

# A challenging high-end data acquisition system in a harsh wind tunnel environment at high rotational speed

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**Abstract:** NLR developed an advanced, high-performance data acquisition system for a generic engine test rig. The test rig is intended for wind tunnel use. The RDAS and MDAS subsystems are bespoke developments, supporting a total of 120 rotating and almost 700 stationary measurement channels. All measurements are made under harsh environmental conditions: wide temperature range and high vibration levels. The rotating section tolerates rotation up to 16,000 rpm.

**Keywords:** Data acquisition; Wind tunnel; Telemetry; High-speed rotation; Contactless.

## 1. Introduction

In the R&T project SA<sup>2</sup>FIR, an acronym for "Simulator of Aerodynamic and Acoustic Fan IntegRation", a generic test rig for wind tunnel testing is being developed to investigate the behaviour of a turbofan propulsion simulator. SA<sup>2</sup>FIR is a co-operative effort of Airbus Operations SAS and Safran Aircraft Engines. In support of this project, an Advanced Data Acquisition System (ADAS) is developed by NLR that forms an integral part of the SA<sup>2</sup>FIR test rig.

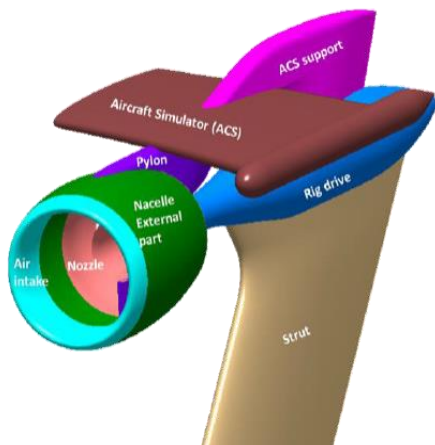


Figure 1. SA<sup>2</sup>FIR test rig

The ADAS acquires all relevant sensors signals, and processes, visualizes and stores the resulting data. The development of the SA<sup>2</sup>FIR ADAS builds on extensive experience gained by NLR in the development of the Z08 telemetry system for Airbus, in 2012 [1]. The SA<sup>2</sup>FIR ADAS differs in that it has approximately twice the rotation rate, five times as many channels, and a much wider temperature envelope. Higher data rates required an

increase of the contactless data transfer rate from 100 Mbit/s to 1 Gbit/s; NLR demonstrated this capability to Airbus in the Z08-S5 project in 2014.

A feasibility study preceded the development and realization phase of the ADAS, which is now (2023) being completed. The third phase (to follow) is training and support.

## 2. Principal requirements

The ADAS will be used in various wind tunnels, which means that it needs to be transportable. The two initial test campaigns will be in the DNW LLF in Marknesse, the Netherlands, and in the ONERA S1MA in Modane, France. The required service life is 25 years.

Measurements need to be made on 120 data acquisition (DAQ) channels rotating, mainly Wheatstone bridges. In addition, there is a need for approximately 700 DAQ channels stationary within the model, mainly microphones.

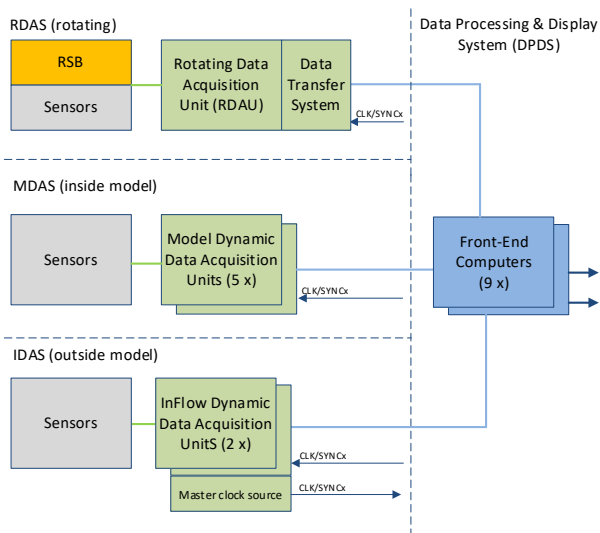
The rotating part of the ADAS needs to provide at least 50 W of electrical blade heater power, switched on and off under software control.

The combination of rotor and stator needs to fit in an approximate volume of 20 x Ø20 cm, in which a shaft bore is required. The available volume for the stationary DAQ units is a cylindrical shell (Ø82 cm) in the nacelle and a rectangular volume in the wing section of the model, indicated as ACS in Figure 1.

The telemetry must withstand vibration levels of up to 10 g<sub>RMS</sub>. The operational ambient temperature range is -10 to +60 °C, while -15 to +90 °C needs to be tolerated. The rotor needs to tolerate a rotational speed of 0 to 16,000 rpm.

## 3. System outline

Figure 2 shows the top-level architecture of the ADAS. The major parts of the system are the three data acquisition subsystems RDAS (rotating), MDAS (stationary in model), and IDAS (stationary outside the model), as well as the Data Processing and Display System (DPDS, including software) as shown in Figure 2. This paper focuses on the electronics for RDAS and MDAS. A separate paper [2] discusses the DPDS.



**Figure 2: ADAS top-level architecture**

### 3.1 Modular design

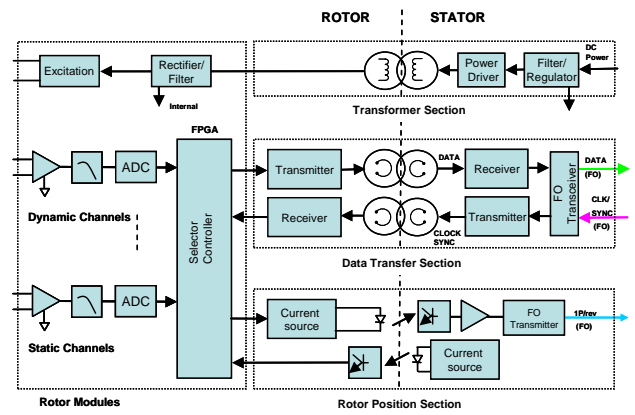
The measurement needs in RDAS and MDAS have a high degree of commonality. In order to maximize design efficiency, most functions (data acquisition, data processing, local power supply) are designed in modules that are re-used in all RDAS and MDAS subsystems. For each of the two subsystems, modules are cast in a form factor that is appropriate to that subsystem. Modularity allows swapping of measurement functions to some degree, and also facilitates repair if this is necessary. Furthermore, standardized data exchange and control within the subsystems simplifies FPGA code design.

## 4. Rotating Shaft Balance

An advanced 8-spoke rotating shaft balance (RSB) is designed and instrumented by NLR specifically for the SA<sup>2</sup>FIR test rig. The steel balance is instrumented with strain gauge bridges for the six balance components and contains thermistors to determine the local temperatures at specific locations within the balance. The central section provides feedthrough connections for the sensor wiring to the blades.

## 5. Rotating Data Acquisition System

Mounted immediately behind the balance and within the model's booster rings, the Rotating Data Acquisition System (RDAS) takes care of all measurements in the rotating domain. There is a stationary part (the stator) and a rotary part (the rotor). The interface between the two is formed by the stator and rotor flanges, which together comprise the contactless transfer part. Figure 3 shows the block schematic for this subsystem.



**Figure 3. RDAS block schematic**

### 5.1 Stator section design

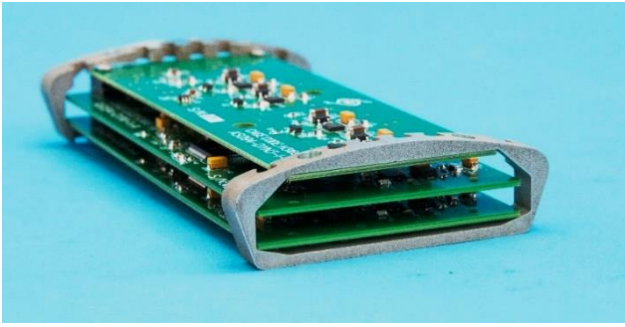
The stator incorporates a number of functions that support the rotor's functionality. Firstly, a power inverter converts the externally applied DC power into an AC voltage that is suitable for transfer through a transformer. The stator also contains the fiber optic transceiver that is used for receiving the clock signal, as well as transmitting the measurement data over a fiber optic cable to an external computer. Finally, a separate stator-mounted fiber optic transmitter sends a once-per-revolution pulse (1p) to external equipment.



**Figure 4. RDAS stator (cover removed)**

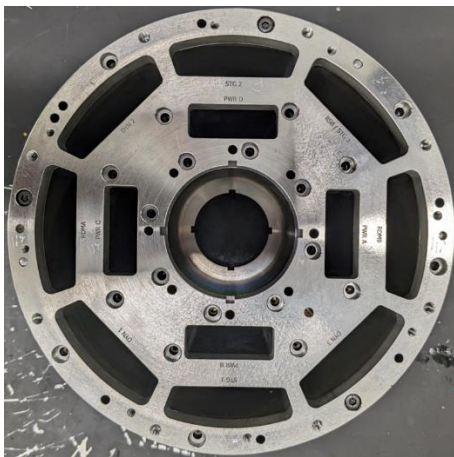
### 5.2 Rotor section design

The rotor section contains the majority of functions for RDAS. The electronics is housed in oblong (10 x 5.5 cm) modules that reside in cavities in the cylindrical titanium RDAS rotor housing. The rotor housing is 10 cm long and has a 20 cm diameter. The modules contain one to three printed circuit boards, cast in carefully selected epoxy.

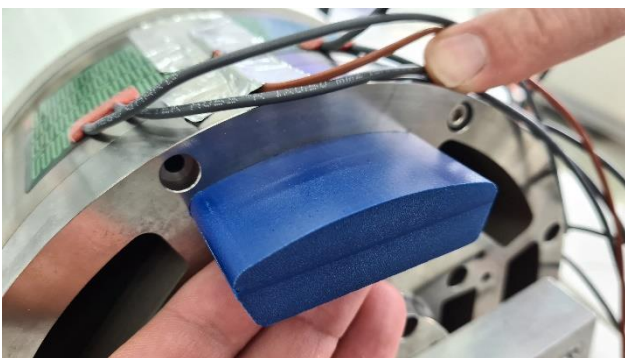


**Figure 5. Typical RDAS DAQ module (before casting)**

The epoxy casting protects the modules from the very harsh environment in the rotor, and most importantly provides the mechanical stability needed to resist the static acceleration of up to 24,000 g. The four central modules provide power conditioning, two outer modules take care of data collection, and the remaining six outer modules are for data acquisition.



**Figure 6. Rotor housing with cavities**



**Figure 7. DAQ module in rotor cavity**

All modules are interconnected by a single backplane. The role of this complex circuit board is to distribute electrical power, enable data exchange between modules, and to cater for all the sensor connections in the RDAS. Four banks of 88 connector pins are intended for connection of the hub and RSB-mounted sensors. These connections are at the lowest available radius to limit exposure to centrifugal

acceleration. Two connectors at the outer edge can be blind-mated for sensor connections to the two booster rings.

### 5.3 Power modules

The four power modules provide power conditioning and generate all the necessary internal supply voltages for the RDAS electronics. Rectification and buffering are performed and all voltage regulation is achieved through the use of efficient switched-mode power supplies in combination with filters. One of the power modules provides a remotely switched output for the optional blade heater.

### 5.4 Data processing modules

Two modules are dedicated to the control of the data acquisition, collection of digitized data, and formatting into a 1000BASE-SX compatible data stream. The two modules are very similar in design. Each contains an FPGA for the control and processing functions, while one of the modules also features a memory to accommodate re-transmission of all data after a fixed delay. The integral re-transmission ensures a very high level of data transfer reliability, even over a simplex data link as is used here. The two data modules mutually exchange control signals and measurement data over a dedicated high-speed link.

### 5.5 DAQ modules for Wheatstone bridges

All data acquisition modules in RDAS are designed to excite and measure 350  $\Omega$  to 1 k $\Omega$  Wheatstone bridges. All measurements are ratiometric, appropriate to such bridges. Typical sensors are pressure sensors (on fan blades, fan disk), strain gauges (RSB, fan blades, boosters), while some channels are allocated to RTDs for measuring local temperatures on the RSB.

Six 20-channel DAQ modules are used here, of three different types. Each type has a different sample rate and corresponding signal bandwidth. DYN type modules provide 24-bit resolution with a sample rate of 132 kS/s. STG and RSB type modules have 16-bit resolution and sample at 33 and 11 kS/S, respectively. Available frequency band is DC to almost the Nyquist frequency. Excitation for each sensor is 10 V DC. The signal conditioning of all channels contains an instrumentation amplifier, an anti-aliasing Bessel low-pass filter and a digital filter.

### 5.6 Contactless power and data transfer subsystem

The rotor requires electrical power to operate. Approximately 60 W is consumed in the rotor electronics and sensor excitation, while an optional heated blade on the fan requires at least an additional 50 W. Furthermore, clock and synchronization signals must be transferred to the rotating domain to ensure that sampling in the rotor is exactly synchronous to sampling elsewhere in the ADAS. Obviously, the rotor produces a sizeable data flow which needs to be sent to the stator. Finally, a signal indicating that the rotor passes its reference position (1p) must be

transferred to the stator in real time to allow external equipment to synchronize to the fan's rotation. The classical solution with slip rings is not viable in this case because of the poor quality of the connection and the extreme rate of contact wear at the high rotation rate. For the transfer of electrical power from the stator to the rotor and for the bi-directional exchange of digital data the NLR-patented Contactless Power and Data Transfer is used [3]. It provides efficient transfer of electrical power through a special bisected transformer, alongside with 1 Gbit/s communication channels. They implement near-field coupled transmission lines to ensure reliable data transfer without physical contact. The set-up is optimized for integrity at high rotational speed. A fast optical link is used for the 1p signal.



**Figure 8. RDAS rotor showing contactless transfer. At the bottom: pedestal and hub simulator.**

### 5.7 Thermal management

Proper thermal management is essential for the electronics given the wide range of temperatures that RDAS can operate in. Under most conditions the most significant source of heat is not the electronics, but the boosters surrounding the RDAS which heat up as a result of adiabatic compression. Heat is removed by leading cooled pressurized air through a maze of channels in the metal RDAS housing. The same method is used to cool the stator. These measures limit the module temperatures to a maximum of 70 °C. The temperature of all critical locations is monitored continuously so that action is taken should any part overheat. DAQ module temperatures are also used to apply temperature-dependent calibration factors in post-processing.

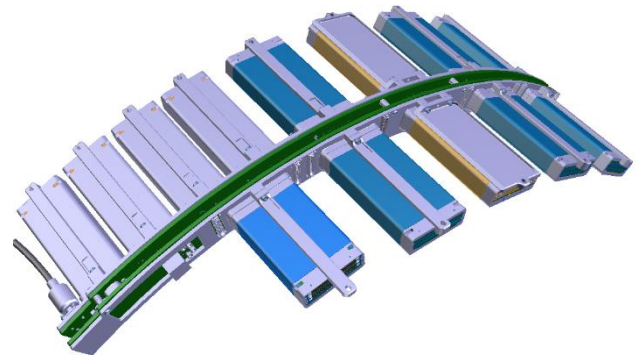
## 6. Model Data Acquisition System

The Model Data Acquisition System (MDAS) performs the measurements in the (stationary) nacelle and wing section of the model. Almost 700 IEPE microphones, pressure sensors, strain gauges, and thermistors are served by a total of five custom-designed subsystems, four of which are identical. The functional and electrical design of these subsystems closely resembles the RDAS rotor design, and uses the same electronic modules. Dedicated DAQ modules for IEPE and RTD sensors are unique to MDAS. Each subsystem utilizes a 1 Gbit/s fiber optic connection to transmit measurement data. MDAS is not exposed to significant static acceleration, but needs a robust design to withstand high vibration levels of up to 10  $g_{RMS}$ . Advection of cooled compressed air is used to remove heat from the MDAS modules.

The MDAS subsystems feature a high degree of flexibility in the types of DAQ modules used. Alternative configurations can be composed, tailored to the actual measurement needs of the campaign.

### 6.1 Nacelle subsystem design

The four nacelle subsystems each occupy a quarter of a cylindrical shell with 82 cm diameter, with each subsystem consisting of two interconnected curved backplanes, four power modules, two data processing modules, and seven DAQ modules. The two backplanes for a subsystem are mounted back-to-back, with modules protruding in opposite axial directions.



**Figure 9. Nacelle-mounted MDAS subsystem**

### 6.2 Wing section subsystem design

The MDAS subsystem in the wing section is similar to the nacelle-mounted parts. The single backplane is however straight and it can accommodate only three DAQ modules. It is used with Kulite pressure sensors and strain gauges.

### 6.3 DAQ modules for IEPE sensors

Special 20-channel modules are designed for exciting and measuring IEPE sensors, usually microphones. Each channel contains a 4-mA low-noise excitation current source, signal conditioning, and A/D conversion to 24 bits at 132 kS/s. The module has excellent performance with >97 dB<sub>FS</sub> signal-to-noise ratio, and <0.06 dB gain ripple over the signal bandwidth which runs from 2 Hz to 60 kHz.

The absence of a coupling capacitor in the signal path avoids the non-linearity and harmonic distortion normally associated with large non-ideal capacitors.

#### 6.4 DAQ modules for RTD sensors

The need for precise temperature measurement is met by designing a custom module that provides 38 four-wire connections to Pt100 sensors. The digital interface of the module is identical to that of the other DAQ modules, but an additional set of connectors is added on the opposite end of the module to provide sufficient pins for the 152 sensor connections. This means that sensor connections are made through the backplane and also directly to the module. An additional connector on the side of the module allows in-system re-programming of the FPGAs in the module. Total measurement errors remain well below 350 mK, while sampling at 10 S/s.

### 7. Inflow Data Acquisition System

A range of 165 in-the-flow sensors is measured by the Inflow Data Acquisition System (IDAS). This is also where the clock and synchronization signals for all system parts of the ADAS are generated. The IDAS is composed of off-the-shelf data acquisition equipment manufactured by National Instruments.

### 8. Sample synchronization

One of the major requirements for the ADAS is for all samples to be taken synchronously. For this purpose, a master clock signal is generated in the IDAS (enslaved to GPS), and it is distributed to all system parts that perform data acquisition. All sample rates are 132 kS/s or integer fractions thereof. To ensure that not only the sample rates are perfectly matched but also the actual phase of the sampling within a sample period is equal, tuning of the delay for the first sample in each subsystem and for each channel type is performed by creating specific synchronization signals. This cancels all group delays that occur in copper and fiber optic cabling, analogue signal conditioning, and analogue-to-digital conversion. The resulting channel-to-channel latency throughout the system is below 1  $\mu$ s.

### 9. Peripheral equipment

In order to power the RDAS and MDAS subsystems, the system contains four off-the-shelf DC power supplies which are located outside the wind tunnel test section. Each power supply is turned off automatically in case of a sustained overtemperature condition in any connected module.

While most digital communication is achieved over fiber optic cabling, some system parts require an electrical signal interface. Dedicated conversion units are designed for distributing the clock and synchronization signal (copper to fiber) and RDAS 1p signal (fiber to copper).

### 10. Data Processing and Display System

The DPDS gathers, processes, displays, and stores the data streams from the MDAS, IDAS, and RDAS subsystems. It consists of a Front-End cluster containing computers which interface with the data acquisition hardware and wind tunnel, and one Proprietary Data Processing cluster each for two distinct users with different privileges. The various computers are linked through network switches. Custom software is developed by NLR to manage the data streams in real time, process acquired data, and present results and status to the users.

### 11 Acknowledgement

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme. This work has been performed in co-operative effort with Airbus Operations GmbH and Safran Aircraft Engines.

### 12 References

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### 13 Glossary

1p	Once per revolution (pulse)
AC	Alternating Current
ACS	Aircraft Simulator (wing section of model)
A/D	Analogue to Digital
ADAS	Advanced Data Acquisition System
DAQ	Data Acquisition
DC	Direct Current
DPDS	Data Processing and Display System
FPGA	Field-Programmable Gate Array
GPS	Global Positioning System
IDAS	Inflow Data Acquisition System
IEPE	Integrated Electronics Piezo-Electric
MDAS	Model Data Acquisition System
NLR	Royal Netherlands Aerospace Centre
RDAS	Rotating Data Acquisition System
RSB	Rotating Shaft Balance
RTD	Resistance Temperature Detector
SA <sup>2</sup> FIR	Simulator of Aerodynamic and Acoustic Fan Integration