

Instrumentation, Measurement and Control of a Helicopter Rotor under Icing Conditions

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Abstract:

For an enhanced performance and reliability of complex technical systems DLR carried out a research project and built-up five demonstrators. One demonstrator covers the topic of icing and de-icing of rotary wing aircraft under realistic environmental conditions. This paper describes the icing facility, the test stand with its instrumentation, the new rotor system, the wired and wireless remote controls and shows an overview of the acquired data.

Key words: Strain gauge, piezoceramic, icing, heating, wireless, helicopter, rotor blade, AI, ML

Introduction

The aim of the DLR research project SAFER² (Sensor and AI Fusion for Enhanced PeRformance and Reliability, 2023-2025) was to combine dedicated and discrete sensors to capture the state parameters of complex technical systems in real time and match them with AI/ML models. With these data both performance and reliability in different application areas can be increased. A number of DLR institutes and facilities collaborated within this project and built-up five demonstrators which ensured hardware-based implementation of the developed technologies in different research fields. The research topic of the demonstrator presented here was icing, ice detection and de-icing of rotary wing aircraft. Icing is a known and recurring cause of accidents in air transport. With an early ice detection, risks can be significantly reduced. De-icing systems for rotor blades of small and medium-sized helicopters are challenging. Due to the high-power requirements and maximum weight constraints, there is currently no system for that helicopter class at the market. The preferred solution for that helicopter class would be the usage of ice protection systems only during icing conditions. There is also a potential advantage of fuel savings for a not continuously running de-icing-system compared to an anti-icing system. Within that framework, a two-bladed rotor system was developed as technical demonstrator operated in a ground-based test facility as follow-up project from the LuFo project InTEnt-H (2018-2022) [1]. The icing tests could be carried out in a repeatable laboratory environment in the ambient temperature range of +5 °C to –20 °C.

Two rotor blades of an Airbus Helicopters H145 D3 served as basis for the rotating demonstrator within SAFER². The rotor blades were equipped with several sensors for load and temperature monitoring. A switchable heating mechanism was installed to cover various test cases. Furthermore, structural health monitoring was applied using piezoceramic sensors. The rotating model was operated within a cooling chamber with water injection for ice build-up. The air condition was measured by a new optical detection system, developed by DLR.

Test Facility

DLR operates several facilities for rotor testing. The capabilities start from the setup of scaled helicopter models for hover testing up to the complete execution of a test campaigns of complete helicopter configurations within a wind tunnel [2]. One of the early days test rigs, the so-called whirl tower, which was built-up in the 1960s, underwent a massive number of upgrades that up-to-date research programs can be carried out. In this facility, whirl and hover tests can be conducted under centrifugal loads both for scaled models and full-scale component tests such as rotors and propellers. One of the major upgrades was a room-filling cooling chamber that was specially designed and mounted in the test section, see Fig. 1. This offers the possibility for a test setup under cooled environmental conditions. Furthermore, a water spray system was developed in-house and installed in the test section. Thus, the whirl tower was converted into an icing test facility EVA (Eis-Versuchs-Anlage). With that system moisture and ice build-up can be applied at the test rig and to the respective test subject.



Fig. 1: Whirl tower – icing test facility © DLR

The installed cooling chamber is shaped like a regular polygon with 16 edges, which closely resembles a circular test section with a diameter of 5.3 m. This diameter defines the maximum rotor radius with some margin (0.1 m) to the side walls for test cases without icing. For safety reasons an ice shedding protection can be mounted within the cooling chamber, the diameter is 3.8 m. With that protection the maximum rotor radius is reduced to 1.8 m. The height of the cooling chamber is 6 m. Fig. 2 shows a CAD model from the test facility with the control room on the left side and the circular test section with the cooling chamber in the middle. The outer cooling infrastructure (pumps, chiller, ducts etc.) is highlighted in blue on the right side of the sketch.

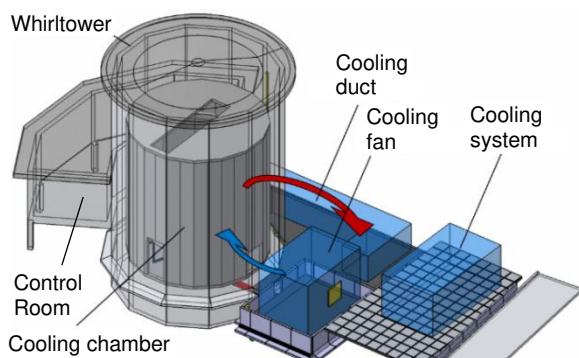


Fig. 2: Whirl tower – CAD model [3]

The designed thermal power for the cooling system (CO₂) is $P_{cool} = 50 \text{ kW}$ with a temperature range down to -25°C for an unpowered test rig and -20°C with rotor in operation. The systems cooling rate is 1.5 K/min . The basic airflow can be seen in Fig. 3.

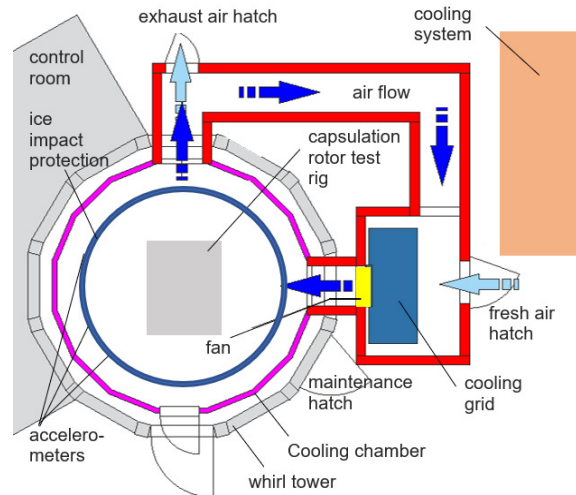


Fig. 3: Whirl tower – airflow cooling system [1]

The rotor's drive system is an electrical engine (DC motor) with $P_{el} = 47 \text{ kW}$. The rotational speed is controlled with a frequency converter which has a current limit of 100 A. The rotor's main shaft is connected via a gear set and a tooth belt to the electrical engine. Depending on rotor size a max. rotational speed of 3000 rpm is possible for a given gear ratio. The proven tip speed without thrust is 250 m/s. The test rig was designed to allow a maximum imbalance of 3000 N for asymmetric icing conditions.

For the ice build-up at ambient temperatures below 0°C a spray system was installed in the test chamber, which was specially developed for the icing test facility. Main part is a ring structure (diameter is 2.7 m) suspended from the ceiling of the test chamber (see Fig. 4). A number of 15 heated air/water nozzles are attached to the ring structure. The system allows a maximum spray flow rate of 3 l/min . With a 30 l water reservoir 10 min of icing tests can be realized. A dedicated LabView based controlling system allows the separate adjustment of water injection and air pressure control. Primary goal for the atmospheric conditions was derived from EASA CS29 appendix C [4] (see Fig. 5).



Fig. 4: Spray system in the cooling chamber [3] © DLR

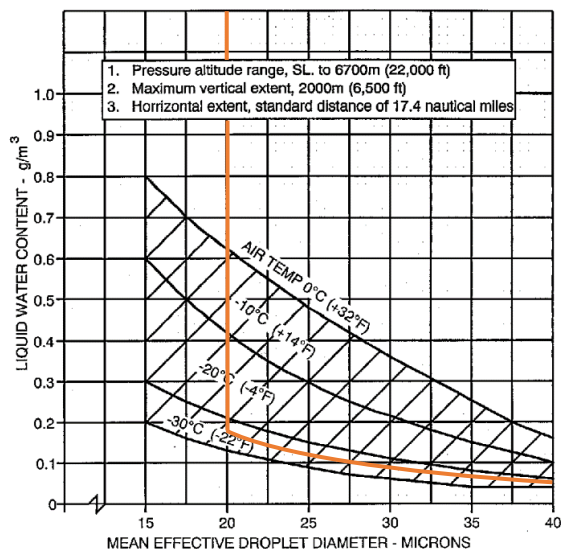


Fig. 5: Continuous max. (stratiform clouds) atmospheric icing conditions; liquid water content vs. mean effective droplet diameter [4]

The atmospheric icing conditions can be defined by the variables of the cloud liquid water content (LWC), the mean effective diameter (MED) of the cloud droplets, the ambient air temperature, and the interrelationship of these three variables. The spray system was designed for a MED between $20\ \mu\text{m}$ to $50\ \mu\text{m}$ and a LWC between $0.2\ \text{g}/\text{m}^3$ to $2.5\ \text{g}/\text{m}^3$.

Rotor Test Rig

Overview

The modular rotor test rig is placed within a sealed case in the middle of the cooling chamber (see Fig. 6). The basic steel structure and the drivetrain is mounted on a concrete block which stands on four rubber bearings. Different rotor head types can be mounted at the main shaft depending on the requirements for the respective research project. The main shaft is connected by an additional tooth belt drive to an incremental encoder (1P, A/B signals) for position and rpm monitoring of the rotor. Two

load cells are mounted in x and y direction for imbalance monitoring. A combined slip ring can be mounted to the main shaft for data, electrical energy, air, and fluid transfer. Up to 44 signal channels from the rotational part can be acquired and five electrical high voltage rings are available. The slip ring has two channels each for fluid and air transfer.

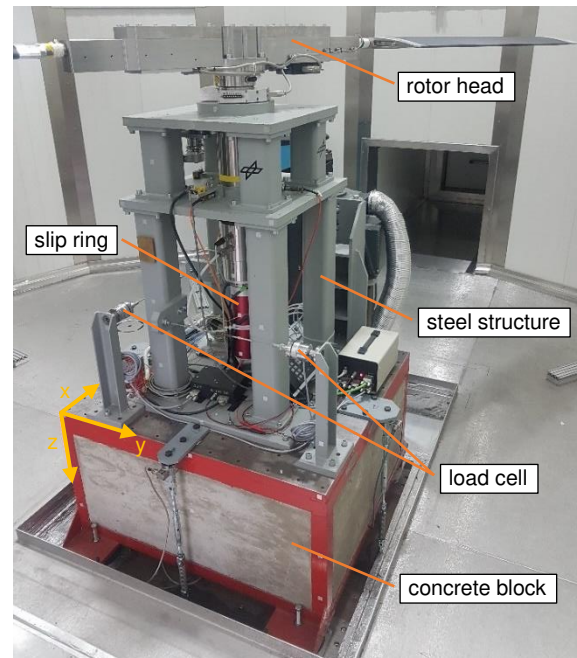


Fig. 6: Rotor test rig © DLR

Rotor head

The rotor head shown in Fig. 6 was used in an earlier project (InTent-H, see [1]). For the SAFER² test a complete new rotor blade set was built up, therefore rotor head and connecting parts for the rotor blades were redesigned. The basic concept is a massive steel block as main rotor head. There is no swash-plate or actuator system mounted. The rotor blade pitch angle can be manually set by oval holes at the connecting joints. For the test it was set to 5° at the rotor blade tip. Each rotor blade is connected with two bolts to the blade attachment. A CAD model of the basic parts with one rotor blade mounted can be seen in Fig. 7.

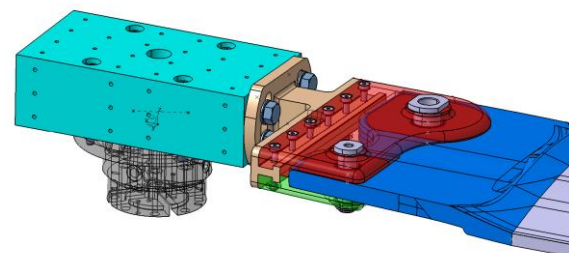


Fig. 7: Rotor head & blade attachment CAD model

Rotor blades

As test object for the icing tests two original rotor blade segments from the Airbus Helicopters H145 D3 were used. The blade segment used for the test can be seen in Fig. 8. The rotor blade tip was cut to fit the complete test subject (rotor head, blade attachment, rotor blade) into the cooling chamber with installed ice protection. For this, the rotor radius was set to 1.8 m.

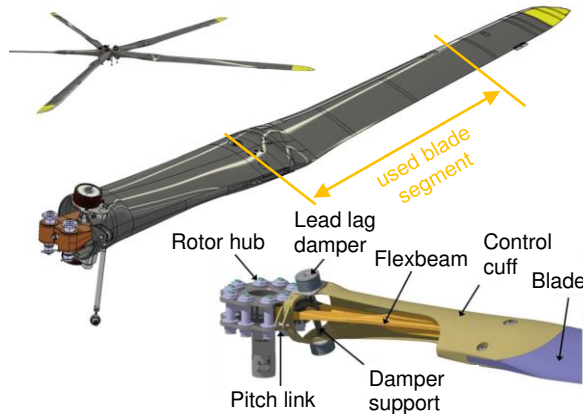


Fig. 8: H145 D3 blade segment

The maximum rotational speed was set to 800 rpm which results in a tip speed of 150 m/s. While the internal structure of both rotor blades is the same, the instrumentation and heating systems differ. One blade can be used for anti-icing (heating continuously on) the other one for de-icing (switchable heating segments on demand).

Anti-icing blade: The continuously heated blade has an electrical heating system with a power consumption of $P_{\max_ai} = 920 \text{ W}$. Four heating foils are connected in series and act as one single heating element. The power supply is current controlled (DC); 2 A max. limited due to the slip ring specification. The heating area is placed at the leading edge of the rotor blade starting from the 70% radius position to the blade tip (see Fig. 9, left side) and covers 15% c of the upper and 25% c of the lower surface. The heated area corresponds to $A = 0.645 \text{ m}^2$ with the maximum power consumption for the anti-icing blade the heating capacity per unit area can be calculated:

$$p_{A_ai} = \frac{920 \text{ W}}{0.645 \text{ m}^2} = 14264 \frac{\text{W}}{\text{m}^2} \quad (1)$$

Below each heating foil a temperature sensor is applied within the blade's skin to monitor the temperature behavior individually. Fig. 10 shows a schematic overview of heating foils (R1 to R4) and temperature sensors (T1 to T4).



Fig. 9: Anti-icing blade with instrumentation © DLR

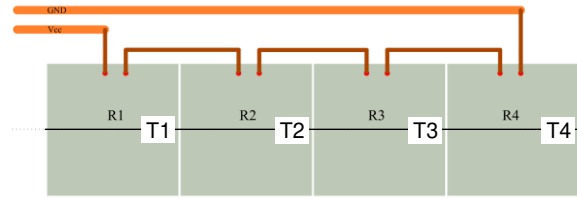


Fig. 10: Anti-icing blade heating foils & temperature sensors

The power supply and the temperature sensors are connected to an industrial control system (B&R). If one of the temperature sensors exceeds a certain limit, the power automatically switches off. Current and heating limits can be adjusted by a control panel which is installed in the test facilities control room.

De-icing blade: This rotor blade has a more complex heating system with a maximum power consumption of $P_{\max_di} = 1002 \text{ W}$. The system is also current controlled (DC) with a current limit of 1.79 A due to the heating foil specification. The heating area is also placed at the leading edge of the rotor blade starting from 70% radius up to the blade tip (see Fig. 11, left side) and covers the same area ($A = 0.645 \text{ m}^2$). With the maximum power consumption for the de-icing blade the heating capacity per unit area can be calculated:

$$p_{A_di} = \frac{1002 \text{ W}}{0.645 \text{ m}^2} = 15535 \frac{\text{W}}{\text{m}^2} \quad (2)$$

In sum 20 heating foils are applied on the blade. Five elements in chordwise direction (A-E); four elements in radial direction (1-4). The chordwise distribution is shown in Fig. 12 (25% chord on the lower 15% chord on the upper blade side). By using this setup different combinations of heating positions on the blade and different intensities can be investigated.



Fig. 11: De-icing blade with instrumentation © DLR

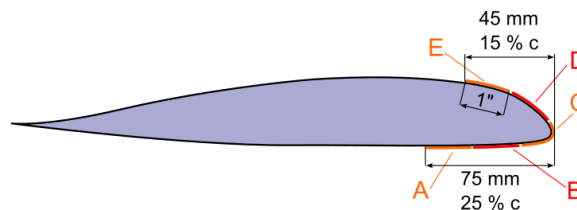


Fig. 12: Chordwise heating foil distribution

With two elements combined to one heating area 10 segments can be controlled individually. Therefore, the heating elements R1 and R2 (A-E) are connected together and also R3 and R4 (A-E). Below each combined segment a temperature sensor is applied within the blade's skin to monitor the temperature behavior individually. Fig. 13 shows a schematic overview of heating foils and temperature sensors.

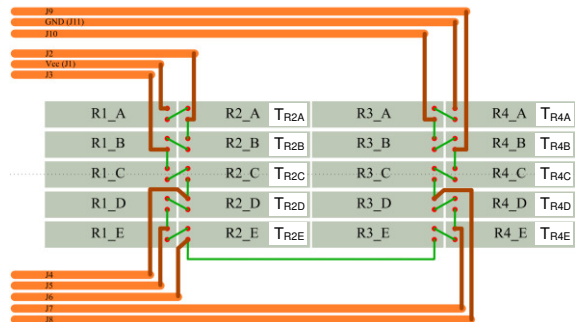


Fig. 13: De-icing blade heating foils & temperature sensors

All combined elements are connected in series with a dedicated cable connection routed to the rotor hub, shown as orange lines in Fig. 13. Copper tape was used as conductive material on the actual rotor blades to minimize the aerodynamic effect on the airfoil. This wiring allows individual elements to be bypassed using switches, so that they are no longer heated. This switching logic is shown in Fig. 14.

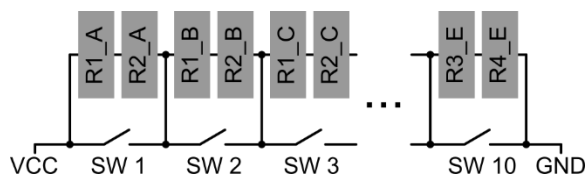


Fig. 14: Heating element bypass

The electrical connection with the switches allows a short circuit from VCC to GND. This switching state has to be prevented by safety algorithms in software which controls the position of the switches or by check lists. Beside that the power supply has an adjustable current limit as protection mechanism in hardware.

Heat element switching

The switching is done by a remote-controlled switching box which is installed on top of the rotor head. An access point mounted in an IP67 housing within the cooling chamber provides a 5GHz WiFi for the switching box. The box contains a number of sub components:

- Computer on Module (CoM) + WiFi
- Solid-State Relays (SSR) PCB
- Logic Power Supply PCB
- Analog DAQ + Logic PCB
- IP67 Plugs

The CoM is used for the remote connection between rotary and stationary model part [5]. The system runs a Linux OS with a TCP Server application that handles incoming client messages. A client PC in the test facilities control room runs a GUI based control software where the logic state for the 10 heating elements can be defined (enable or disable). A manual or automatic mode was implemented into the control software. The CoM is connected with a digital interface to an analog DAQ PCB which has a number of logic outputs that controls the SSR PCB. The use of low resistance solid-state relays is due to the fact that they are unaffected by centrifugal forces in the rotational part. This type of switch (TLP3546AF) serves to bypass the heating elements. The connection between SSR PCB and the copper tape on the blade is done by a dedicated plug and a blade cable for each blade. The plugs are IP67 rated and can handle high voltages and currents. The heating power supply is placed in the basement below the cooling chamber and connected with the energy transfer part of the slip ring and then routed to the SSR PCB. Beside the heating elements power supply plugs two sensor connection plugs are mounted within the switching box. These connectors are also IP67 rated and routed to the signal channels at the slip ring.

Instrumentation

Beside the basic test rig instrumentation, a number of sensors was installed on the rotor blades, in the rotational part and also within the cooling chamber.

Rotational Instrumentation

On the anti-icing blade, a LILD sensor system (Local Ice Layer Detector) was used for detection of ice accretion. The system is developed by the DLR Institute of Lightweight Systems [6] and uses ultrasonic waves (Lamb waves) traveling through the structure. The waves are transmitted and received by piezoelectric transducers with a distance of 30 to 50 cm. When ice is growing on the surface, the transmission characteristic (damping, stiffness) changes and thus, sensing of ice is possible.

On the de-icing blade a structural health monitoring (SHM) system was implemented [7]. This system was also developed by the DLR

Institute of Lightweight Systems and uses guided waves for monitoring of the characteristics of materials and structures. Therefore, a net of several piezoelectric transducers was applied on the upper and lower blade surface. Aim of the test was to investigate the behavior of the system under variation of temperature, rotational speed, surface water or ice accretion conditions.

To monitor the blade bending moments in flap and lead-lag direction two sensors were installed on the blade attachment position, as can be seen in Fig. 15. By using $350\ \Omega$ strain gauges in Wheatstone full bridge configuration, the moments could be observed online. An overview of the rotational instrumentation can be found in Tab. 1.

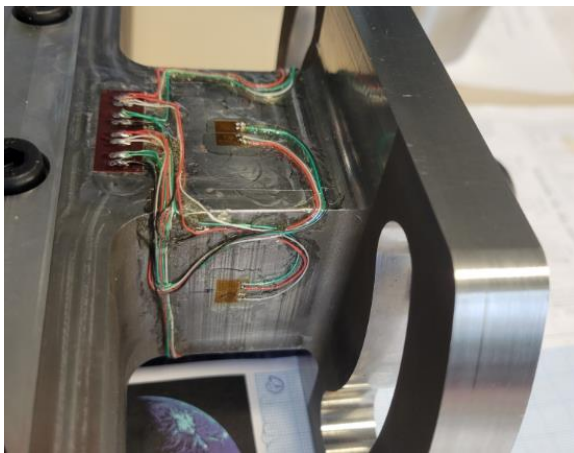


Fig. 15: Strain gauge sensors for blade bending moments © DLR

Tab. 1: Instrumentation of rotor blades

	Number	Specifications
Anti-icing blade		
Temperature	4	Digital – TMP235
Piezoelectric transducers	3	
De-icing blade		
Blade bending	2	Strain gauge $350\ \Omega$
Temperature	10	Digital – TMP235
Piezoelectric transducers	22	

Non-Rotational Instrumentation

Beside the basic sensors like ambient temperature inside the cooling chamber, motor temperature and online imbalance monitoring a new sensor system was installed for measuring

the icing conditions and detecting water and ice particles in the air. The system was developed at the DLR Institute of Aerodynamics and Flow Technology. The so-called ODIC sensor (Optical Detection of Icing Conditions) is a system directly sensitive to atmospheric icing conditions. It is an image-based sensor with pulsed laser light illumination (see Fig. 16). A differentiation between super-cooled droplets and ice crystals ($d = 4 - 4000\ \mu\text{m}$) can be done. The aim for this system was the collection of experimental data under icing conditions and the development of machine learning (ML) algorithms for fast and robust data processing. The system was mounted in the vicinity of the blade tip and about $0.50\ \text{m}$ above the rotor (Fig. 17). During the icing tests a large number of camera images were taken and the analysis was done in the aftermath. From preliminary results of the varying spray nozzle conditions, it can be stated that the mean effective diameter (MED) of the droplets is dependent of water and air pressure. Larger droplets can be created with a higher water pressure in combination with a decreased air pressure. This analysis of the data provides guidance on how to configure the spray system for future tests. In addition to the configuration of the spray bar system, ambient temperature is another factor that must be taken into account in order to obtain a specific icing condition.

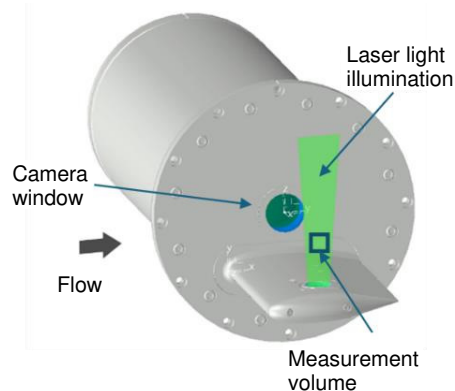


Fig. 16: ODIC sensor CAD model



Fig. 17: ODIC sensor in EVA © DLR

Experiments and Data Evaluation

The experiments in SAFER² took place in August 2025. In a four days test campaign 10 icing and 7 de-icing cases were conducted at different rotor speeds (400 / 750 / 800 rpm). During testing the ambient temperatures were varied between +5 °C to –20 °C and by a variation of the water and air pressures of the spray system different icing conditions were generated.

As an example, a de-icing case at –8 °C is analysed in more detail. In advance to the de-icing, the rotor was iced at 400 rpm for 5 minutes. Fig. 18 shows the R4 temperatures of the de-icing blade during the heating procedure. The heating was switched on at second 2 with 900 W power. The temperature then is rising from the starting point at –5 °C with about 40 K/min. After about 8 seconds when the blade temperatures are between +2 °C and +5 °C the accelerometer at the ice impact protection shows a strong peak (see Fig. 19). Thus, ice shedding took place and at the same time the rotor imbalance decreases drastically from 1.3 kN to 0.8 kN, as expected. Looking at the blade bending moment in lag direction in Fig. 20, which is corresponding to a drag force at the airfoil, also a clear reduction by about 60 Nm can be observed. With a reduced drag force the power demand differs for that operating condition. The electrical rotor power is decreasing from 9 kW to about 7.5 kW at the time of the ice shedding.

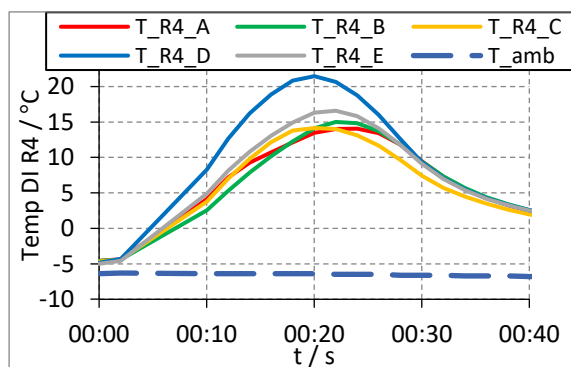


Fig. 18: R4 temperatures of the de-icing blade

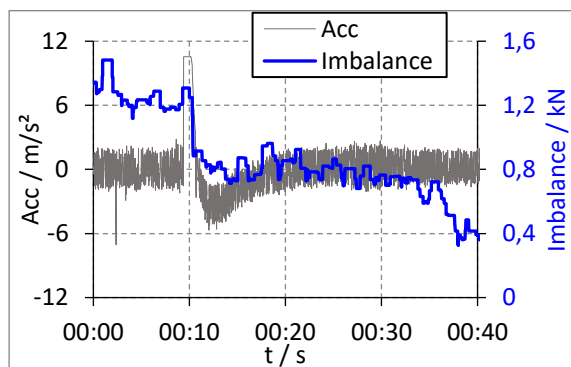


Fig. 19: Impact sensor, rotor imbalance

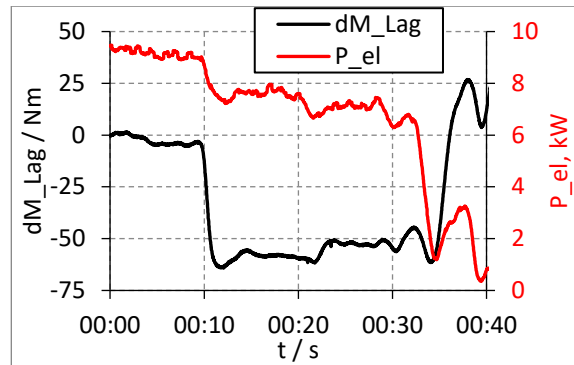


Fig. 20: Blade lag bending moment, electric rotor power

After the de-icing procedure the rotor was stopped for inspection and documentation. Thereafter another icing was started for 2 minutes. In Fig. 21 the resulting ice shapes are visible. At the outer blade radius, a thin ice layer is present from the second icing, at the inner radius a thick layer of ice is visible, as result of the two icing tests. At an ambient temperature of –8 °C clear ice is developing as expected.



Fig. 21: Rotor blade after de-icing and icing © DLR

Conclusion

The test campaign was conducted successfully. The test rig was put into operation with a completely new rotor head and a new set of rotor blades. Instrumentation was applied on the rotor blades, for load and temperature monitoring and two different systems for ice detection. Both rotor blades had a functional remote controlled electrical heating system for anti-icing and de-icing with automatic and manual heating foil selection switching. The slip ring limited the maximum power for the electrical heating system but it was sufficient to trigger the ice shedding from the rotor blade at different rotational speeds. The imbalance of the test rig was continuously monitored for model safety and damages due to ice shedding could be prevented. Temperatures were measured at various locations in both rotor blades and the blade root strains were monitored in the rotational part. Data in the fixed system were collected as well. Ambient temperature and the

spray bar configuration were continuously monitored and acquired for further analysis. The accelerometers mounted at the ice impact protection indicated ice shedding from the rotor blades. A new developed sensor system measured the atmospheric icing conditions in the cooling chamber and a database for AI training was created. In combination with the ambient air conditions the spray bar configuration can be done more accurately for future tests to achieve a specific icing condition. In a first evaluation step all measured data look plausible and can be used for further analysis and optimization of the ice sensors and de-icing systems.

Acknowledgments

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Glossary

<i>AHD:</i>	Airbus Helicopters Deutschland
<i>AI:</i>	Artificial Intelligence
<i>CAD:</i>	Computer Aided Design
<i>CoM:</i>	Computer on Module
<i>DAQ:</i>	Data Acquisition
<i>DC:</i>	Direct Current
<i>EVA:</i>	Eis-Versuchs-Anlage
<i>LWC:</i>	Liquid Water Content
<i>MED:</i>	Mean Effective Drop Diameter
<i>ML:</i>	Machine Learning
<i>PCB:</i>	Printed Circuit Board
<i>SSR:</i>	Solid-State Relay