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The development of a Dedicated Signal Transfer System

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Summary

This paper describes the development of the Dedicated Signal Transfer System (DSTS) to fulfill the instrumentation requirements of a tilt-rotor wind tunnel model. The system is used to amplify the low level signals of the blade strain and blade pressure sensors of the model.
The DSTS Front End Unit contains modular signal conditioners with built-in excitation regulators, which amplify and digitize the sensor signals in the rotating part of the model. The resulting digital data are sent to the ground part of the system using a fiber-optic cable. The signal conditioners can be remotely configured for gain, input offset compensation, AC/DC input and filter bandwidth.
This approach reduces both the size of the cable and the size of the electrical slip ring normally used for analogue transfer of the data. Application of a fiber-optic cable further improves the susceptibility to Electromagnetic Interference caused by the model driving electrical motor.

Contents

(18 pages in total)

1 Introduction

Within the 5th research framework of the European Union, a project on the tilt-rotor concept has been partially funded and launched in 2001, called Tilt Rotor Interaction Aerodynamics, acronym TILTAERO [1]. The project is coordinated by AGUSTA. For this project a Mach-scaled, half-span wind tunnel model of a tilt-rotor was developed and tested, for accurately predicting the efficiency of tilt-rotor surfaces and investigating aerodynamic interaction phenomena in different flight conditions. Fig. 1 presents the overall TILTAERO model as mounted in a wind tunnel.

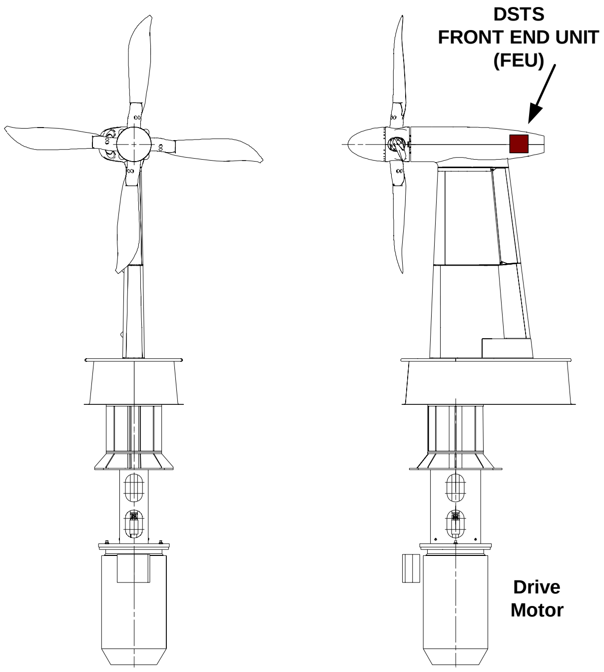

Figure 1. TILTAERO Model.

The model contains a large number of sensors, of which a total of 128 sensors are embedded in the rotor blades for measuring the blade strains and blade pressures. The sensor signals normally pass the rotor mast, the external balance and the shaft driving electric motor. Due to its relatively high power, high interference levels could be expected from the electric motor.
This paper describes the status of the development of the Dedicated Signal Transfer System (DSTS) before the start of the actual TILTAERO measurement campaign, planned –after publication of this paper– in November 2005 in DNW's Large-Low Speed Facility (LLF) [2]. The function of the DSTS is to amplify and digitize the blade sensor signals in the rotating part of the model (Front End Unit). The resulting digital measurement data are sent to the related Ground Station through a fiber-optic cable. This approach reduces both the size of the cable and

the size of the electrical slip ring normally used for analogue transfer of the signals and also prevents possible disturbance to the signals caused by the interference of the drive motor. DSTS is a system specifically designed for the TILTAERO Model and builds on the experience of former systems developed by NLR for rotating signal conditioner applications like the Rotating Amplifier System RAS [3] and the Signal Transfer System STS [4].

2 System design description

A. Block diagram description

The DSTS consist of four major elements; a rotating Front End Unit (FEU), a Slip Ring Assembly and a FEU Power Supply, all located in the rear section of the model behind the gear box, and a Ground Station located in the wind tunnel control room.
Refer to Fig. 2 for the overall block diagram.

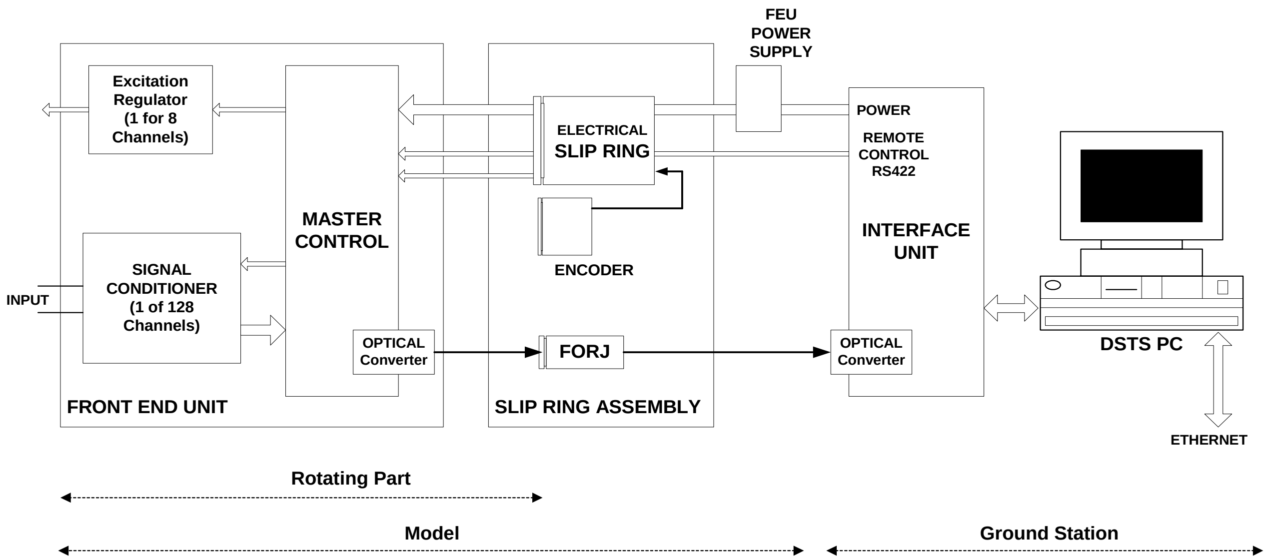

Figure 2. DSTS Block diagram.

The rotating FEU is a 24 cm diameter cylinder of 23 cm length and houses in total 128 remotely configurable signal conditioner channels, including excitation regulators for supply of the sensor bridges. A signal conditioner channel contains an input offset compensation circuit, a differential amplifier, an anti-aliasing filter and an individual Analogue to Digital converter (ADC).
A requirement for the system is the ability to measure the relatively high frequency phenomena of Blade Vortex Interaction (BVI) of the rotor blades. BVI occurs when a rotor blade strikes the vortex created by the tip of the preceding blade. For interpretation of the data it is necessary to be able to accurately map the measured data on the rotation position with a high resolution.

Therefore a rotary incremental Encoder, which is part of the Slip Ring assembly, is coupled to the shaft providing 1024 trigger pulses per revolution to all ADC's of the signal conditioners. The parallel data acquired by the ADC's are fed to a master control circuit and converted into a fiber-optic data link. The advantage of a fiber-optic data link is reliable high speed data transfer in a noisy environment and a major reduction of the cable diameter. The optical measurement data downlink passes the model all the way to the Ground Station located in the wind tunnel control room over a distance of 100 meters.
The optical fiber is routed from the rotating part to the stationary part requiring an optical slip ring or a so-called Fiber Optic Rotary Joint (FORJ). In the TILTAERO model such a FORJ is integrated with a through-bore conventional electrical slip ring. Refer to Fig. 3 for an overview of the location of the DSTS Model components.

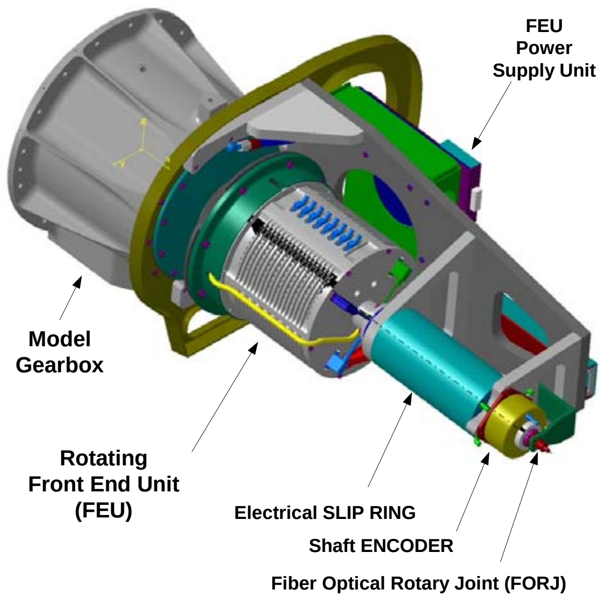

Figure 3. DSTS Model components.

A conventional electrical slip ring is still required for providing power to the FEU circuitry. For safety reasons it is also used to pass a number of 26 direct channels for safety and piloting sensors located in the rotor blades and the rotor hub. The safety and piloting signals are amplified by means of a simple straightforward analogue amplifier located on a printed circuit board mounted in the front panel of the FEU.
The conventional electrical slip ring is also used for transfer of the signal conditioner configuration settings by means of a low rate serial data link.
The FEU Power Supply Unit contains a multi-voltage power supply for the FEU circuitry and an Excitation power supply, and is mounted in the vicinity of the Slip Ring Assembly.

The Ground Station of the system consists of an Interface Unit and a system PC connected to the wind tunnel data processing computer. In the Interface Unit the optical data are converted to a parallel format and fed to a high speed parallel interface of the PC. The PC contains dedicated software for Data storage, Configuration Set-up and quick-look Data presentation.

B. Signal Conditioner Module (SCM)

The FEU contains the signal conditioner for the blade strain and the blade pressure sensors. The blade strains are measured with high impedance strain gages and the pressures are measured with full bridge type pressure sensors.

Refer to Fig. 4 for a block diagram of the Signal Conditioner Module

The signal conditioner channel contains the following circuit functions:

- Input offset compensation circuit, range +/-100mV
- AC/ DC input selector
- Post amplifier with gain 1,2,4,8
- Anti-aliasing filter
- Post amplifier for gain 1, 10, 100 and 1000
- Analogue to Digital converter (ADC)

The FEU input circuit is laid out as a +/- 2.5 Volt differential type and accordingly the Excitation Voltage is provided as +/- 5Volt. This is the optimum concept for bridge type sensors.

The input offset compensation circuit offers the possibility to compensate bridge unbalance. This unbalance is caused by pre-loading of strain gages or by the static pressure in case of a pressure sensor. The bridge unbalance effect results in a DC offset and will limit the dynamic range of the signal to be measured, specifically at high gains and high offset voltages. An offset range of +100mV to –100mV can be compensated at the input. The input offset compensation circuit is realized by means of two adjustable differential current sources generating a voltage over a resistor in series with the input amplifier. The value of the current sources is controlled by a 12-bit Digital to Analogue converter.

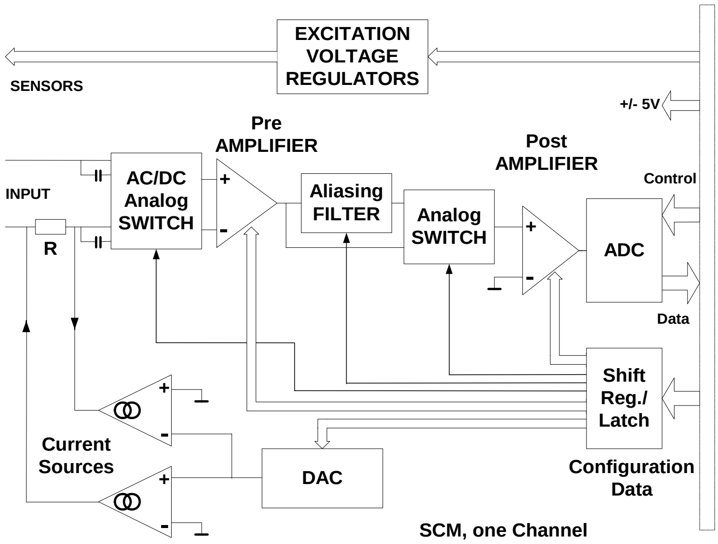

Figure 4. SCM Block diagram.

The signal conditioner uses two programmable amplifiers to obtain a gain range in steps 1,2,4,8 and 1,10,100,1000.
The system bandwidth and sample rate is optimized for measurements of the TILTAERO model, in which the measurement of the BVI frequencies is important. The rotation frequency of the rotor at a maximum speed of approximately 1400 rpm is 23Hz. Based on the requirement for 1024 samples per revolution the resulting sampling rate is 23 kHz for the ADC's. The maximum rotor frequency of interest is the 8th harmonic, or about 186 Hz, but the bandwidth of the signal conditioner channel is chosen at 5 kHz (@ -3dB), providing sufficient bandwidth to measure the expected BVI effect. Along with the requirement for an efficient suppression of unwanted signals, aliasing suppression is determined to be 40dB. This figure is realized by means of a relatively simple 4^{th} order Bessel type filter. A selection can be made between the 4^{th} order filter and a 1^{st} order filter, in case a higher bandwidth is required, however the anti-aliasing suppression will be decreased.
During the design phase of the DSTS project it was decided to use one ADC for each channel, rather than to use an analogue multiplexer and a common ADC. The amount of circuitry is not much less in this case and using an individual ADC for each channel results in a high degree of flexibility.
The applied ADC is a fast, charge redistribution type and has a resolution of 16 bit. During acquisition the ADC uses an internal capacitor array as sampling capacitor acquiring the signal. In this way the input signals are simultaneously sampled, preventing data latency.
The configuration settings of each signal conditioner channel can be remotely set from the system PC.
Table 1 presents the major specifications of the SCM.

Table 1 SCM major specifications

Input	
Input Full Scale	± 2.5Volt @gain 1
Input Offset compensation	± 100mVolt
Transfer	
Gain	Pre 1,2,4,8 , Post 1,10,100,1000
Filter	5kHz,@ -3dB, 4^{th} order LP Bessel
Coupling	DC/ AC, 1Hz, 1^{st} order
Signal to Noise ratio	Better than 70dB
Gain accuracy	± 0.3%, basic, can be improved by calibration
Gain drift	± 8ppm/ºC
Offset	<± 3mVolt, @gain 1, basic, can be improved by calibration
Offset drift	<± 15µVolt/ºC, @gain 1
Excitation output	
Voltage	± 5 Volt
Accuracy	± 8mVolt
Current	< 300mA

A software task implemented in the system PC is able to perform an automatic offset compensation procedure. All applicable sensors will be put in the zero state and the resulting voltages will be measured. The measured voltages values will then be loaded to the configuration set-up of the compensation circuit.

The signal conditioner circuitry is organized as a 16-channel Signal Conditioner Module (SCM). The channels are packed on both sides of the printed circuit board in two groups of 8 channels. Each group of 8 channels has its own excitation regulator for supply of the sensor bridge excitation voltage. The SCM has two miniature 21-pin connectors oppositely mounted in the module ring. Refer to Fig.5 for a picture of the SCM, including an input connector.

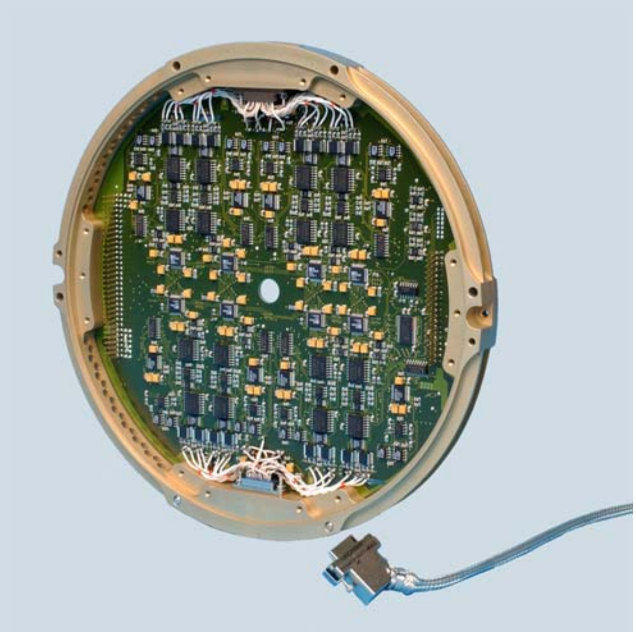

Figure 5. Signal Conditioner Module SCM.

C. Master Control Board (MCB)

The Master Control Board is located in the rear part of the FEU, refer to Fig. 6 for a picture of the MCB. This board collects all data of the Signal Conditioner Modules by means of a parallel databus. This databus is realized using stack-through connectors connecting all modules. The power supply and control lines are also connected by means of stack-through connectors.
The Master Control Board basically consists of a CPLD (Complex Programmable Logic Device), which triggers and addresses the signal conditioners ADC's.
The trigger signal is generated by the shaft Encoder, providing 1024 trigger pulses for each full rotation. The CPLD converts the output pulses of the Encoder as trigger pulses for each ADC. The Encoder also generates a pulse at the start of each full rotation. This index pulse is used by the MCB to mark the start of a measurement cycle of 1024 samples.
The parallel data from the ADC's are sent to a dedicated piggyback board mounted on the MCB. This piggyback board contains a GigaSTaR® Full-Duplex High Speed Serial Link parallel to fiber-optic interface [5].
This compact piggyback board contains a transmitter and a receiver device and an optical transceiver module providing up to 1.32 Gigabit/s bandwidth for long distance transmission on

multimode fiber. The transmitter and a receiver device have a synchronous 36 bit parallel interface. The measurement data rate for 128 channels (including overhead) amounts to approximately 100 Mbit/s. The piggyback board is only used as transmitter for the measurement data to the Ground Station, but the design is prepared to use the receiver device for the configuration data uplink. Both an optical measurement data downlink and configuration data uplink would require a more complicated FORJ. Such units are not readily available regarding the relatively high speed of the unit. The applied single-fiber FORJ can be used up to a rpm of 2000. Furthermore, the configuration data are very slow compared to the available data speed and therefore the configuration data are sent from the Ground Station PC to the FEU via a conventional RS422 low speed serial link. Such a serial link is relatively immune to interference.

The MCB is mounted at the FEU rear panel providing connectors for FEU circuitry power and Excitation power. The MCB also processes the configuration data for remote setting of the channel configuration.

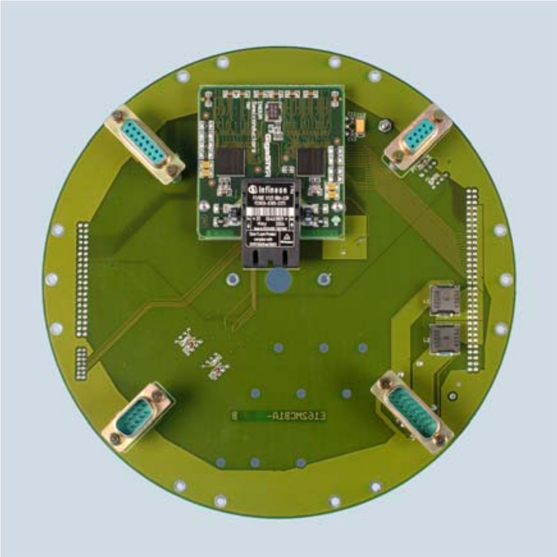

Figure 6. Master Control Board.

D. Mechanical Design FEU

The FEU rotates at a maximum of 1400 rpm and at this speed mechanical balancing is important. The main vibration source in the model originates from component unbalance, therefore each FEU module is designed in such a way that the component mass is evenly distributed as much as possible. After assembling, each module is statically balanced to a defined balancing grade.

The FEU housing concept is modular and thus enables the following minimum configuration for 16 channels: Front panel, one SCM and Rear Panel containing the MCB.

For the TILTAERO application 8 SCM are used, resulting in a total amount of 128 channels. The maximum amount of SCM’s is 12, offering a total amount of 192 channels; this limitation is mainly caused by the capacitive loading of the module databus.
The earlier mentioned amplifier for amplification of safety and piloting signals is completely stand-alone, and is located on a printed circuit board (not present in Fig. 7) mounted in the front panel of the FEU. Refer to Fig. 7 for an exploded view of the FEU.
The FEU modules are designed to fit accurately and are secured by 6 mounting rods. In this way a solid housing is realized, capable of sustaining the mechanical loads during rotation.
The FEU is coupled to the Model by means of a Drive Adapter connecting the outer part of the Model shaft coupling and the FEU Front Panel. Refer to Fig. 3. The cable bundles of the input connectors can be fixed at cable fixing bars mounted next to the input connectors of the SCM’s.

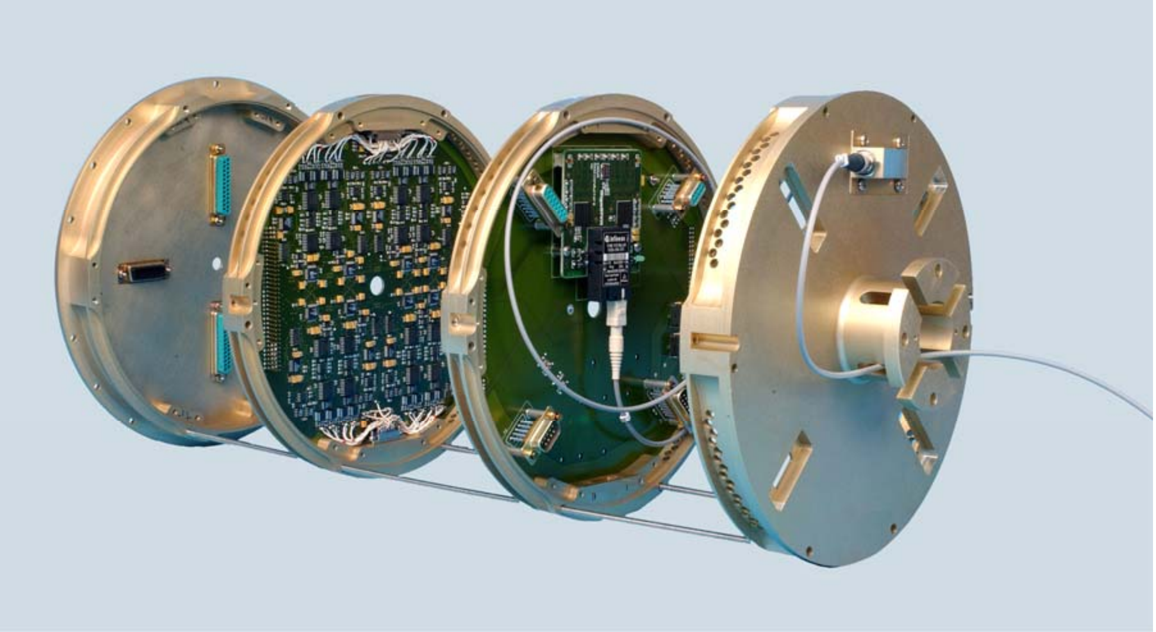

Figure 7. Front End Unit exploded view, with one SCM.

The Rear Panel of the FEU is coupled to the Slip Ring Assembly by means of a slotted flange. The electrical cables and the optical fiber of the FEU pass the four slots and run into the hollow shaft to the electrical slip ring rotor. After removal of the Slip Ring Assembly, the FEU cables can slip out of the slotted flange without dismounting the connectors. Refer to Fig. 8 for an overview of the assembled FEU.
The tight fit FEU housing construction provides a completely shielded enclosure in order to comply to EMC requirements. The connectors of the FEU are all equipped with an EMI back-shell, providing a possibility to apply an overall cable braid (refer to Fig. 5).

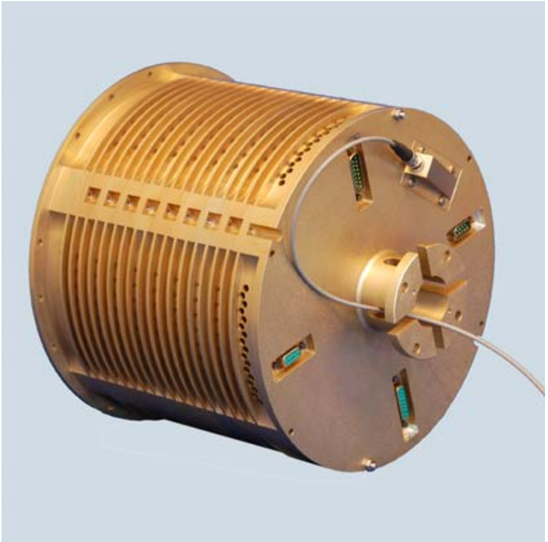

Figure 8. Assembled FEU.

The physical dimensions and the weight of the FEU can be found in the Table 2.

Table 2 FEU Physical Dimensions & Weight

Item	**Diameter [cm]**	**Length [cm]**	**Weight [gram]**
Front Panel	242	2.5	900
SCM	228	1.7	500
Rear Panel	228	6.6	1400
FEU, 8 SCM's	242	228	6400

E. Thermal issues

The FEU dissipates typically 65 Watt of power and is able to operate at a maximum ambient temperature of 60º Celsius.

The thermal control measures applied to the FEU are:

- All PCB's are in contact with the module ring
- Ventilation holes in the module ring
- Cooling fins at the module ring

A fan is mounted in the rear part of the Model to provide forced air cooling to the FEU. The Model has a special air-intake and an air outlet. The airflow is directed perpendicular to the

FEU in such a way, that the airflow is not be obstructed by the Slip ring Assembly support frame.
Temperature sensors located at each SCM of the FEU will generate an alarm to the DSTS PC if, for some reason, the local PCB temperature passes a certain level. This assures protection if the airflow stops due to a failure.

F. Ground Station

The Ground Station of the system consists of an Interface Unit (IFU) and a Personal Computer (PC). Refer to Fig.9 for a front view of the Interface Unit. The DSTS Interface Unit contains the following functions:

- Control board
- Analogue Outputs for 16 sensors channels
- 48Volt Power Supply module

The main function of the Interface Unit is to convert the optical data into a parallel format using the same GigaSTaR piggyback board as mounted in the Front End Unit. The resulting parallel data are passed to a standard high-speed parallel interface located in the PC. For one continuous data point of 60 revolutions the amount of data is 35Mbyte.
The Control Board of the IFU contains an error status circuit providing error status information of both the measurement data downlink and the configuration data RS422 uplink. The circuit acts as a Built-in Test (BIT) function for the data transfer. The GigaSTaR receiver of the IFU is able to set-up the connection automatically, and provides status information about the receiver lock, synchronization status and parity status. If the combined status is true, the measurement data can be considered reliable. If the combined signal is false, no data will be recorded by the PC and an error message will be displayed to the operator user interface of the PC.
The function of the configuration data uplink is checked in the Master Control Board of the Front End Unit, which puts the error status back in the header part of the measurement data. The IFU error status circuit reads this status information and in case of an error, presents a warning to the operator.
The Interface Unit contains 16 independent analogue output channels, arranged as two 8-channel modules. Each analogue output channel can present any of the sensor channels as acquired by the Front End Unit. The sensor channel selection is controlled by PC software through a specific user interface control panel. Each analogue output channel consists of a 16-bits DAC and an output driver able to drive a long cable. All analogue output channels are updated simultaneously after all the data for each sample are received from the FEU. The analogue data can be used for real-time quick look or control purposes.

Figure 9. Interface Unit.

The Interface Unit houses a power supply for internal purposes and a 48Volt power supply for feeding the FEU Power Supply located in the rear part of the Model. The reason for this approach is to limit the number of supply lines and to prevent losses over the long distance from the Ground Station to the Model.
The PC contains a number of software tasks for Data Storage on local disk, Data Presentation for quick-look purposes and Front End Unit configuration set-up. After the test the stored data can be sent to the wind tunnel Data Processing system via an Ethernet link.
The Data Presentation task can be used for quick-look, stand-alone presentation of the data if there is no possibility to use the wind tunnel data presentation system. The data cannot be presented during the recording of a measurement. Data presentation is always off-line, because the large amount of data prevents any additional task running. A selectable number of channels can be presented on the PC monitor.
The Configuration data set-up task enables the operator to set-up the configuration of the Signal Conditioner Modules.

3 Test and calibration

The DSTS was subjected to an extensive testing process before release to operational service. After development and production a performance test has been performed, covering all important parameters. All measured results have been recorded for optional calibration purposes.
EMC tests have been performed to verify compliance with the IEC61000 standards.
Temperature tests have been performed to verify the FEU internal temperature and to measure the actual drift of the gain and offset.
The gain and offset accuracy and drift specifications have been defined by evaluating the applied model sensors specifications. Without additional calibration the basic accuracy of the

DSTS is better than the sensors. In case higher accuracy figures are required, calibration can be build into the software, further improving the gain and offset accuracy.
The acceptance test will be carried out without blades, but with dummy blade transducers installed. These dummies simulate nominal DC blade pressure and blade strain signals, so in absence of the transducer signal, the operational performance of the channel can be measured.

4 Results

The DSTS successfully passed all the functional, performance and environmental tests. Further installation and testing will be performed before the actual TILTAERO measurement campaign, which is planned to start in November 2005. Fig. 10 shows the typical overall accuracy figures of the entire measurement chain. The two columns at the left indicate the DSTS accuracy distribution for gain 1 and gain 100 assuming ideal sensors. The other columns indicate the overall accuracy distribution including a pressure sensor and a blade strain sensor.

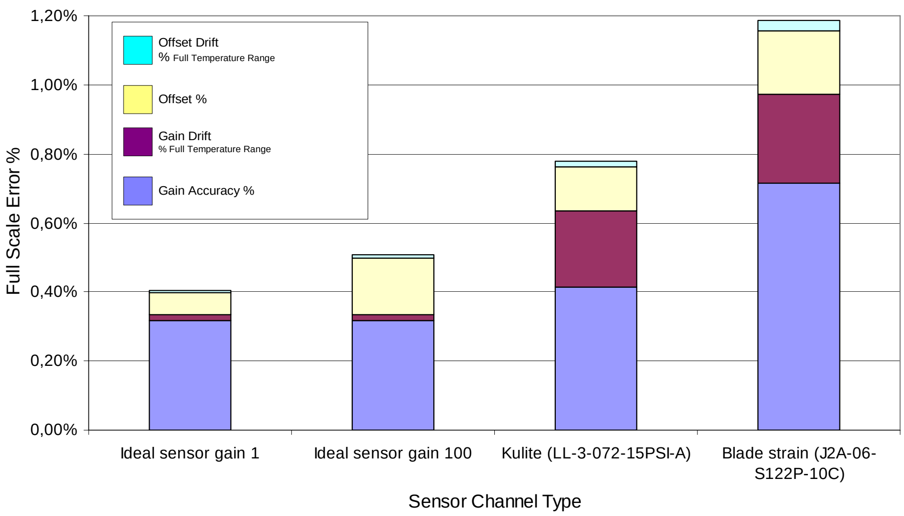

Figure 10. Overall Accuracy Figures.

5 Conclusions

The FEU is specifically designed for the TILTAERO model. The fact that the FEU is truly modular enables efficient application in other rotating model applications. The FEU is not a very small unit, but due to the extended, remotely configurable, functions it can serve a wide range of applications. The system can also be used in non-rotating applications.
Using a fiber-optic measurement data downlink greatly reduces the amount of conventional electrical slip rings and also results in a drastic reduction of the cable size. On top of that, the system is immune to Electromagnetic Interference normally affecting conventional measurement data downlink cables and systems.
Integration of a conventional electrical slip ring with a FORJ is relatively simple; however a through-bore (hollow shaft) type electrical slip ring must be applied in order to pass the optical cable. For non-rotating applications both the measurement data downlink and the configuration data uplink can be realized by optical fibers, increasing the reliability of the latter.

References

[1] European Commission, Aeronautics research under the Growth Programme (1998-2002), Project Synopsis. http://europa.eu.int/comm/research/growth
[2] The German-Dutch Wind Tunnels (DNW), Large-Low Speed Facility (LLF). http://www.dnw.aero
[3] RAS: A Miniature rotating amplifier system for wind tunnel application packs 256 pre-conditioning channels in 187 cubic inch., M.H.J.B. Versteeg and H. Slot. NLR TP 97351U Presented at the 17th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF), 29 September - 2 October, 1997, Monterey. http://www.nlr.nl
[4] STS: The development and operational aspects of a Signal Transfer System for use in wind tunnel propeller models. R.Zwemmer, A Quartel and D.L. Veltman, NLR TP 2001-429. Presented at the 19th International Congress on Instrumentation in Aerospace Simulation Facilities (ICIASF), Cleveland, OH (USA), 27-30 August 2001. http://www.nlr.nl
[5] Full-Duplex High Speed Serial Link, GigaSTaR® Piggyback board ING_TRF, Inova Semiconductors. http://www.infineon.com

Abbreviations

ADC	Analog to Digital Converter
BVI	Blade Vortex Interaction
CPLD	Complex Programmable Logic Device
DNW	German-Dutch Wind Tunnels
DSTS	Dedicated Signal Transfer System
EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interference
FEU	Front End Unit
FORJ	Fiber Optic Rotary Joint
LLF	Large-Low Speed Facility
MCB	Master Control Board
PC	Personal Computer
PCB	Printed Circuit Board
RAS	Rotating Amplifier System
SCM	Signal Conditioner Module
STS	Signal Transfer System
TILTAERO	Tilt Rotor Interaction Aerodynamics