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Measuring the aeroelastic properties of a tiltrotor aircraft in a wind tunnel model

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Abstract

The EU-funded Advanced Testbed for Tiltrotor Aeroelastics-project (ATTILA) aims to investigate whirl flutter in *tiltrotor* aircraft. In order to do this, a *wind tunnel model* was developed, which represents a scaled version of a section of Leonardo's Next Generation Civil Tilt Rotor – Technical Demonstrator. The model was successfully tested in DNW's Large Low-speed Facility in the Netherlands in November 2023.

This paper focuses on the sensors, electronic instrumentation and channel synchronization. The system consists of *rotating* and *static* model parts, complemented by several computer systems which capture and store the data.

Both the stator and rotor parts of the model contain electronic sensors, such as strain gauge bridges, vibration sensors, and digital rotary encoders. Additionally, the rotor blades contain Fiber Bragg Gratings, sampled by an interrogator, supplied by PhotonFirst.

The dedicated Data Acquisition System for the rotor (RDAS) is a bespoke development by NLR. The physical implementation of the RDAS consists of three disc-shaped boards, with interconnects to the sensors, and two Ethernet interfaces to connect to both the data storage computer and the interrogator. The measurements enable the comparison between 'classical' strain gauge measurements and FBG measurements.

To acquire the sensor signals in the static domain, the Static Data Acquisition System was realised by DLR-FT, with the TEDAS-system at its core. Model vibrations were measured by a separate acquisition system of DLR-AE for an online modal analysis during the wind tunnel test.

All measured signals are collected by a storage computer, and simultaneously passed to the piloting station, both supplied by DLR-FT.

Key words: tiltrotor, wind tunnel model, rotating, telemetry

Introduction

Whirl flutter is a significant consideration in the design of tiltrotor aircraft. No less so in the Next Generation Civil Tilt Rotor Technology Demonstrator (NGCTR-TD) which is currently under development by Leonardo Helicopters. To aid in these development efforts, the Advanced Testbed for Tiltrotor Aeroelastics project (or ATTILA for short) was conceived.

Multiple parties were involved. NLR provided the model itself, along with the rotary data acquisition, the latter of which was augmented by a fibre-optic measurement solution by PhotonFirst. The DLR Institute of Flight Systems (DLR-FT) provided static domain data sampling and model piloting. The DLR Institute of Aeroelasticity (DLR-AE) provided aeroelastic stability measurements and real-time monitoring.

This paper discusses the measurement system as it was implemented in the ATTILA model. First, a brief overview of the model is given, followed by a discussion of the requirements. This is followed by an overview of the sensor and data acquisition setup. Finally, the data storage and display are discussed, and a brief synopsis of the test campaign is given.

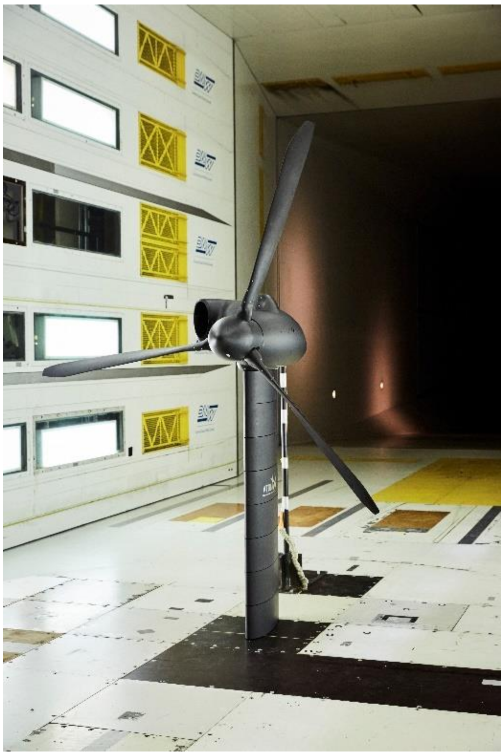


Figure 1: The ATTILA model in the LLF at DNW Marknesse, Netherlands

Model overview

The model is a scaled representation of a wing and nacelle, including a powered rotor. The wing is composed of a carbon fibre rectangular beam, which is enclosed by removeable wing sections. The nacelle is made up of several parts. The rotor pylon acts as a central mounting, to which all other key parts are attached, such as the balance, drive train and so-called TEDs, which allow for trim control and a mechanical excitation device to stimulate the flutter effect. A water-cooled electric motor and gearbox are used to drive the rotor.

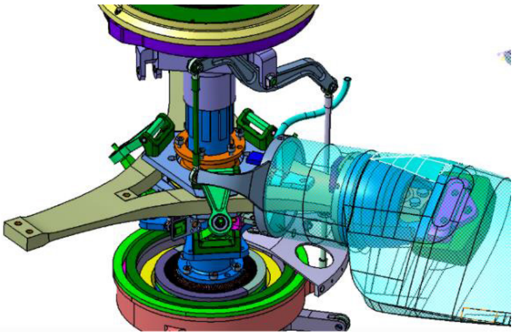


Figure 2: Detail of the rotor system

The rotor system consists of a central shaft, on which the other parts are mounted. The system incorporates a cyclic swashplate and collective control chain for blade pitch control. The rotor consists of a hub, gimbal joint and yoke, which connects the blades to the hub, and the blades themselves.

The driveline includes an in-line torque meter. At the aft-end of the rotating collective tube, which is part of the collective control chain, the rotary data acquisition assembly is mounted.

Measurement and other requirements

In summary, the following is to be measured:

- Strains and torsion in the blades
- Strains in the yoke
- Forces (normal and side) on the shaft.
- Torque of the shaft
- Yaw and pitch in the hub
- Position data from the blades (pitch) and gimbal flaps;
- Temperatures in the blade pitch bearings and static balance
- Strains from the pylon balance
- Strains from the wing balance
- Vibrations in the rotor shaft
- Vibrations in the wind and pylon

Other related requirements included:

- Produce a synchronization signal (one-per-rev) (1P);
- Transmit data and 1P-signal to storage devices and pilot station
- For the rotating acquisition electronics: withstand the acceleration and vibrations caused by flutter excitation at maximum RPM and whirl flutter as well.
- For the rotary system, the following mechanical constraints had to be considered:
    - Limited space due to enclosure/nacelle covers;
    - Minimum imbalance;
    - Placement at end of shaft: mass constraint;
    - No forced cooling: conductive thermal dissipation.

Sensor overview

To measure flap bending, two pairs of strain gauge bridges are placed to measure the lag bending, at different radial locations in the blades. Furthermore, one bridge was placed as a torsion meter. This setup is similar for all three blades, with one exception. That being that one blade is instrumented with an additional lag bending and torsion sensor.

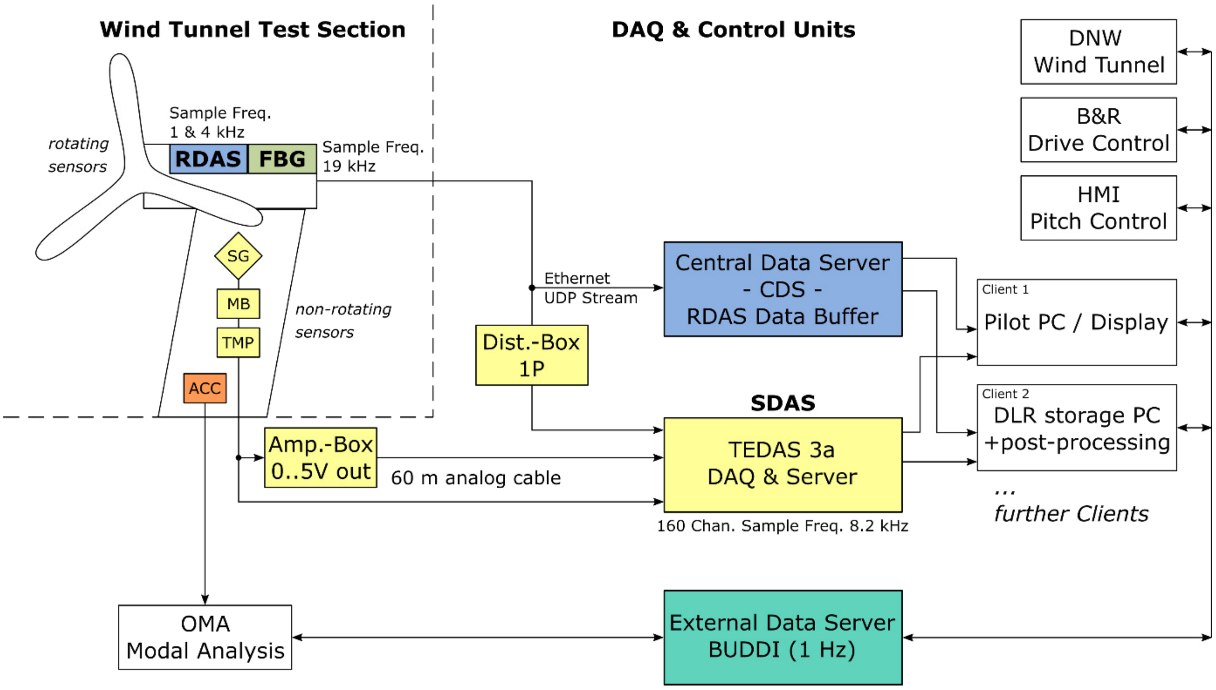


Figure 3. ATTILA System Setup.

In addition to the strain gauge bridges in the blades, optical fibers with Bragg gratings (FBG) are installed. Eight of these FBGs are contained in a single fiber. A number of FBGs are placed near the strain bridges, to allow for a direct comparison of the data produced by the different types of sensor. Two fibers were installed per blade, resulting in a total of six fibers containing 42 FBG strain and 6 FBG temperature measurements.

In the yoke, two flap and lag strain bridges are installed per arm. Another direct strain sensor is placed as a safety sensor.

For measuring the torque in the shaft, a torque sensor using a strain gauge bridge is used. In addition, bending moments in the mast are measured to enable derivation of rotor in-plane shear loads. For this, two pairs of bridges are placed under 90 degrees offset.

For all the measurements mentioned above, 750 Ohm-bridges are used.

To measure yaw and pitch, the hub is instrumented with two tri-axial accelerometers. These are placed 180 degrees apart. Dytran's 3333A3T MEMS-sensors were used to achieve this.

To measure rotary position data, incremental encoders are used. These are placed on the blade pitch bearings, and in the swashplate. The latter give rotational information, as well as the one-per-rev signal. The sensors used are the Celera Motion Optira-sensors. These are A-quad-B encoders, with RS422-output.

Furthermore, there are a number of sensors in the fixed frame of the wind tunnel model which are acquired by the SDAS. Table 1 shows these sensors.

The wing bending moments are strain gauge full bridges which are located at the root section of the wing beam. The rotor balance is an NLR-designed mechanical structure which connects the wing beam with the nacelle. It also features full strain gauge bridges. All the strain gauges in the non-rotating part are connected to the DLR Amplification Box which is placed close to the model below the test section.

Table 1. Static sensor list

Description	Unit
Wing Beamwise bending	Nm
Wing Chordwise bending	Nm
Wing torsion	Nm
Balance Fx (thrust direction)	N
Balance side force	N
Bal. vertical force (spanwise)	N
Balance Mx	Nm
Balance yaw bending	Nm
Balance pitch bending	Nm

Description	Unit
Temperature balance 4 measuring points	°C
Temp. gearbox 3 measuring points	°C
Temperature cable	°C
Temperature collective tube bearing front	°C
Rotor speed from digital/analogue conversion	V
1P encoder signal	V

For the placement of accelerometers in the static domain, a sensor optimization was performed using QR factorization and the Finite Element (FE) model. The target was to accurately identify and track the first four elastic modes which were predicted to be critical to the dynamic stability. Based on these results, uniaxial and triaxial accelerometers were mounted in the leading and trailing edge of the wing, as well as on the tilting, and non-tilting part of the nacelle. The sensor positions and directions can be seen in Figure 4. In total twenty-nine signals are measured at 13 positions. This setup allows optimal identification of the 1st normal wing bending, 1st chordwise bending, first wing torsion and nacelle yaw modes.

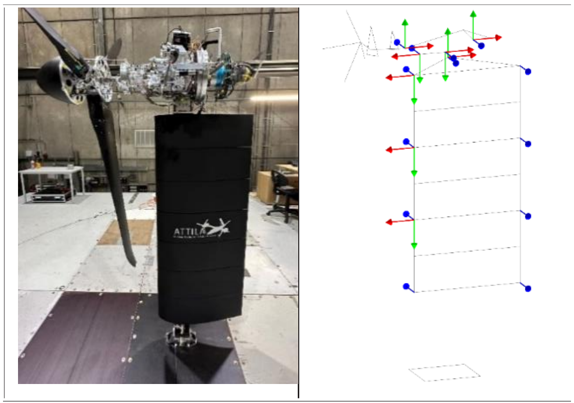


Figure 4. Accelerometer locations and directions for whirl flutter monitoring

Data acquisition

The signals coming from the sensors are sampled by three different systems: one for the rotating domain, and two in the static domain. The Rotating Data Acquisition System (RDAS) handles the rotating subsystem, while the Static Data Acquisition System (SDAS) tends to the static domain. In turn, the RDAS is split up into two subsystems. The Rotating Sensor Conditioning System (RSCS) acquires all the data from the electronic sensors, while the Fibre Optic Sensor System (FOSS) acquires the data from the fibres in the blades.

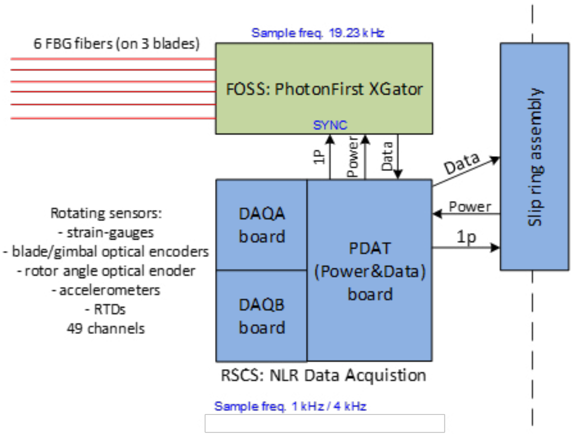


Figure 5. RDAS block schematic.

The core of the RSCS is formed by the Power Supply and Data Processing board (PDAT). It receives 28 VDC electrical power from the slip ring and converts this in switch-mode power supplies to a range of supply voltages that are needed internally for operation of the electronics. An extensive sequencing scheme is built in to ensure a proper and safe power-up procedure. Electrical power is forwarded to the other printed circuit boards in the RSCS.

The PDAT also contains a Field-Programmable Gate Array (FPGA). The FPGA implementation supports the collection of data, and transmission to a receiving computer. The design can be split up into three parts.

The first part handles control of the hardware elements in the acquisition chain, i.e. the setup of, and data readout from, the ADCs, and conditions the 1P signal for external application.

The second part collects the data, and packages it into Ethernet packets. Since the data comes in three different frequencies, care had to be taken to ensure consistent data output. This was achieved by having set packets lengths, containing:

- 28x 4 kHz-samples per package
- 7x 1 kHz-samples per package
- 1x 'slow' samples per package (temperatures, time-since-1P)

Finally, the data is sent out by the third part. This part controls the Ethernet link, which performs the required buffering, as well as arbitrating between passing through the data from the FOSS or own data.

The different sampling speeds and signal processing result in different ADC group delays. This yields significant, but deterministic time offsets between the different data types. If these time offsets are known, they can be compensated for in the FPGA firmware.

The true group delays were determined through measurements, using a custom-made calibration source that applies synchronous signals to all types of channels. Measurements were initially taken without group delay compensation. The next step was to program the FPGA to correct for the observed relative group delays, so that a true synchronous-sampling DAQ system is established. A check measurement was performed to confirm proper implementation of the correction. The determination of the relative group delays from the measurement data is a tedious and time-consuming task; for this reason, NLR automated this step through a dedicated MATLAB program. Using MATLAB's App Designer, an application was developed to speed up this process. This 'Channel Synchronization Tool' reads the data in Excel format or CSV format of two channels with the same common frequency and determines the phase difference in degrees, seconds and 'time since 1P increment' counts.

The application uses FFT to compute the fundamental frequencies of both signals and uses these as initial values for the MATLAB *fit* and *fittype* functions to precisely determine the three coefficients of the expression `a*sin(b*t+c)` to reconstruct the original waveform without any DC-offset. The phase '*c*' is then used to compute the phase difference between both signals. This phase difference is specified to 0.01 'time-since-1P increment' count, 0.1 µs and 10^{-7} degree. This is in line with the manual results, but can be done in tens of seconds.

Sensor conditioning and digital-to-analogue conversion are performed by the DAQA and DAQB-boards. These data acquisition boards have very similar functions. Both feature 16 strain gauge bridge measurement channels with 10 VDC excitation supply. Readings are taken with 16-bit resolution in a 500 Hz bandwidth. Local electronics temperature readings are taken to allow temperature-dependent calibration and posterior correction of the channels' transfer functions.

The DAQA board is complemented with seven IEPE measurement channels with 4 mA excitation. These are used for the aforementioned two triaxial hub-mounted accelerometers. Readings are taken with 16-bit resolution in a 3 to 2000 Hz bandwidth.

The DAQB board is complemented with four RTD channels, for Pt100 temperature measurement on the pitch and centrifugal bearings. Sampling occurs with 15-bit resolution at a rate of 1 kS/s.

All of the sensor connections are on the outer perimeter of the RSCS printed circuit boards, with locking connectors to counteract centrifugal forces. The stack of boards is supported by a metallic structure with spokes, providing both structural integrity and a thermal frame for removal of generated heat, see Figure 6. The latter aspect is relevant because of possible future application of the electronics in a low-pressure heavy-gas wind tunnel environment in which convective cooling is less efficient.

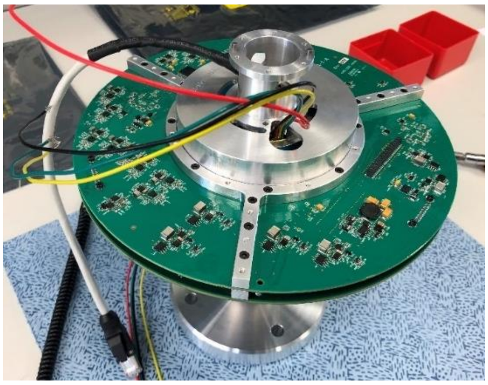


Figure 6. Partly assembled RSCS, showing thermal frame.

An XGator interrogator takes care of acquisition of the FBG sensors. This XGator interrogates the six different fibres sequentially, the sensors in each fiber are measured in parallel at 19.23 kHz. The fiber interrogated changes every 50 ms. The acquired data is sent to the storage computer (via the RSCS) through an UDP Ethernet-link.

The XGator allows up to 8 connections. Six connections were used for the different fibers, while the eighth was used as an input for the 1P-signal. The electronic 1P-signal coming from the RSCS is converted into a light input using a laser based optical sync signal. The XGTR interrogator is built on an integrated photonics platform which allowed the system to function in this harsh environment.

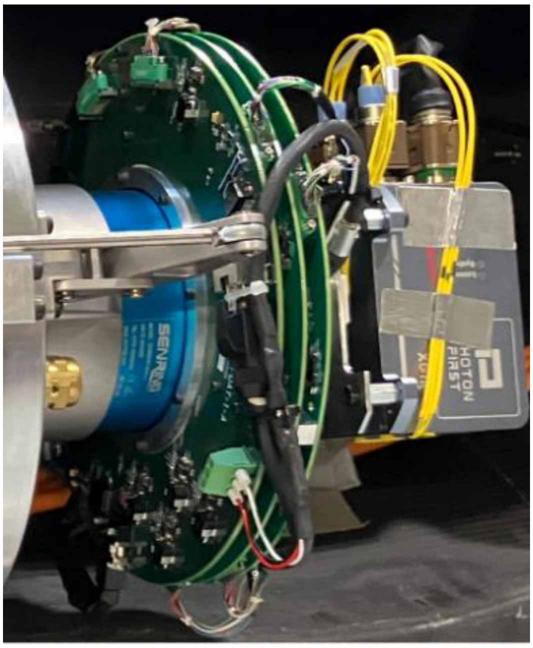


Figure 7. The complete RDAS, as mounted in the model.

In the stationary domain, the SDAS consists of two parts, namely the AmpBox and TEDAS.

The AmpBox is used for strain gauge sensor supply and signal conditioning of up to 48 input channels. The output is in the range of 0 to 5V and directly connected to the TEDAS signal input. Figure 8 shows this box which was specially designed for the usage within wind tunnel models.

Figure 8. Signal Conditioner – Amplification Box

The millivolt signal from a strain gauge is connected to programmable gain amplifiers (PGA) which allow offset adjustment to reach that suitable output range. The parameters from the PGAs can be remotely adjusted through a sophisticated network-communication interface over Ethernet (software “AmpManager”) such that no hardware changes or soldering is necessary. Apart from the PGAs, the AmpBox contains constant-current sources for Pt100 temperature sensor supply.

The AmpBox passes the conditioned signal to the TEDAS. DLR-FT developed the TEDAS (Throughput Enhanced Data Acquisition System) for rotor-triggered measurement in combination with several software modules for online monitoring, pre-processing and data analysis. It is custom developed by DLR. Key specifications of the TEDAS 3 DAQ system are:

- 496 channels analogue DAQ
- Simultaneous sampling
- 16-bit ADCs
- ±5 V buffered signal input
- Up to 3000 rpm = 50 Hz sampling
- 1024/2048 samples per revolution
- Rotor triggered measurement or fixed frequency
- Independent simulator/rotor switching

The complete system is currently mounted in a modular rack (see Figure 9) so that the measurement system can be used for different types of wind tunnel models or test rig configurations. The hardware front-end performs simultaneous sampling on all channels. The data volume for the internal ring buffer is about 100 MB/s.

Figure 9. TEDAS 3 rack system.

The overview in Figure 10 shows the structure of the rack-mounted hardware components.

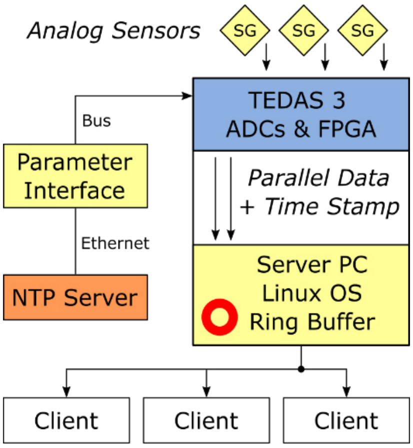


Figure 10. TEDAS 3 Block Diagram.

The sensors are electrically connected through buffers to the sampling hardware (ADCs) on the analogue frontend. The digital part of the system gets configuration parameters from a separate parameter interface (e.g. simulator/rotor switch point etc.). Apart from these parameters, a time stamp with 1 ms accuracy is included in the data block. This feature was provided for data merging in a separated DAQ system approach. The sampled data are continuously streamed out through a digital interface. A Linux-based Server PC reads the data stream and saves these data in a ring buffer with a special-developed server application. Multiple client requests can be handled simultaneously.

For the ATTILA test campaign, the system was configured in a fixed clock setup with a sampling frequency of 8.2 kS/s.

This setting was used to obtain a software compatibility for data analysis tools which are based on handling samples per revolution (rotor-triggered data packets).

The wing and nacelle acceleration signals are measured with an analogue to digital measurement system called CRONOSflex from IMC. All signals are acquired with 500 Hz sample frequency and the appropriate low pass anti-aliasing filters. The model RPM is also measured as an analogue input to the IMC system. Furthermore, a synchronization signal (sine sweep) is created by a signal generator and shared between the DLR-FT measurement system and the DLR-AE measurement system for post test data synchronization. A real-time interface was developed using ActiveX to acquire the data measured by IMC directly from the measurement computer RAM. This data is received by the DLR online monitoring OLM software in MATLAB. A listener function is used to execute appropriate events each time a new data block is received.

Data storage and processing

To store the data from both the RSCS and FOSS, a separate computer system, known as CDS (Central Data Server) was implemented.

The data was first received by the Rotary Data Processor. This processor performs sanity checks on the incoming packets and parses these. From here, the data was spread in three different streams.

First, the data is sent to the Data Storage Handler. This unit is responsible for the continuous data storage. It writes the parsed data into a binary file. This file can then be processed (offline) by a separate script to either a .csv or .m (MATLAB) file.

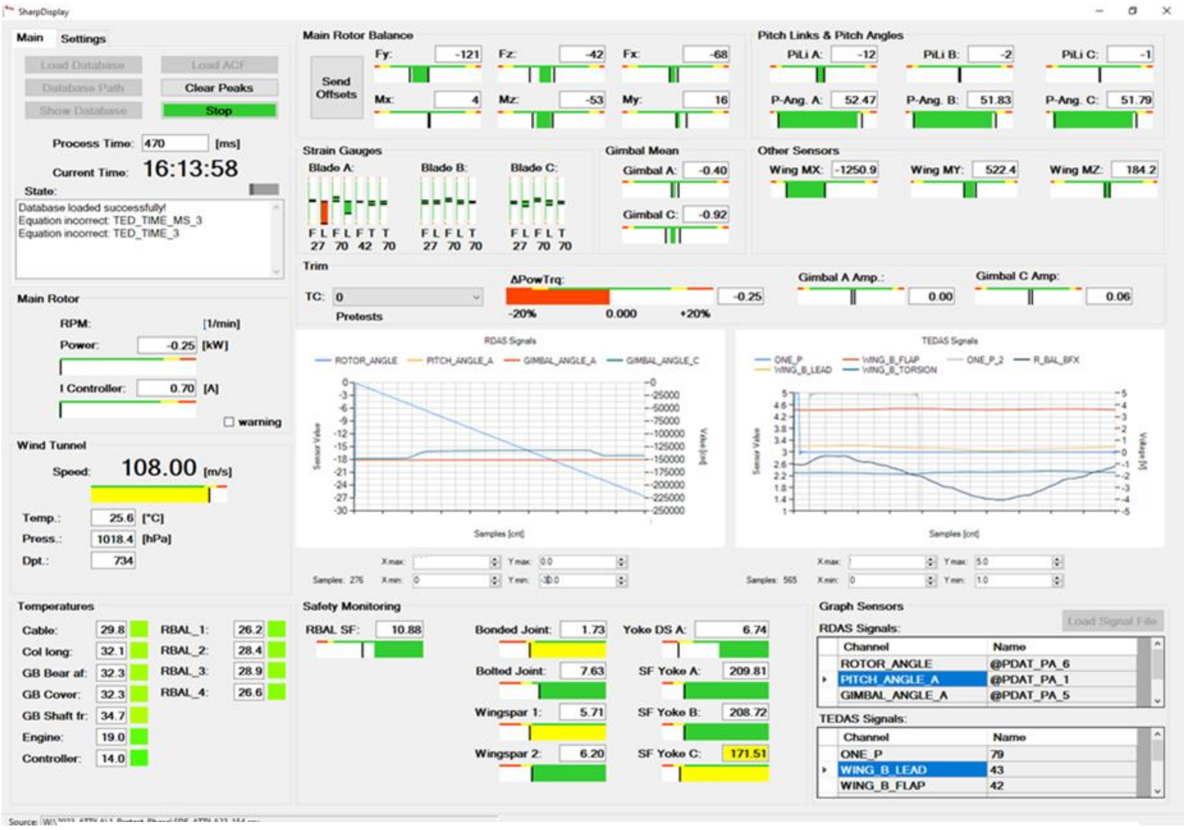
To be able to have a real-time overview of the data, quick-look functionality has been implemented, using Grafana for the presentation. The RDAS-message processor sends the parsed data by MQTT to a database. In turn, the Grafana dashboard periodically requests data from this database, and displays it.

Moreover, the processed data was stored in a ring buffer. A separate TCP message handler receives requests from the DLR pilot and measurement stations, and serves the data according to these requests.

The pilot station is the main monitoring and control station for the wind tunnel model during a test campaign. The responsible engineer at that station is in close contact via an intercom system to the wind tunnel operator and experimental systems operator. The pilot station constantly monitors the model's sensor data and actual load limits and can control further actuators (TEDs) mounted in the model with a dedicated HMI system (Figure 11).

Figure 11. ATTILA HMI system – pitch control.

For the ATTILA test the HMI system was able to control the collective pitch of the rotor blades, which is essential for the rpm control in power off condition (model acts as windmill). In addition, actuators for longitudinal and lateral cyclic pitch, similar to a conventional swash plate, control rotor tilt.



Process Time: 470 [ms]

Current Time: 16:13:58

State:

Database loaded successfully!
Equation incorrect: TED_TIME_MS_3
Equation incorrect: TED_TIME_3

Fy: -121
Fz: -42
Fx: -68
Mx: 4
Mz: -53
My: 16

PiLi A: -12
PiLi B: -2
PiLi C: -1
P-Ang. A: 52.47
P-Ang. B: 51.83
P-Ang. C: 51.79

Gimbal A: -0.40
Gimbal C: -0.92

Wing MX: -1250.9
Wing MY: 522.4
Wing MZ: 184.2

TC: 0
Pretests
ΔPowTrq: -0.25
Gimbal A Amp.: 0.00
Gimbal C Amp.: 0.06

RPM: [1/min]
Power: -0.25 [kW]
I Controller: 0.70 [A]

Speed: 108.00 [m/s]
Temp.: 25.6 [°C]
Press.: 1018.4 [hPa]
Dpt.: 734

Samples: 276 Xmax: Xmin: 0 Ymax: 0.0 Ymin: -30.0
Samples: 565 Xmax: Xmin: 0 Ymax: 5.0 Ymin: 1.0

Cable: 29.8
Col long: 32.1
GB Bear af: 32.3
GB Cover: 32.3
GB Shaft fr: 34.7
Engine: 19.0
Controller: 14.0
RBAL_1: 26.2
RBAL_2: 28.4
RBAL_3: 28.9
RBAL_4: 26.6

RBAL SF: 10.88
Bonded Joint: 1.73
Bolted Joint: 7.63
Wingspar 1: 5.71
Wingspar 2: 6.20
Yoke DS A: 6.74
SF Yoke A: 209.81
SF Yoke B: 208.72
SF Yoke C: 171.51

RDAS Signals:

	Channel	Name
	ROTOR_ANGLE	@PDAT_PA_6
▸	PITCH_ANGLE_A	@PDAT_PA_1
	GIMBAL_ANGLE_A	@PDAT_PA_5

TEDAS Signals:

	Channel	Name
	ONE_P	79
▸	WING_B_LEAD	43
	WING_B_FLAP	42

Figure 12. ATTILA Pilot Display.

In power-on condition (electric motor drive) there is a dedicated RPM control system for the model’s drive system. With that separate system a target rotational speed could be set and the actual speed was controlled automatically.

The main monitoring device is the pilot display PC with specially developed online monitoring software: The Pilot Display.

The Pilot Display collects the data from different acquisition systems:

- CDS – Central Data Server, stores and buffers all RDAS + FBG data
- SDAS – Stationary DAQ TEDAS, stores and buffers all non-rotating data
- EDS – External Data Server, operates the Basic Utility for Double Data Interchange, handles slow data (update rate ~1 Hz) between different network participants (see Figure 3 → system setup)

All these raw data streams are merged by the display program which shows all necessary data in engineering values.

For the ATTILA test the SDAS internal ring buffer memory was extended to realize the decay measurement after flutter excitation. A maximum of 60 seconds decay time can be requested from the server.

Due to the model setup with different data acquisition systems for rotating and non-rotating sensors, the request order had to be defined to get a synchronized data-set after post-processing the data. Figure 13 shows the setting used for the ATTILA test. The CDS collects the RDAS data stream and handles client requests comparable to the TEDAS server. First, the CDS is requested which delivers data "from now on" to the requested length. Next, the TEDAS server is requested to deliver historical data from the internal ring buffer. This procedure ensures an overlap of both data blocks from the two different DAQ systems.

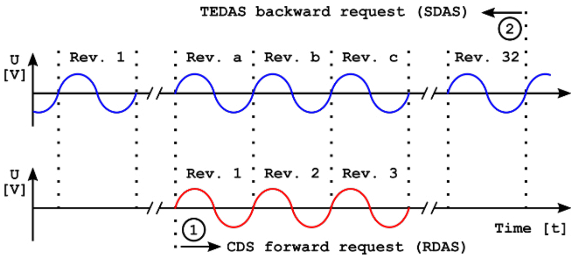


Figure 13. Overlapping data.

Apart from the request order that ensures data overlapping in time, the same 1P signal is measured on both systems. This rotor position sensor is mounted in the rotating model part. It is connected to one analogue RDAS input channel as well as fed through the slip ring to the distribution box which is connected to one analogue SDAS channel.

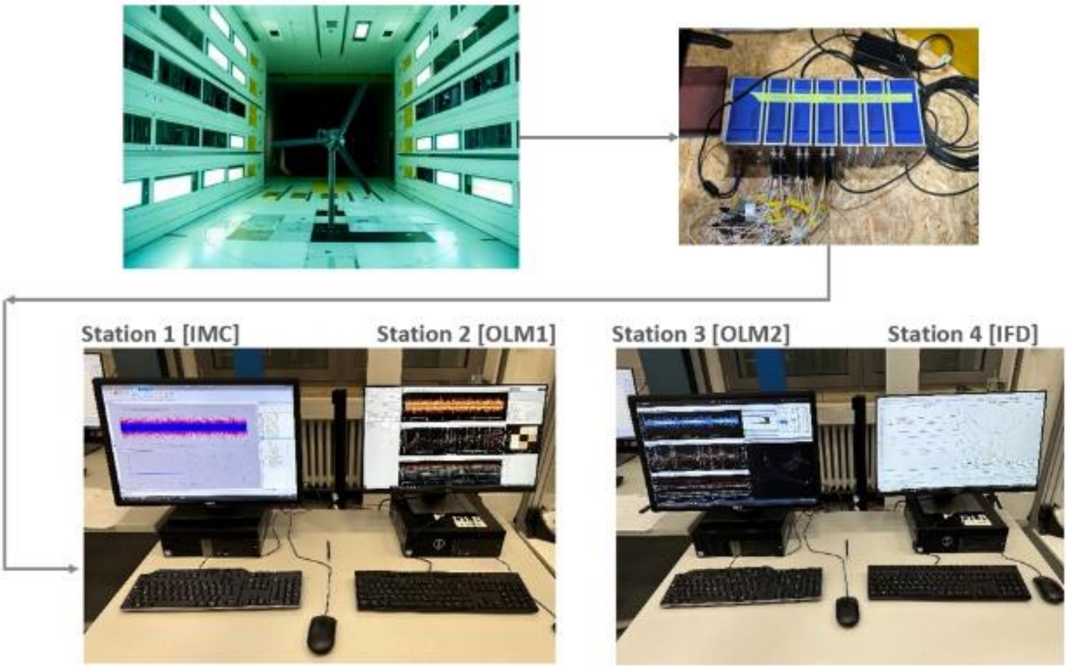


Figure 14. Whirl flutter stability monitoring system.

The DLR-AE OLM software performs signal processing, operational modal analysis (OMA) and mode tracking in near real time – updated every 2 seconds. When a new data block is received the data is processed using optimized code for the specific modal analysis method selected e.g. SSI or LSCF. If filtering, decimation and spectral calculations are required these are performed first. The data is then passed to the OMA algorithms which estimate the natural frequencies, damping ratios and mode shapes. The modal parameters are then tracked using various quality indicators and a machine learning method called DBScan. A configurable GUI is used by the engineer to monitor the results during the test. The data is saved at each stage of the above-mentioned process, and is fully traceable. Raw data is saved on the measurement PC in binary file format. The results of the OMA and tracking are saved locally on each PC and finally to an SQL data base on a network attached storage NAS. Finally, all data is batch copied each day to the NAS. An overview of the OLM system can be seen in Figure 14. Whirl flutter stability monitoring system.

Model commissioning and exploitation

After the completion of the sub-assemblies, the model was functionally integrated at the workshop facilities located at NLR Marknesse in May 2023. Following integration, a first low-RPM test was performed, to check the functioning of the drive train and to investigate any surface issues or defects. Following these tests, the model was then transported to the DLR Institute of Flight Systems, where the data acquisition and actuation systems in the model were integrated with the piloting and measurement stations. Further checks, such as balancing and calibration measurements were made.

After transport back to Marknesse, the model was prepared for the first wind tunnel campaign, aimed at testing the model in real conditions. Furthermore, testing and communication procedures were evaluated. This campaign was performed in August 2023.

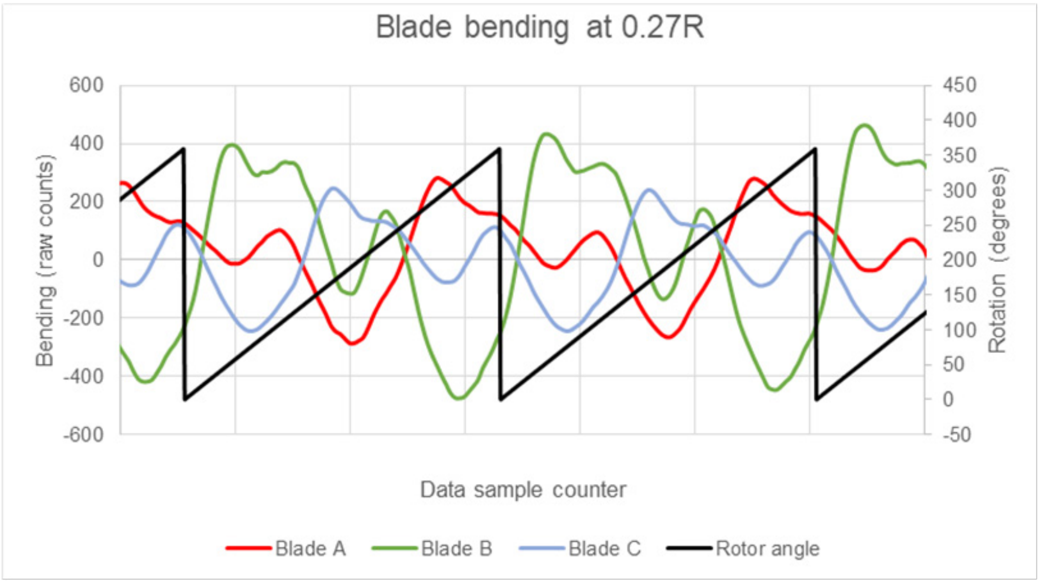


Figure 15. A data snippet representing blade bending signals, related to the rotor angle.

The shakedown campaign revealed a few issues. For the measurement system, these were a communication error between the piloting station and the CDS, as well as a signal integrity issue of the 1P-signal. The first was addressed with a software fix in the CDS, while the latter was eventually compensated for in the FPGA firmware. Furthermore, CAN communication issues between HMI and TED were solved successfully.

Having addressed these issues, and after performing final tasks such as synchronization and final calibration of RDAS, the system was ready for the final wind tunnel campaign which was performed during the late November and early December 2023.

To give a small insight into the collected data, *Figure* 15 provides a data snippet collected during this campaign. The sawtooth (in black) shows the rotor angle, as measured by the encoder mounted in the swashplate. The red, green and blue lines are the signals coming from the strain gauge bridges in the blades. As can be seen, the peaks (although differing in amplitude) are shifted 120 degrees with respect to each other.

In general, the measurement system was able to perform to expectation. A comprehensive analysis is still underway, but sanity checks of the data have found no data breaks or other anomalies. Accurate RPM control in unpowered state, i.e. controlling the RPM by changing the pitch of the blades has been possible thanks to the successful integration of encoder data coming from the RDAS and served through the CDS to the pilot station, as displayed in figure 12. In addition, the data coming from the strain gauge bridges was also able to be used for monitoring the safety factors in the model.

Preliminary results have identified near-flutter behaviour, in unpowered state. [1]

Acknowledgement

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