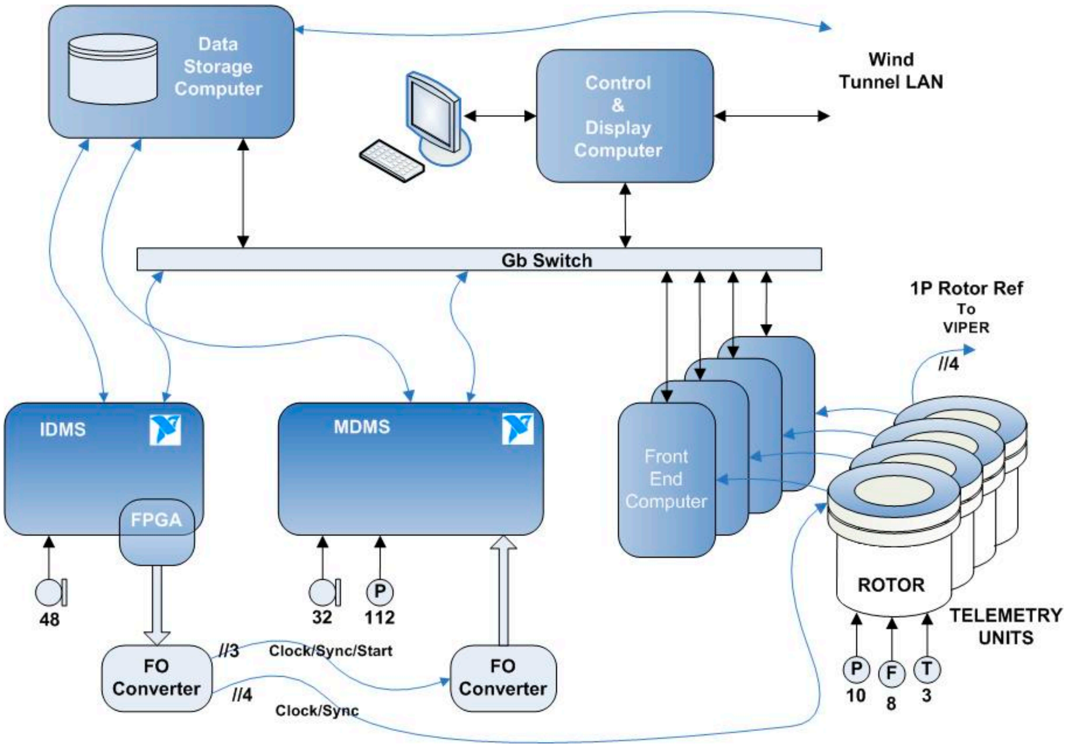

Figure 2. Model Instrumentation System block diagram.

4.3 IDMS and MDMS implementation

Both the In-flow Dynamic Measurement System and the Model Dynamic Measurement System were realized using off-the-shelf PXI equipment from National Instruments. The modules used in this equipment are able to provide the required functionality and performance. 24-Bit resolution and a sample rate of up to 200 kSPS enable capturing all harmonics that may be present in the acoustic signals. The equipment also provides off-the-shelf solutions for synchronizing data acquisition modules and PXI racks together by using a programmable FPGA-based FlexRIO module.

The Model Dynamic Measurement System consists of a PXI chassis mounted inside the fuselage of the aircraft Model. This chassis houses two 16-channel high-accuracy data acquisition modules and 14 8-channel bridge input modules. A total of 144 microphones and pressure sensors in the model are accommodated.

The In-flow Dynamic Measurement System (IDMS) is realized using an 8-slot PXI chassis with three 16-channel high-accuracy data acquisition modules for the connected microphones. The IDMS also acts as the master time base for the entire system using a PXI System Timing Controller Module together with the FPGA module. The latter distributes all necessary timing signals (clock, start and sync) to all subsystems including the four Telemetry Units. A specific compensation scheme was devised in order to compensate for delays introduced by cable propagation and the data conversion in the Telemetry Units and PXI boards.

Each data output sample of both aforementioned systems and from each Telemetry Unit has a unique sample number. Tests were performed to measure initial group delays and to demonstrate correct synchronization to within 1 µs after careful tuning of the timing.

4.4 Data infrastructure

All data and synchronization signals are transferred using fibre optic cabling to prevent EMC problems. The measurement data from all subsystems are sent to a Data Storage Computer. Thanks to the Ethernet interface, standard IT equipment can be used for this purpose. A central Command and Display Computer supervises the entire system, enabling the user to check the data and sensors, and to monitor whether overloading or clipping occurs. From this computer, a synchronization command can be sent to the IDMS, which then synchronizes the clocks and acquisition of all systems. Once synchronization is established, the system is ready for measurements. During the actual measurement, the IDMS and MDMS data is sent in a binary format over a TCP/IP Ethernet connection at a rate of almost 50 MB/s to a Data Storage Computer for offline analysis. The data from the TU is buffered in the FEC and transferred to the Data-storage computer after each measurement point.

A typical test point takes up to four minutes, with a maximum of 10 minutes and a typical test day generates up to 512 gigabyte of data.

4.5 Monitoring infrastructure

The FEC software continuously performs a number of monitoring and pre-processing functions on rotor data:

- Monitoring the temperature of subsystem components to ensure that the electronics does not overheat
- Pre-processing of a selection of the measured rotor sensor data into engineering units, including the generation of non-rotating domain forces and moments acting upon the rotor.
- Monitoring the forces and moments acting upon the rotor, to avoid fatigue problems of the rotor using a Goodman diagram.

These functions enable efficient assessment of installation correctness and subsystem checkout after each of the many configuration changes that occurred in the course of the campaign. Additionally, the monitoring of critical mechanical parameters ensures continued mechanical integrity of the rotating system parts.

The IDMS and MDMS monitor the temperature of the subsystem components, especially in the fuselage of the model, where the temperature is likely to rise due to restricted ventilation, frictional heating, and electronics power dissipation.

The Control and Display Computer performs real-time conversion to engineering units of a selected subset of the acoustic channels of the IDMS and MDMS for checkout and monitoring purposes. A flexible data distribution system supports multiple displays of this monitoring information at various locations.

5 Telemetry Units

5.1 Overview

The Telemetry Units of the Model Instrumentation System measure and digitize the rotating sensor signals that represent forces and temperatures in the force balances and pressures in the blades. The measured data is transferred in a contactless manner from the rotating part to the fixed part; clock and synchronization commands are transferred vice versa, as well as electrical power. The picture below shows the rotating strain balance, the related Telemetry Rotor, and the Telemetry Stator at the far right. The balances and the Telemetry Units are identical for the inner and outer shaft of the air motor for improving efficiency in design, production, and maintenance.

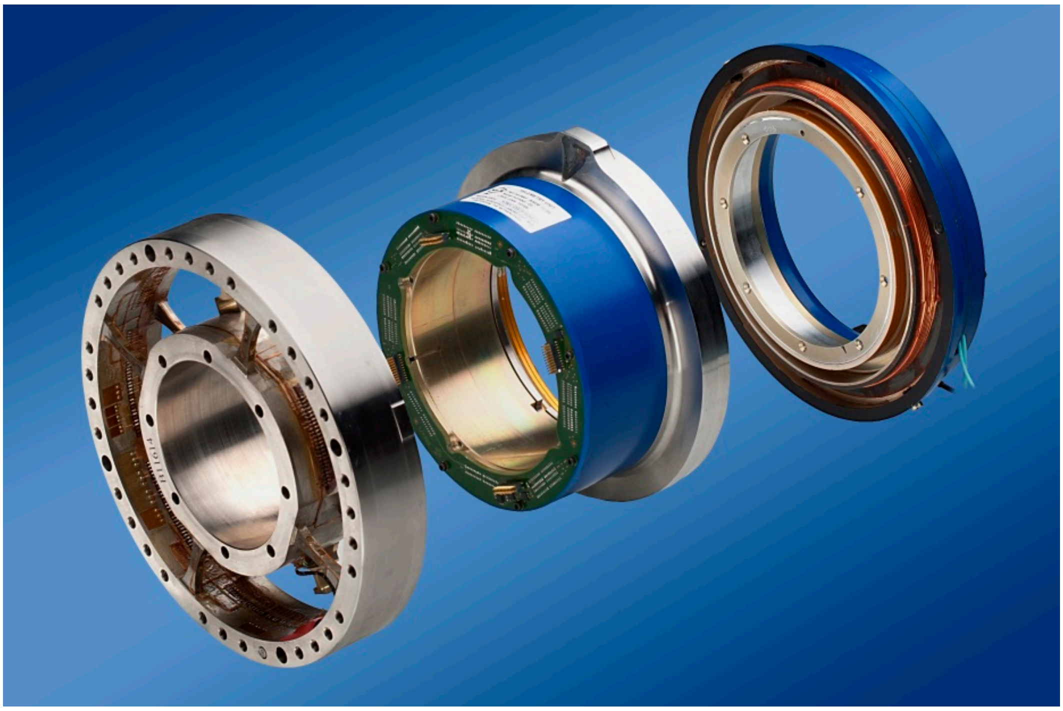

Figure 3. Balance and Telemetry Unit rotor and stator.

The Telemetry Rotor consists of a Rotor Module Housing containing data acquisition and service modules and a Rotor Flange Assembly comprising one part of the contactless power and data transfer equipment. The modular design provides for fast and easy maintenance in case of malfunctions. Prior to commissioning the rotor, static balancing is performed to allow rotation at elevated speed. This is done in a staged approach: first the balance, then the balance with the Rotor Module Housing and modules, and finally the entire assembly of balance, modules, Module Housing, and Rotor Flange Assembly. Balancing weights are added as required in every stage.

Data transfer between the Telemetry Stator and Rotor is accomplished using a bi-directional transfer mechanism for which NLR has a patent pending. The Telemetry Unit Stator directly interfaces to a Front-End Computer using a standard 100 Mb/s Ethernet connection. All interface connections between the Telemetry Unit and other MIS subsystems is realized using low bend radius fibre optic cables. This allows routing of the cabling through narrow spaces and past tight corners.

An optical rotor position encoder mechanism is mounted in the Telemetry Rotor and Stator in order to provide accurate rotor position information. Power to the Telemetry Unit is provided by a power supply which is located inside the model.

The figure below shows the block diagram of one Telemetry Unit.

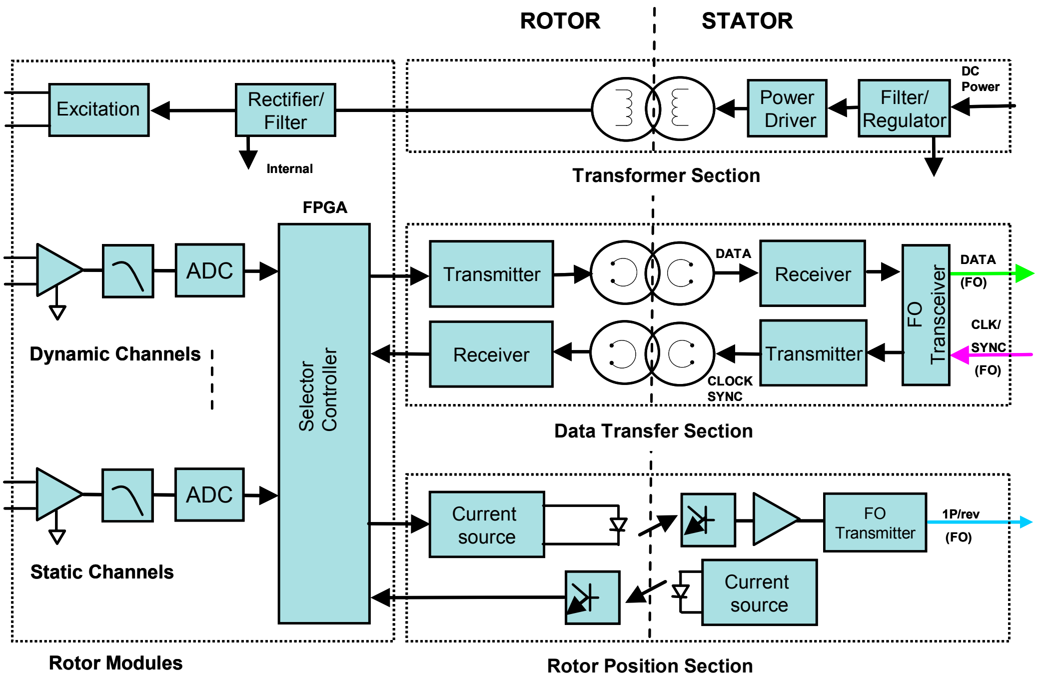

Figure 4. Telemetry Unit block diagram.

5.2 Contactless power and data transfer

The strain gauge bridges, pressure transducers, and telemetry electronics require approximately 15 W of electrical power per Telemetry Unit. This power must be transmitted from the stator to the rotor in a contactless manner. For this purpose a special transformer design was developed, with magnetic core material organized in a toroidal shape and both the primary and secondary windings following a tangential path with respect to the axis of rotation. The segmented magnetic core material is mounted in a special construction, to make it withstand the high centrifugal force in the rotor. The primary winding is driven with a 50 kHz signal. The frequency of this drive signal is locked to the telemetry unit's sample clock, to prevent any influence of crosstalk on the data acquisition channels.

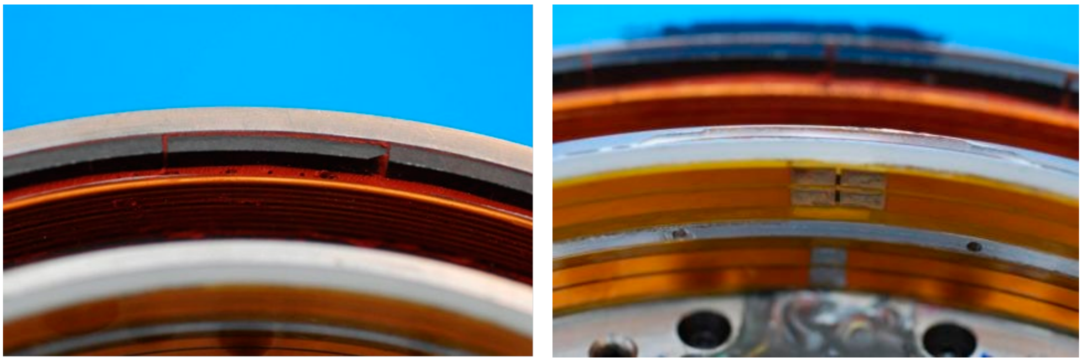

Figure 5. Rotor transformer windings (left) and rotor transmission lines (right).

Contactless data transfer is required in two directions: a composite clock / synchronisation signal to the rotor, and measurement data to the stator. The data transfer towards the rotor is accomplished by driving a circular transmission line on the stator with the desired signal, and placing a second transmission line in close vicinity on the rotor. With the broad sides of these transmission lines facing each other, there is near-field coupling between the two and a signal wave is induced in the rotor transmission line as a result. Signal transmission from the rotor to the stator is established in the same manner. Again, a special mechanical construction is required to ensure integrity at high rotational speed.

The Ethernet downlink is half duplex; hence the receiver cannot request re-transmission of particular data. All data is therefore sent twice as a redundancy measure. The uplink (to the Telemetry Unit) is used to send a 12.5 MHz clock signal modulated by synchronization commands from the central FPGA module housed in the In-flow Dynamic Measurement System.

5.3 Rotor Modules

All rotating functions are located in modules which are mounted in the Rotor Model Housing. The data acquisition circuitry is housed in 5 modules, each comprised of 5 full bridge type channels.

For measuring the rotor balance signals, a total of 3 modules are used with an analogue bandwidth from DC to 5 kHz. These "static" acquisition channels are grouped in modules with 5 channels each, are sampled at a rate of 10 kSPS with 16 bits resolution; they are able to measure quasi-static signals. The analogue front end of the static acquisition channels is designed for low offset drift, high DC stability and low noise. The channels can be configured for a ratiometric full-scale range between 0.5 mV/V and 20 mV/V. The channels' excitation supplies are not mutually isolated.

Two modules are used to measure the rotor pressure sensors in the DC to 50 kHz frequency band. These "dynamic" acquisition channels are similar to the static acquisition channels, but the sample rate is 100 kSPS at 24 bits resolution. The analogue front-ends of the dynamic acquisition channels are designed for optimum AC stability and dynamic range, with measurements again being made in a ratiometric manner.

All acquisition modules supply 10 V_{DC} excitation voltage to the sensors; separate power supplies are used for each group of 2 or 3 channels. Minimum sensor resistance is 350 Ω. All acquisition modules are equipped with an internal temperature sensor and the temperature is readily available in the data stream. This actual module temperature can be used to apply thermal post correction to the measured signal values to improve accuracy, providing the system was previously calibrated for its thermal behaviour.

Apart from the data acquisition modules, three other modules reside in the rotor: A data module, for data handling and control, and two power supply modules, for pre-regulation of the excitation voltages and for providing the necessary supplies to the electronics.

The data module features an FPGA, which handles the data from the ADCs and formats the data for transmission. The FPGA processes the received system clock and the synchronization pulse and provides correct handling of the sample timing and the rotor position. An external system clock is required to ensure continued sample synchronicity. Each data output sample has a unique sample number and rotor position information.

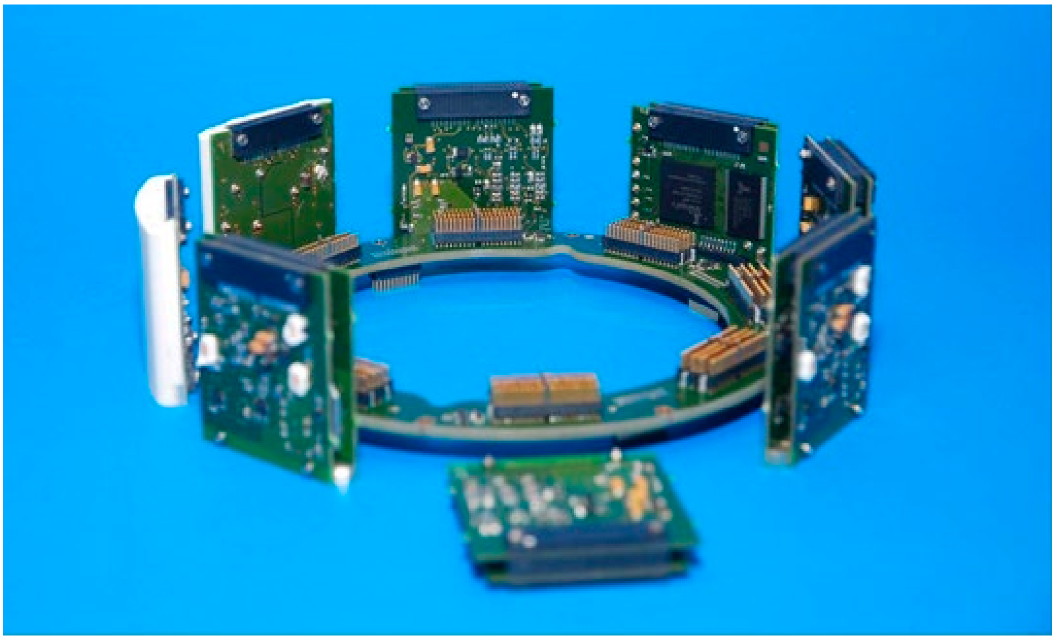

Figure 6. Rotor modules, arranged around a rotor backplane board. Two modules are already cast in epoxy.

All rotating modules are cast in a carefully selected hard type of epoxy in order to protect the printed circuit boards and their components from the high centrifugal forces. The modules have shown to tolerate static acceleration up to $5.5 \cdot 10^4$ m/s^2 (≈ 5,500 g) while in operation. In the photo above two modules can be seen at the left that are encapsulated. The encapsulated module shape perfectly fits into the Rotor Module Housing for optimum support.

5.4 Rotor position encoder mechanism

A high-resolution counter value is appended to each sample taken. It indicates the time elapsed since the latest passing of the angular reference position ("1P") of the rotor. From this value and the known sample rate of the respective sensors, it is possible to accurately determine both the actual rotational speed and the angular position relative to the reference position of each measurement sample. This is important for rotating force sensors, since it enables presentation of the measurement results in the angular domain.

The 1P pulse is generated by an infrared optical sensor when the rotor is at the reference position. A LED is mounted on the stator and is continuously on. The IR sensor is mounted on the rotor. Tightly focussed light from the stator's LED passes through a slit when the rotor is in the reference position and excites the very fast IR sensor. The signal from this sensor is used to reset the high-resolution counter that is used to indicate the time since the latest ‘1P moment’ for each 10 kSPS and 100 kSPS sample. For monitoring purposes an additional fibre optic output carrying the 1P pulse is available on the stator as well.

6 System performance

In a 10-month time span, approximately 750 hours of measurements were accrued. The entire system operated satisfactorily and the measurement campaign was very successful. The Telemetry Units performed well, despite the extremely harsh environmental conditions in the rotor. The modular approach showed to be a great advantage in case of component failures. In the occasional event when a hardware failure did occur in a Telemetry Unit, it was possible to either swap a module in the rotor module housing or to exchange an entire Telemetry Unit for a spare unit in a short time interval. This meant that the measurement campaign was not interrupted for a significant amount of time by such events.

Data transmission from the Telemetry Units to the Front-End Computers was highly reliable. Analysis of received data showed that the redundant transmission of data yields an effective error rate (non-received or corrupt packet) of 10^{-14} per 1.5 kB packet.

7 Acknowledgement

Parts of this paper were published previously in the following document:

[1] Goldhahn, E., Zwemmer, R., Nahuis, B.R., Negulescu, C. (2014). *Advanced wind tunnel testing of Counter-Rotating Open Rotors at low-speed conditions.* Conference paper at "Greener Aviation 2014: Clean Sky Breakthroughs and worldwide status", 12-14 March 2014, Brussels, Belgium.

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