

ROTOR ICING AND DE-ICING TESTS IN THE DLR ROTOR TOWER

R. Bartels, DLR, Institute of Flight Systems, Braunschweig, Germany
O. Schneider, DLR, Institute of Flight Systems, Braunschweig, Germany
M. Pohl, DLR, Institute of Lightweight Systems, Braunschweig, Germany
R. Konrath, DLR, Institute of Aerodynamics & Flow Technology, Göttingen, Germany
S. Galiana, DLR, Institute of Lightweight Systems, Braunschweig, Germany
P. Marquardt, DLR, Institute of Aerodynamics & Flow Technology, Göttingen, Germany
C. Postrach, DLR, Institute of Flight Systems, Braunschweig, Germany

Abstract

The paper presents experimental rotor icing investigations in the DLR rotor icing test facility EVA (Eis-VersuchsAnlage) within the frame of the DLR project SAFER². The project mainly addressed the challenges arising from the combination of sensor technology, machine learning methods, and artificial intelligence in the control of complex technical systems, with regard to functionality and operational safety. In this project, the rotor test stand inside EVA was one of five selected demonstrator platforms for gathering data for ML (Machine Learning) algorithms. In this case, the measurement data comes from sensors integrated or attached to the rotor blades, as well as from a novel optical sensor in the non-rotating frame. The blade-mounted units include piezo sensors using guided waves for structural health monitoring (SHM) and the DLR technology for local icing layer detection (LILD). Additionally, the DLR concept sensor for optical detection of icing conditions (ODIC) measures liquid water droplets, ice particles, and the liquid water content of the ambient air. For testing purposes, the rotor system was equipped with new blades featuring electrical heater systems at the blade tips for de-icing and anti-icing. These tests aim to investigate energy-efficient blade de-icing methods. This technology is essential for small and medium-sized helicopters, which currently lack dedicated rotor de-icing systems. The paper gives an overview of the sensor systems as well as the test campaign. Selected results from de-icing and anti-icing measurements, including temperature and load measurements from the rotating system, as well as results and findings from the guided surface wave sensors used for ice detection and measurement are presented. The measurement results from the ODIC sensor are highly relevant for assessing the quality of the icing conditions. The results presented show that the icing conditions set correspond to those specified in EASA CS-29, Appendix C.

Keywords

helicopter rotor icing & de-icing tests; local icing layer detection; SHM; optical detection of icing conditions

1. INTRODUCTION

In-flight icing, a well-known aviation phenomenon, occurs when supercooled water droplets in the air freeze onto an aircraft's surfaces during flight. Icing particularly on lifting surfaces reduce the aerodynamic performance and increase the aircraft mass. This poses a threat to flight safety and can lead to catastrophic accidents if it goes undetected and no countermeasures are taken. Besides engine air intakes, tail planes or wind shields, the rotor blades of helicopters are the surfaces which are most prone to icing. The development of efficient rotor blade de-icing (removal of adhering ice) or anti-icing (prevention of ice formation) systems for helicopters presents a significant challenge. For contemporary large helicopters, ice protection systems are available that typically operate electrically and provide immediate heating when icing conditions arise. However, due to the extensive energy demands, adapting these technologies for small or medium-sized helicopters is problematic due to the weight of such a system. To date, helicopters of this size, which are often utilized as air ambulances or for mountain search-and-rescue operations, lack rotor de-icing or anti-icing systems.

To experimentally investigate rotor icing and to support the development of energy efficient de-icing systems for helicopter rotors, the DLR rotor tower in Braunschweig was converted into an icing test facility within the nationally-funded project InTEnt-H (2018-2022) [1]. For that, a cooling chamber and a water droplet spaying system were installed into the rotor tower. In the chamber, different icing conditions can be set to simulate realistic atmospheric icing conditions. Since then, the modular experimental rotor test rig operated in the chamber offers the possibility of investigating icing situations under the influence of centrifugal forces. In the first investigations, a liquid-based blade heater system was tested that utilizes the abundant and normally unused waste heat from systems already installed in the helicopter for thermal anti-icing as well as for de-icing of the rotor blades. Therefore, a special rotor system with integrated fluid-circuits along the blade leading edges was developed, built, and successfully tested [2].

The subsequent internal DLR project SAFER² (Sensor and AI Fusion for Enhanced PeRformance and Reliability) aimed for the development of robust and real-time capable AI-based methods for monitoring and controlling complex technical systems based on actual sensor data. The main objectives of the project were hardware-based

demonstrations and proof of concepts of the developed methods for applications from different research fields like traffic systems, wind energy systems, turbo machinery, and aeronautics. The rotor in the icing test facility was selected as one of five demonstrators within the project to gather data from different sensor systems for ice and icing conditions detection, and from de-icing systems during various icing situations.

Ice sensors offer a significant safety gain for all flying systems by measuring icing conditions or detecting actual icing on the aircraft structure in order to provide data to activate ice protection systems or to leave the icing area. The combination of sensor data with ML models provides access to information that is difficult or impossible to measure, e.g. area-wide information on icing conditions on all aircraft components and the combination of information from different sensor systems.

For that purpose, a new two-bladed rotor system was developed and built-up using two Airbus Helicopters H145 D3 rotor blades as basis for the rotating icing demonstrator [3]. The blade attachments of the new rotor heads were equipped with strain gauges to capture the moments at the blade roots. Several small piezo sensors were fitted to the surfaces of the rotor blades using guided waves for ice detection and icing layer measurement. In addition, different switchable electric heater foils were affixed to the leading edges of the blades in the tip region, which can be used for anti-icing and de-icing purposes. In the non-rotating frame, a novel sensor for optical detection of icing conditions (ODIC) was installed into the cooling chamber measuring water droplets and ice particles in the ambient air just above the rotor disc. With this test setup a measurement campaign was carried out, and the measurement data was used to train several ML models. The following sections describe selected findings from this study.

2. DLR'S ROTOR ICING TEST FACILITY

The DLR rotor tower (Figure 1), originally designed in the late 1950s for hover tests of model rotors with diameters up to $D = 4.2$ m, is one of two rotor test facilities in Braunschweig.



Figure 1 DLR's rotor tower with the cooling system

In the years 2000 till 2018 it was exclusively used for rotational single blade testing of new rotor blades as a safety measure before a complete rotor is allowed to be tested in the DLR rotor test hall. In the years that followed, the rotor tower was upgraded with an icing function, making it possible to conduct icing and de-icing tests on rotors under the influence of centrifugal forces. To this end, the rotor tower was equipped with an external CO₂ cooling system, an internal cooling chamber, and a spraying system for the injection of an adjustable mixture of compressed air and water droplets (Figure 2).

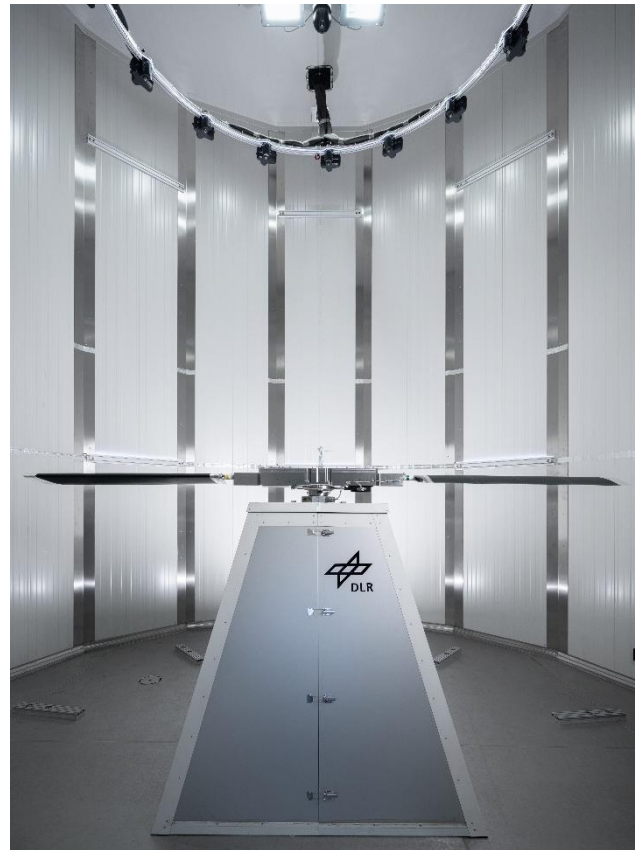


Figure 2 Encapsulated rotor test rig with two-bladed icing rotor inside the cooling chamber and the spray ring system below the ceiling

The cooling chamber is made of thermal insulating sandwich panels covered by thin metal skins. The chamber has an almost circular cross section with an inner diameter of $d = 5.3$ m and an inner height of $h = 6$ m. The cooling system has a cooling capacity of $P_{cool} = 50$ kW, which allows temperatures of $T = -25$ °C (or $T = -20$ °C when the rotor is spinning) to be achieved inside the chamber. The rotor stand is protected by its own thermal enclosure to shield it from moisture during testing and to prevent heat from the electric rotor drive from entering the cooling chamber. When the rotor is spinning with blade pitch angles of $\vartheta > 0^\circ$, the rotor produces thrust and a recirculation flow is created in the chamber, which ensures uniform temperature distribution within the chamber and also generates a downward flow. This flow is used to transport water droplets from the spray ring down to the rotor during the icing tests. To separate downwash and upwind zones of the recirculation flow, a cylindrical flow guide up to 4 meters high can be installed to enclose the rotor. This flow guide divides the cross section of the chamber into a

circular area inside and an annular area outside of it of approximately the same size. The guide also serves as ice shedding protection, helping to prevent damage to the walls of the cooling chamber. If the flow guide is not installed, at least a separate ice shedding protection ring has to be installed. Due to the protection ring the rotor radius for icing tests is limited to $r = 1.8$ m (Figure 3).

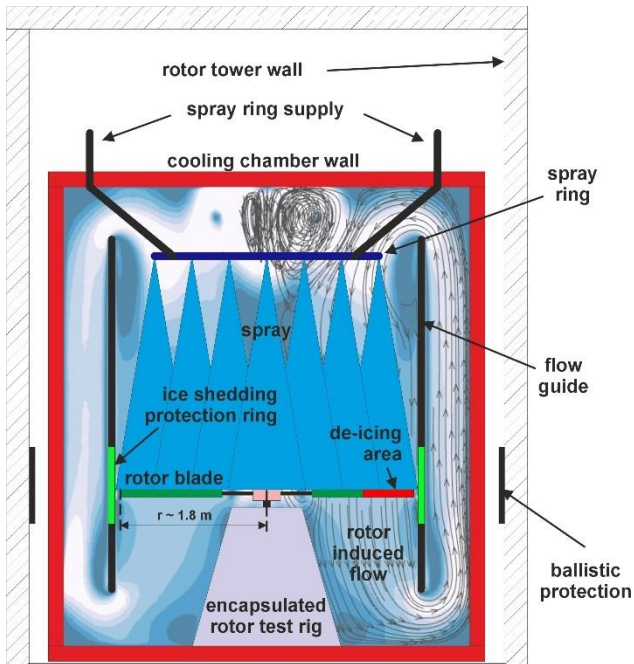


Figure 3 Principle of the test setup inside EVA (Eis-VersuchsAnlage)

2.1. Test rig

The rotor test rig (see Figure 4) is designed to carry rotor systems of different sizes. The electric motor-driven system can achieve rotational speeds of up to $\Omega = 3000$ rpm.

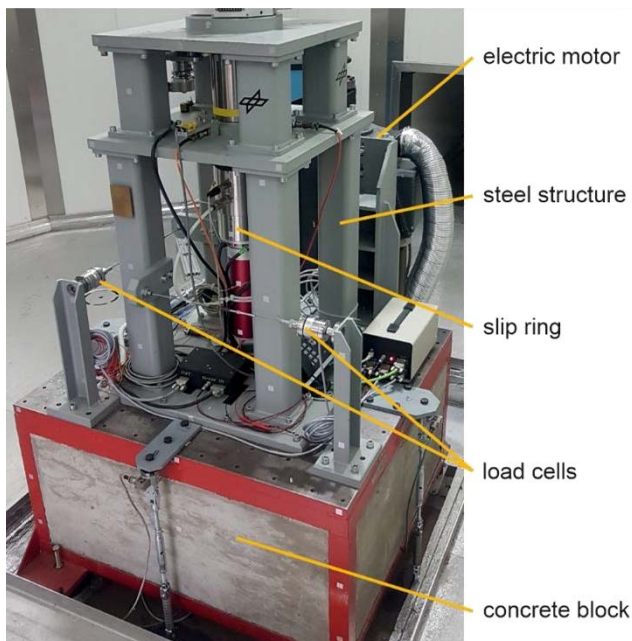


Figure 4 Rotor test rig

For the rotor icing tests this speed is limited to $\Omega = 800$ rpm. The basic structure is able to endure side forces of up to $F_{side} = 3000$ N resulting from a possible rotor unbalance due to icing. Inside the test rig two load cells are mounted perpendicular to each other for monitoring of rotor unbalances.

To measure the system's power consumption, both the rotor torque and the current of the electric drive are acquired. A slip ring located below the rotor mast comprises 5 high-voltage rings, 44 data channels, 2 fluid lines and a compressed air channel. The main shaft is further connected with an additional tooth belt drive to an incremental encoder for the acquisition of the azimuthal position of the rotor and for the rotor speed measurement.

2.2. Rotor system

For the SAFER² tests a new rotor head was developed and manufactured in-house (Figure 5). For the experimental icing rotor two original blades of an Airbus Helicopters H145 D3 were used as basis. The rotor radius was adapted to $r = 1.8$ m to fit into the icing test section.

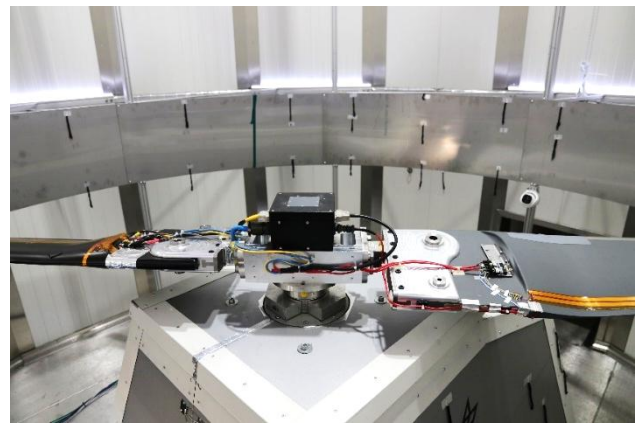


Figure 5 New rotor head system for SAFER² icing tests

A new blade attachment to the rotor head was developed including an option to measure the blade bending moments in flap and lead-lag direction by means of strain gauge full bridges, as can be seen in Figure 6.

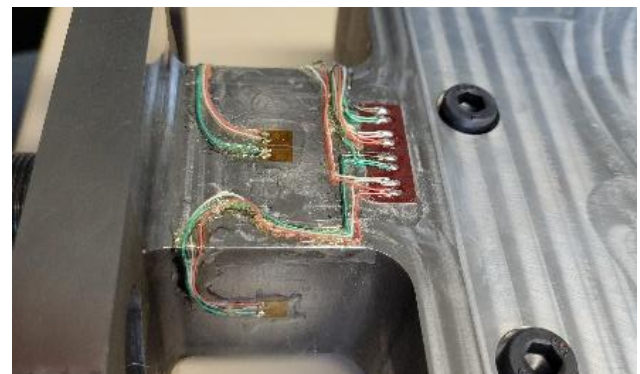


Figure 6 Strain gauges to measure the root bending moments

2.3. Heater systems

The new rotor system is equipped with heater elements. One blade can be used for anti-icing the other one for de-icing tests. The anti-icing blade has an electrical heater system with a maximum power of $P_{max,ai} = 920 \text{ W}$. Four heater foils are installed at the leading edge of the rotor blade starting from the 70 % radius position to the blade tip and up to 15 % chord at the upper side and 25 % chord at the lower side (Figure 7). They are connected in series and act as one single heater element. Under each foil a temperature sensor is mounted into the blade skin for monitoring purposes. Since the rotor blades are rejects from the Airbus Helicopters production line, the foil heaters are glued to the surface rather than integrated into it. For the same reason, the wiring is also located externally, rather than inside the rotor blades.



Figure 7 Anti-icing blade heater foils

For the de-icing blade a more complex heater system with a maximum power of $P_{max,di} = 1002 \text{ W}$ was mounted. It covers the same radial and chord area as the anti-icing blade starting from the 70 % radius position to the blade tip in two radial segments. The chordwise distribution is shown in Figure 8.

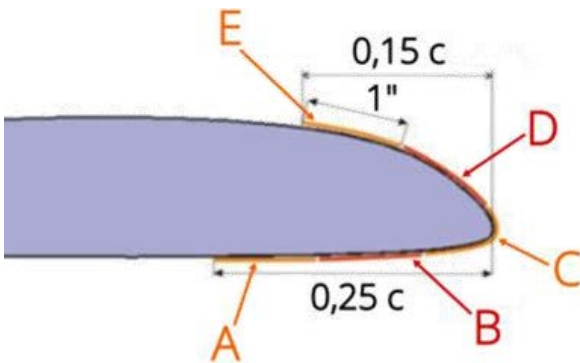


Figure 8 Chordwise distribution of heater foils at the de-icing blade

Here, five different sections were separated which are switchable on demand to be able to test different combinations of heater positions on the blade and also to investigate different heating intensities. In total 20 heater foils were applied to the blade; five elements in chordwise direction (A-E); four elements in radial direction (R1-R4) as shown in Figure 9, while elements 1 and 2 as well as 3 and 4 are combined to one radial segment each.

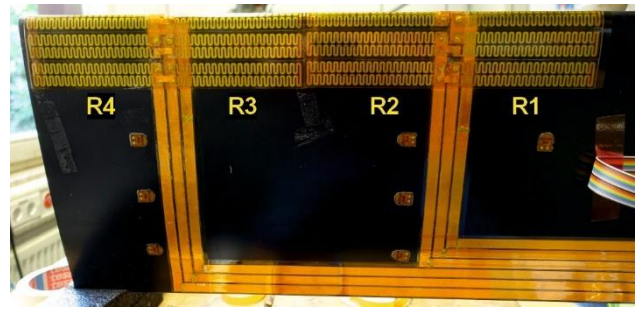


Figure 9 De-icing blade heater foils at outer radius

For each of the ten different heater elements one temperature sensor was installed below the foils. All combined elements are connected in series with a dedicated cable connection routed to the rotor hub. The wiring allows individual elements to be bypassed using switches. Switching is done by a remote-controlled switching box on top of the rotor head via a 5 GHz WiFi connection.

3. LOCAL ICE LAYER DETECTION

3.1. Sensor principle

The DLR concept of the Local Ice Layer Detector (LILD) is an ice accretion sensor based on the wave guide behavior of aircraft structures. A Lamb wave pulse is sent along an icing prone surface on an aircraft where the presence of ice needs to be detected, e.g. a leading edge of a lift surface. Between the transmitter and the receiver, an ice accretion can be detected as shown in Figure 10.

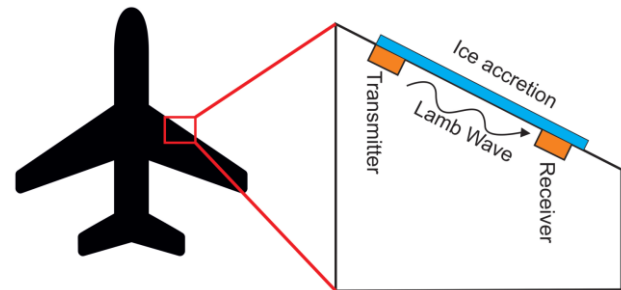


Figure 10 LILD sensor principle

The wave guide behavior of structures for Lamb waves is determined by their mass, stiffness and damping distribution. If a layer of ice is present on said structure, all of these parameters will change. Most prominent, an ice layer influences the amplitude of the Lamb wave.

An example is provided in Figure 11, where the amplitude for a Lamb wave pulse is shown measured in a wind tunnel test. This test has been performed on a 2 mm thin aluminum leading edge. More information on wind tunnel and flight testing of the LILD sensor can be found in [4].

In contrast, in this paper, the LILD principle is tested on a rotating helicopter rotor blade.

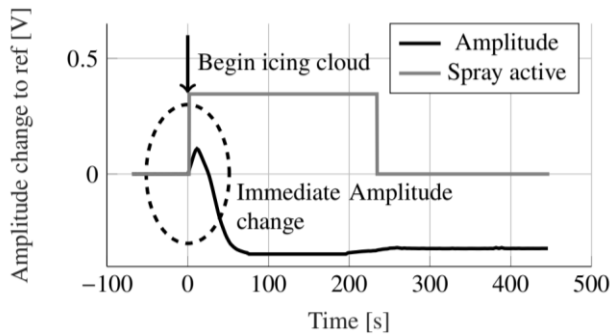


Figure 11 Lamb wave amplitude change due to ice accretion

3.2. Sensor setup and pretest results

The principle was generally assumed to work in rotating conditions, but the structural design is totally different compared to the already tested sheet metal leading edge. Helicopter rotor blades have their main fiber composite spar in the front section of the rotor blade, where only a thin metal erosion shield is added. Therefore, the Lamb wave transmission behavior is expected to deviate from the previously used thin panel structures.

To assess the general feasibility of using Lamb waves to detect ice with Lamb waves traveling directly through the leading edge of helicopter rotor blades, an initial test was performed on a non-rotating section of a real rotor blade (Airbus H145). To transmit and receive Lamb waves, piezoelectric transducers were attached to the leading edge as shown in Figure 12. A distance of 15 cm is kept between each transducer to allow measurement distances of 15 and 30 cm.



Figure 12 Piezoelectric transducers added to rotor blade leading edge

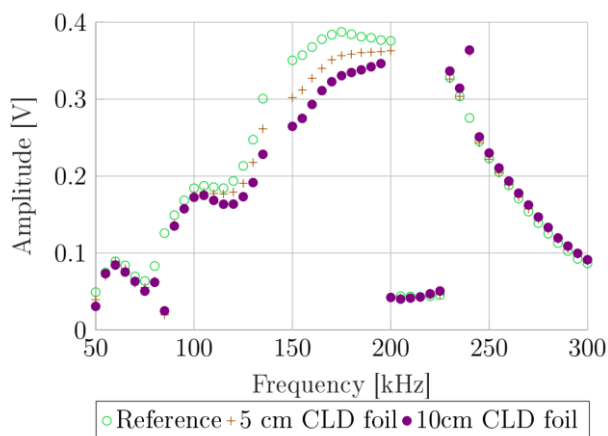


Figure 13 Measured Lamb wave amplitudes vs. frequency for 15 cm distance with different damping settings

A Lamb wave sweep with carrier frequencies between 30 kHz and 1 MHz was performed on the leading edge of the helicopter blade. There Lamb wave pulses could be received, where the maximum amplitudes were obtained between 100 kHz and 300 kHz. The behavior was comparable for both distances albeit with lower amplitude for 30 cm distance. To simulate an ice accretion constraint layer damping (CLD) foil was added between the piezoelectric transducers. As shown in Figure 13, CLD lowers the Lamb wave amplitude hence a sensitivity for ice accretion is likely.

4. GUIDED-WAVE SHM FOR ROTOR-BLADE ICING MONITORING

4.1. SHM Purpose and measurement principle

A guided-wave structural health monitoring system was investigated as a blade-integrated method with the potential for permanent monitoring of icing-related changes on a rotating rotor blade, icing being a recognized operational hazard for rotorcraft [5]. The objective was to determine whether signatures associated with active icing and acoustically coupled surface accretion could be detected and distinguished from the competing effects of temperature, rotation and measurement-system variability. The investigation builds on the project partners' previous work on guided-wave system architectures for aircraft applications [6] and on combined guided-wave and impedance measurements under controlled temperature and icing conditions [7].

The system uses thin piezoelectric transducers bonded to the composite blade shells. The transducers are operated as an active pitch-catch network: one transducer generates a short ultrasonic tone burst, while the remaining transducers record the guided-wave response propagating through the blade structure. Water or ice acoustically coupled to the blade surface modifies the propagation and attenuation of these waves [8] and therefore changes the signals measured between the transducer pairs.

Two acquisition modes were applied during the icing campaign. Broadband frequency sweeps were used to characterize the blade response, while repeated measurements at 80 kHz provided time-resolved monitoring during the icing sequences. The recorded excitation signal was used to normalize each measurement against variations in the applied drive voltage.

Component-level wavefield measurements on a spare rotor-blade tip showed that the internal blade structure, including the shells, spar, foam core and trailing-edge web, produces a strongly reverberant wave field. Consequently, the monitoring parameter selected for the rotating-blade tests was the signal power within a frequency band around the excitation frequency, rather than the amplitude or arrival time of an individual wave packet.

4.2. Installation onto the rotor blade

Two independent eight-channel transducer networks were installed on the blade. This contribution focuses on the leading-edge network used primarily for icing monitoring; the second network, located closer to the blade tip, was

intended mainly for the investigation of centrifugal-load effects.

The icing-monitoring network consisted of four spanwise stations with a spacing of 125 mm. The transducers were positioned on the upper and lower blade shells approximately 90 mm forward of the trailing-edge web, as illustrated in Figure 14.

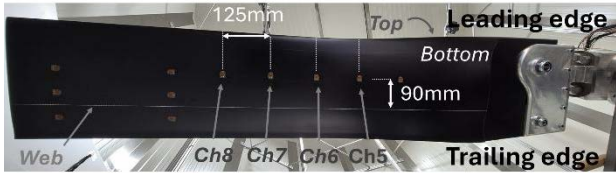


Figure 14 Guided-wave transducer network installed on the rotor blade. Four spanwise measurement stations are mirrored on the upper and lower shells.

The transducers were adhesively bonded to the blade surface, and the cables were routed along the blade to the slip-ring interface. Reciprocity and cross-path consistency checks were used to assess the condition of the complete measurement chain, including the transducers, cabling and slip ring. These checks identified two faulty channels at the outer station (Ch4 and Ch8), which were excluded from the evaluation. The remaining six transducers provided 30 valid directed measurement paths.

5. ODIC-SENSOR

The icing sensor technology of ODIC (Optical Detection of Icing Conditions) [9], [10] is currently under development at DLR to continuously measure size distributions of atmospheric aerosols, whereas the sensor is able to distinguish between water droplets, ice crystals as well as dust particles. The objective is to realize an airborne sensor, that is sensitive to all relevant icing conditions (App. C, P and O of CS-25 and CS-29 of EASA [11], [12]) in order to detect critical icing conditions at an early stage. In this work the sensor is tested in the DLR rotor icing test facility (EVA) under icing conditions. Furthermore, droplet size distributions are measured for different settings of the facilities spray bar.

5.1. Working principle of ODIC-Sensor

The ODIC-Sensor uses pulsed laser light to illuminate a well-defined measurement volume in the flow (Figure 15, top). The scattered light of aerosols is captured at a right angle with respect to the incident light beam by two camera sensors for different light polarization states. From the intensity patterns getting visible in the images, such as glare points or speckled regions, particle sizes and types can be clearly identified. To process the images for a precise determination of the current droplet size distribution and corresponding water content, a machine learning algorithm was developed as part of the DLR project SAFER². The algorithm is based on a convolutional neural network (CNN), which is generally well suited to pattern recognitions in images. Running the algorithm on GPUs enables very short processing times to be achieved, thereby ensuring that the sensor's response times are

sufficiently short to meet the EUROCAE/SAE – MOPS for an advisory ice sensor [13].

Using artificially generated image patterns, the average root mean square (RMS) error in the determined droplet size distributions can be estimated at 2 to 3 μm for a droplet size range from 1 μm to 400 μm [9], with the RMS error being lowest for medium-sized droplets, i.e. less than 1 μm for 70 μm droplets, and highest for larger diameters, i.e. a maximum of about 6 μm for 260 μm droplets.

In order to test the sensor technology under realistic icing conditions, a sensor head was developed (Figure 15, bottom) which combines almost all sensor components within a compact housing. The flanged housing enables an easy installation of the sensor in the side wall of an ice wind tunnel or in the skin of an aircraft fuselage. Optics inside an airfoil boom directs the laser light to the measurement volume. The distance from the flange is selected (currently 12.5 cm) so that the measurement volume lies outside the boundary layer of the wall. This, however, is not relevant for the current measurement setup in the EVA.

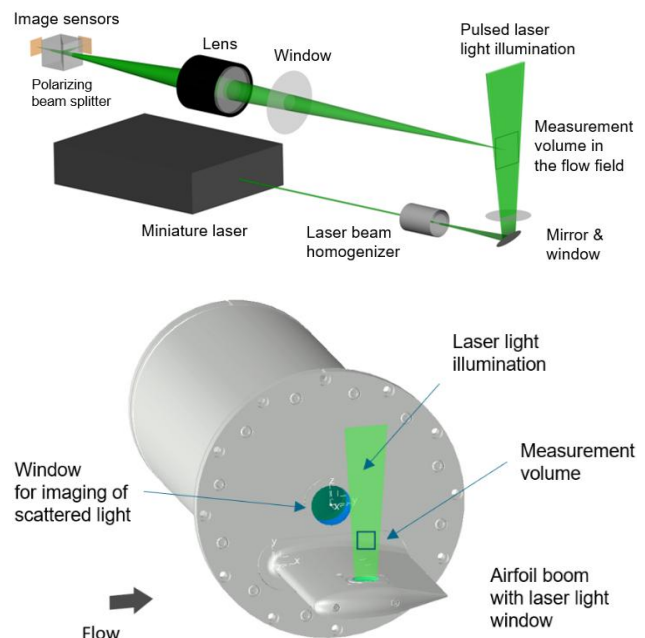


Figure 15 Schematic illustration of the working principle (top) and the sensor head developed (bottom) for testing in icing facilities.

5.2. Test of ODIC-sensor in EVA

The measurements with the ODIC-sensor were carried out with two objectives in mind. Firstly, to demonstrate the sensor's operation under harsh conditions that occur within EVA, i.e. a moist environment with low temperatures down to $T_{\text{amb}} = -20^\circ\text{C}$, as well as vibrations caused by the two-bladed rotor and ice shedding. Secondly, the sensor is used to determine the water droplet size distributions and water contents that are present within the flow upstream of the rotor plane. For this, the sensor is placed within EVA such that the measurement position lies about 65 cm above the rotor plane (Figure 16) and at a radial position of 87 % of the rotor radius.

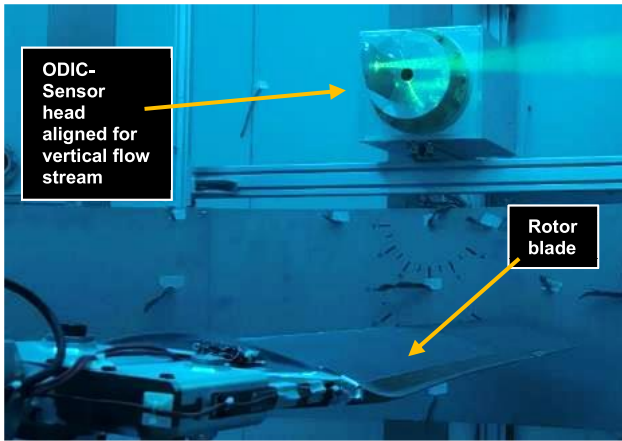


Figure 16 ODIC-Sensor installation in the EVA above the rotor plane.

The measurement time of the ODIC-sensor for each test run was two minutes using an image recording rate of 47 Hz. The test matrix comprises variations of the spray nozzle pressures, ambient temperatures ($T_{amb} = -20\text{ °C}$ to $+5\text{ °C}$) and rotor speeds ($\Omega = 400$ and 750 rpm).

6. RESULTS

6.1. Test campaign

The rotor icing and de-icing experiments within SAFER² (Figure 17) took place in August 2025. In a four days test campaign the test matrix contained ten icing cases (*Ice-1* to *Ice-10*), seven de-icing cases (*De-Ice1* to *De-Ice-7*), and several non-icing test cases at different rotor speeds ($0 / 400 / 750 / 800\text{ rpm}$). The ambient temperature was varied between $T_{amb} = +5\text{ °C}$ to -20 °C . Different icing conditions were generated by changing the water and air pressures of the spray system. All in all, about 60 datapoints between 30 seconds and five minutes were recorded. Since the measurement campaign was quite extensive, only selected results can be presented here.

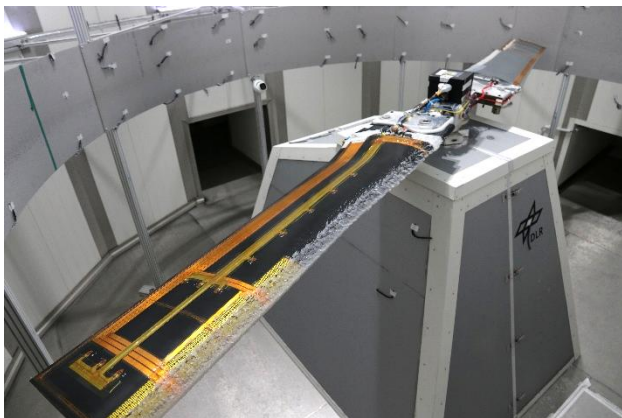


Figure 17 Rotor test stand in EVA with new icing rotor blades equipped with on-blade sensors and electrical heaters after icing test

6.2. Icing results

A rotor icing test at an ambient temperature of $T_{amb} = -8\text{ °C}$ (test case *Ice-5*) is analyzed here in more detail. Here, the

rotor was iced at a reduced rotational speed of $\Omega = 400\text{ rpm}$ for about five minutes. Due to the spray of water droplets the ambient temperature inside the test chamber (see Figure 18, top) increased shortly after the start of the test. After about two minutes the maximum change of about $\Delta T = +3\text{ °C}$ was reached.

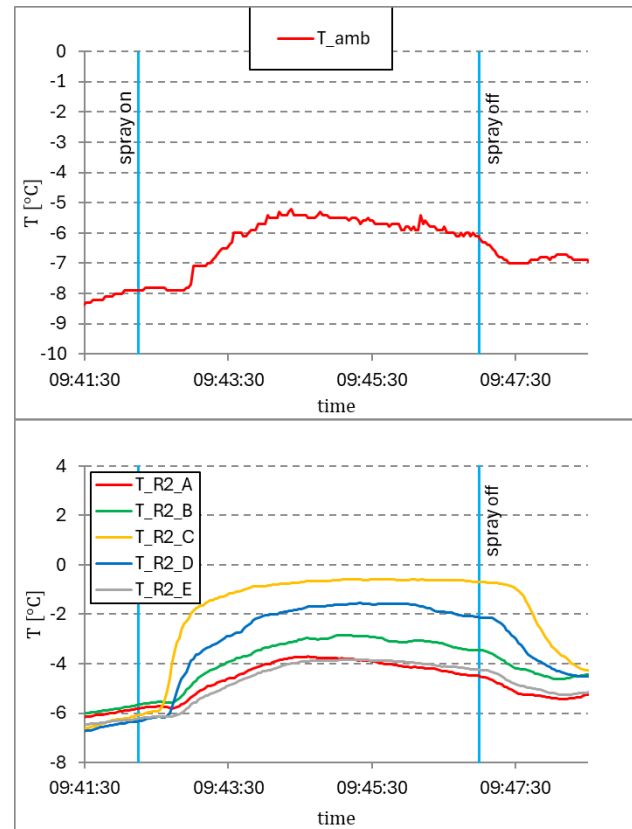


Figure 18 Test case *Ice-5*: ambient temperature (top), de-icing blade temperatures (bottom)

In Figure 18 (bottom) the blade temperatures at the radial station R2 are shown for the five different chord sections (A-E). It clearly can be seen that very short after the start of the droplet injection the temperatures at all chord sections increase from their starting point of about $T = -6\text{ °C}$. Depending on the chord position the change is different. As expected, the most influence can be found at section C (nose part, see Figure 8) where an increase of up to $\Delta T = +5.5\text{ °C}$ can be observed. The rise is caused by the heat of crystallization of the water droplets as soon as they hit the surface and freeze immediately. Shortly after the spray injection process ends, all temperatures return to a similar level. So, temperature sensors integrated into the surface can detect the icing process relatively well.

During the icing phase the electrical rotor power is increasing from $P_{el} = 4\text{ kW}$ to about 10 kW (Figure 19, top), while the rotor speed was kept constant. The cause of this power increase is the growing airfoil drag due to the ice accretion on the blade surface near the leading edge. This behavior can also be recognized in the lead-lag bending moment $M_{lead-lag}$ at the same time. The increasing aerodynamic drag and the increasing blade mass due to icing result in a changing bending moment in the lead-lag direction. Due to the mass distribution of the used rotor blades and the centrifugal forces acting on it, the lead-lag

bending moment without ice is negative (in rotational direction). The aerodynamic drag and the additional ice buildup at the leading edge both counteract this effect.

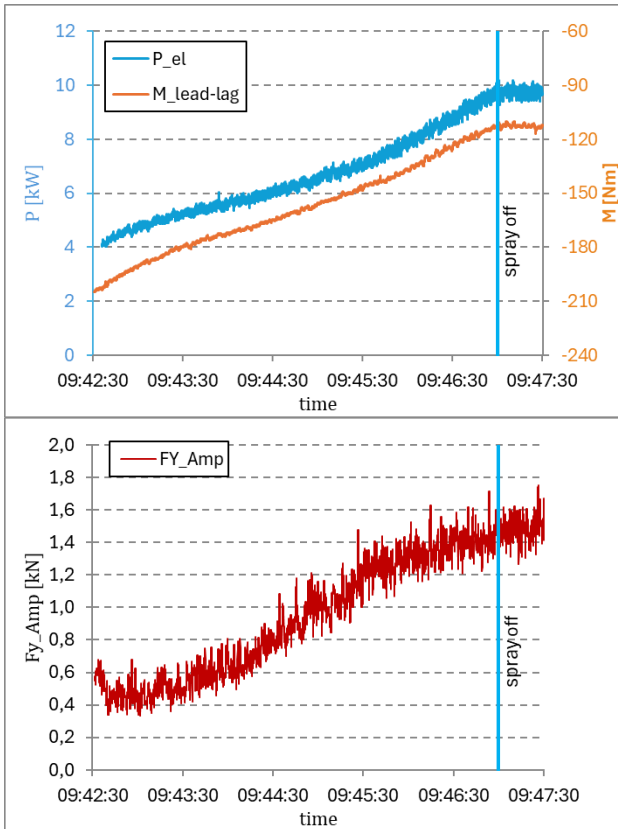


Figure 19 Test case *Ice-5*: electric power & lead-lag bending moment (top), unbalance force $F_{y_{Amp}}$ (bottom)

In Figure 19 (bottom) the measurement of the amplitude of the rotor unbalance force is plotted. Again, a clear rise starting from $F_{y_{Amp}} = 0.5$ kN up to 1.4 kN can be observed due to icing. The unsymmetric rotor icing bases on the fact, that icing only occurs on the area of the non-activated heater of the de-icing blade while for safety reasons the heater of the anti-icing blade is permanently switched on and therefore that area remains ice-free.

The ice shapes at the de-icing blade of test case *Ice-5* can be seen in Figure 20 and Figure 21. After five minutes of spraying, icing was present over the complete radius range, while at inner radii the thickness was about 5 – 8 mm, and thus less than at the outer region, where about 12 – 15 mm of ice could be observed.



Figure 20 Test case *Ice-5*: ice shape at the root of the de-icing blade



Figure 21 Test case *Ice-5*: ice shape at the tip of de-icing blade

6.3. Thermal de-icing results

Directly after the icing procedure of test case *Ice-5* the test case *De-Ice-2* was performed at $\Omega = 400$ rpm. All ten heater elements were switched on with a total electric power of $P_{el} = 900$ W to de-ice the rotor blade. The temperatures at the blade nose are increasing immediately with a rate of about $\Delta T = +40$ °C/min, as can be seen in Figure 22 for the radial index R4 (blade tip).

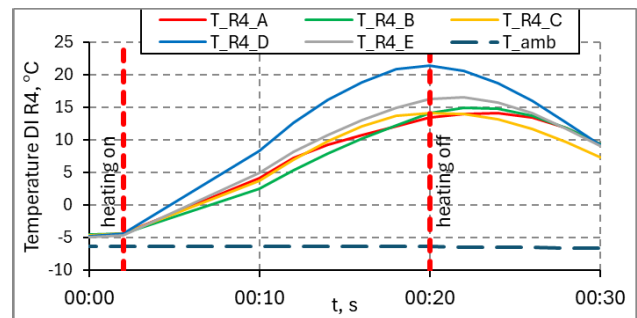


Figure 22 Test case *De-Ice-2*: R4 temperatures during de-icing

Approximately eight seconds after the heater elements were switched on (time index 10 s) and the blade temperatures reached $T = +2$ °C to $+5$ °C, the accelerometer at the ice impact protection ring shows a strong peak (see Figure 23). This is clear evidence that, at this point, the shedding ice collided with the protective ring. As expected, at the same time the rotor unbalance $F_{y_{amp}}$ dropped drastically from about 1.2 kN to less than 0.8 kN.

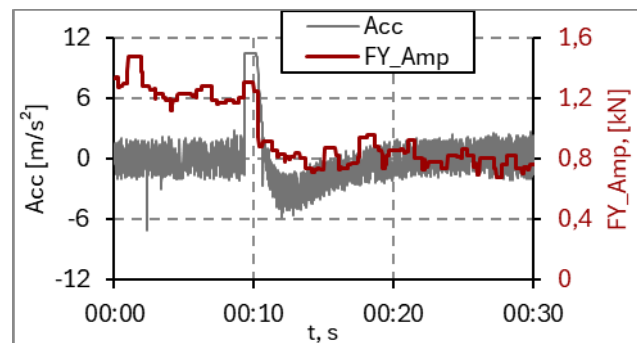


Figure 23 Test case *De-Ice-2*: accelerations and unbalance force $F_{y_{Amp}}$ during de-icing

The variations of blade lead-lag bending moment and electric rotor power over time are shown in Figure 24 for the

de-icing phase. Corresponding to a decreased drag force at the airfoil and mass due to the loss of ice, an immediate change of about $\Delta M_{lead-lag} = -60$ Nm can be observed in the lead-lag bending moment. With the reduced drag force the rotor power is also decreasing. The electrical motor power is reducing instantly from $P_{el} = 9$ kW to about 7.5 kW at the time of the ice shedding.

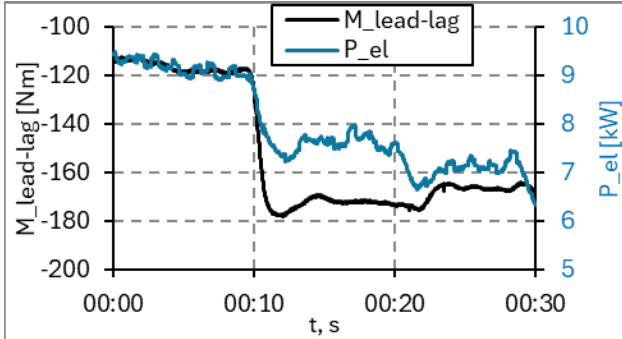


Figure 24 Test case *De-Ice-2*: lead-lag bending moment and electric motor power during de-icing

After the rotor was stopped, it was observed that the rotor blade tip – which had previously been completely iced (shown in Figure 21) – was now free of ice in the radial area of the heater. The boundary between the remaining ice and the ice-free area coincides with the start of the heater, as visible in Figure 25, indicating the area where the ice cracked before shedding. The centrifugal force acting on the ice helped to shed it more quickly.



Figure 25 Test case *De-Ice-2*: ice shape after de-icing

6.4. Exemplary LILD results

For the icing tests in EVA, the test blade was equipped with the same setup as describes previously in section 3. Multiple icing tests were performed where an ice accretion was visible every time on the test surfaces as shown in Figure 26.



Figure 26 Ice accretion on LILD transducer and test surface

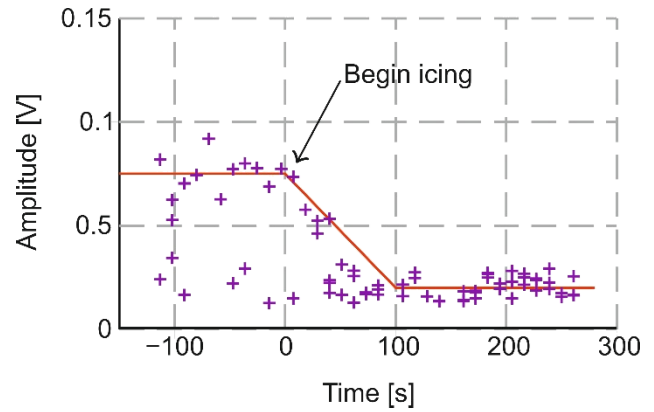


Figure 27 Lamb wave amplitude reduction due to ice accretion

Unfortunately, the signal quality of the Lamb waves was severely affected by high frequency noise caused by the power supply of the electric heating elements. Therefore, an investigation was only partly possible. Several filtering techniques have been implemented to reveal the real Lamb wave signal. For a carrier frequency of 250 kHz this filtering was in so far successful, that the expected amplitude change with the ice accretion could be made visible as shown in Figure 27 although it is still very noisy. There a reduction of the Lamb wave amplitude is apparent for a time of 0 s. After 100 s, no further change in the amplitude is visible.

This proves the expected sensitivity of Lamb waves traveling through the leading edge of a real rotor blade. Due to the low signal quality, no further investigations of the signals, e.g. by training neural networks, were possible.

6.5. Exemplary SHM results

Figure 28 presents the drive-normalized network power during the strongest icing event recorded under rotation.

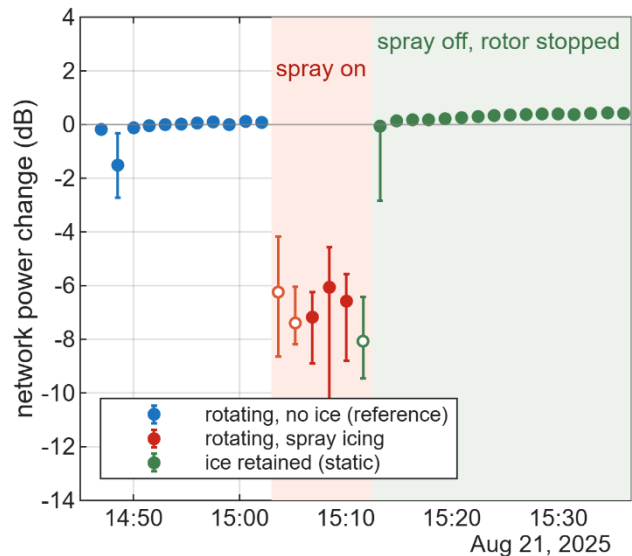


Figure 28 Drive-normalized 80 kHz network power during the strongest icing event, relative to the rotating no-ice reference: stable reference, network-wide attenuation during spray, after spray stop with ice retained on the blade.

During the preceding rotating reference condition, the network power remained stable within a few tenths of a decibel. After the spray was activated, the median power across the valid paths decreased by approximately 6.8 dB. All evaluated paths showed attenuation, with changes typically ranging from -4 to -11 dB. The event was therefore detected throughout the network within the temporal resolution of the monitoring measurements.

The measured effects of the competing operational conditions were substantially smaller within the investigated test range. Tests from the static condition to 800 rpm produced changes of approximately 1 dB or less at the selected monitoring frequency. During a 26°C blade cooldown, the sensitivity of the power feature was bounded to approximately 0.04 dB/K. The response recorded during spray therefore clearly exceeded the measured temperature- and rotation-related variations.

After the spray was stopped and the rotor brought to rest, the network response returned close to its pre-spray reference level within a few acquisitions (Figure 28, green markers; Figure 29, bottom), although accreted ice remained visible on the blade. This indicates that the guided-wave network is particularly sensitive to water and ice strongly acoustically coupled to the composite shell, while ice accreted only along the leading edge has little effect on the monitored shell paths. The leading-edge region lies outside the most sensitive propagation paths of the network.

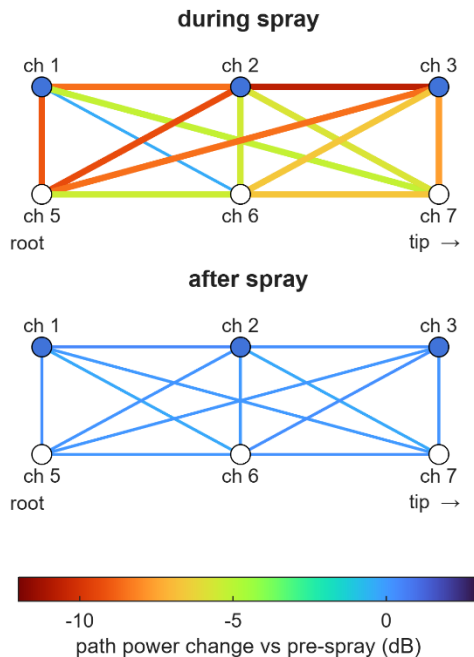


Figure 29 Path-resolved power change of the valid transducer network for the same event: during spray (top) and after the spray stopped (bottom), both relative to the pre-spray reference.

At a single monitoring frequency, the effects of the liquid water film and the ice forming during spray cannot be separated unambiguously. The reported signal reduction should therefore be interpreted as the detection of an active icing process or a strongly coupled surface layer, rather

than as a direct measurement of ice thickness. Broadband measurements and complementary local sensors may provide additional information for distinguishing wetting, freezing and retained dry accretion.

The tests demonstrate the feasibility of time-resolved, blade-integrated guided-wave monitoring during full-scale rotating icing tests. They also show that sensor placement, measurement-chain self-diagnosis and complementary sensing near the principal accretion regions must be considered in the development of a future operational monitoring concept.

6.6. Droplet size distributions

Figure 30 shows examples of the measured droplet size distributions for various test conditions in EVA, i.e. at different ambient temperatures ($T_{amb} = -8^\circ\text{C}$ to -16°C), rotor speeds ($\Omega = 400$ and 750 rpm) and spray nozzle (air) pressures ($p_a = 1.5$ and 2 bar). The number of droplets decreases as the droplet size increases, whilst in all cases shown a second peak is visible at a droplet size of approximately $8\ \mu\text{m}$. The distributions for test IDs 36 and 53 correspond very closely, indicating good reproducibility of droplet generation. Increasing the air pressure (p_a) at the spray nozzles reduces the mean volume diameter (MVD) of the distributions, i.e. from approximately $40\ \mu\text{m}$ (test ID 36) and $41\ \mu\text{m}$ (test ID 53) to $28\ \mu\text{m}$ (test ID 28). The determined time-averaged liquid water content (LWC) values are approximately 0.6 , 0.7 , and $0.3\ \text{g/m}^3$, respectively. However, a further increase in air pressure to higher values may lead to the formation of ice crystals.

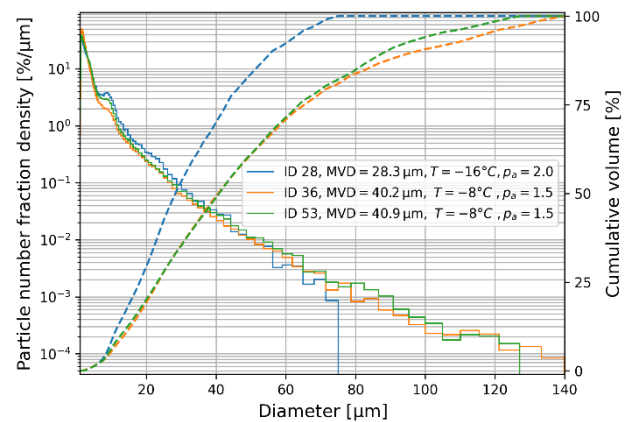


Figure 30 Selected droplet size distributions determined by the ODIC-Sensor in EVA.

7. CONCLUSIONS

- A new two-bladed rotor system for icing tests in the DLR rotor tower was developed, assembled, and successfully tested during a measurement campaign. For that, Airbus Helicopters provided two original rotor blades from an H145 D3 as the basis for the new rotor. The new rotor serves as a test platform for rotational tests as part of icing tests and to support the development of rotor ice protection systems. Since the new rotor blades are lighter than those of the formerly used rotor, a previously existing speed limitation was overcome, and speeds of up to 800 rpm can be achieved.

- The new blades are equipped with thermal anti-icing and de-icing systems for the tests. These systems consist of electrically powered heater foils, affixed to the leading edges of the blade tips. The heater foils cover the same area of both blades but are different in design and control. While the complete heater area of the anti-icing blade is permanently activated during tests, the ten heater elements of the de-icing blade can be controlled separately with different power settings as needed. In this paper only tests with a combined de-icing heater control are presented.
- The slip ring used to transfer signals and power between the rotating and the non-rotating system 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 general feasibility of the LILD principle of using Lamb waves to detect an ice accretion on the leading edge of a real rotor blades could be demonstrated. As the signal quality in the test was insufficient, a follow up test with reduced high frequency noise is required to further quantify the sensor data.
- To monitor icing with guided waves, the rotor blade was fitted with a network of thin piezoelectric transducers bonded to the upper and lower shells. The transducers take turns exciting ultrasonic waves and recording them across the blade. The built-in consistency checks of the measurement chain proved valuable, as they revealed two faulty channels.
- The strongest icing event was clearly detected across the entire network: the received signal power dropped by about 6.8 dB as soon as the spray started, while rotation up to 800 rpm and the cooling of the blade changed the signals only marginally.
- Once the spray was stopped, the signals returned almost to their initial level even though accreted ice remained visible on the blade. The guided waves thus respond mainly to water and ice that are strongly coupled to the blade surface, while ice accreted only on the leading edge had no significant effect on the monitored paths.
- The test results demonstrate that the ODIC sensor is able to provide droplet size distributions and liquid water contents for various spray settings, ambient temperatures and rotor speeds, even under the harsh environmental conditions in the rotor icing test facility.
- The results presented show that the icing conditions set correspond to those specified in EASA CS-29, Appendix C.

8. ACKNOWLEDGEMENTS

The authors would like to express their gratitude towards the team at Airbus Helicopters for providing the DLR with two original rotor blades of an Airbus Helicopters H145 D3 needed to build the new icing rotor for testing purposes. The authors would also thank everyone involved at DLR during the planning, preparation and execution of the icing tests and the subsequent data analysis within the project SAFER².

Contact:

rainer.bartels@dlr.de

9. REFERENCES

- [1] S. Kalow, R. Bartels, O. Schneider, D. Sahyoun and R. Keimer, "Icing and De-Icing under Centrifugal Loads in DLR's Whirl Tower Facility," in *49th European Rotorcraft Forum ERF*, Bückeburg, Germany, 2024. ISBN 978-3-932182-92-1.
- [2] R. Bartels, S. Kalow, O. Schneider, D. Sahyoun, R. Keimer and R. Konrath, "Rotor Icing and De-Icing at DLR's Whirl Tower Test Facility," in *80th Vertical Flight Society Annual Forum and Technology Display, FORUM 2024*, Montréal, Canada, 2024. DOI: [10.4050/F-0080-2024-1317](https://doi.org/10.4050/F-0080-2024-1317).
- [3] E. Brehl and O. Schneider, "Instrumentation, Measurement and Control of a Helicopter under Icing Conditions," in *ETTC 2026 - European Test & Telemetry Conference*, Nürnberg, Germany, 2026.
- [4] M. Pohl, "Wind tunnel and flight testing of a lamb wave based ice accretion sensor," *CEAS Aeronautical Journal*, 2025. DOI: [10.1007/s13272-024-00781-3](https://doi.org/10.1007/s13272-024-00781-3).
- [5] Y. Cao, W. Tan and Z. Wu, "Aircraft icing: An ongoing threat to aviation safety," *Aerospace Science and Technology*, vol. 75, pp. 353-385, 2018.
- [6] S. Galiana, M. Moix-Bonet, D. Schmidt and P. Wierach, "Effect of cryogenic temperatures on guided waves structural health monitoring using acousto-ultrasonic piezocomposite transducers on composite structures," *e-Journal of Nondestructive Testing*, vol. 29, no. 7, 2024. DOI: [10.58286/29667](https://doi.org/10.58286/29667).
- [7] S. Galiana, B. Patel and P. Wierach, "Environmental and icing effects on EMI and guided wave SHM for aerostructures using piezoelectric transducers," *e-Journal of Nondestructive Testing*, 2026. DOI: [10.58286/32452](https://doi.org/10.58286/32452).
- [8] H. Gao and J. L. Rose, "Ice detection and classification on an aircraft wing with ultrasonic shear horizontal guided waves," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 56, no. 2, pp. 334-344, 2009.
- [9] P. Marquardt and R. Konrath, "An Image-based Sensor for Detecting Atmospheric Icing Conditions," in *International Workshop on Atmospheric Icing of Structures (IWAIS)*, Sapporo, Japan, 2026.
- [10] P. Marquardt and R. Konrath, "Detection of Atmospheric Icing Conditions by an Image-based Sensor," in *Deutscher Luft- und Raumfahrtkongress (DLRK)*, Aachen, Deutschland, 2026.
- [11] EASA, "Certification specifications and acceptable means of compliance for large aeroplanes," European Aviation Safety Agency, CS-25, Amendment 18, Appendix C, O and P, 2016.
- [12] EASA, "Certification specifications, acceptable means of compliance and guidance material for large rotorcraft," European Aviation Safety Agency, CS-29, Amendment 11, Appendix C - Icing Certification, 2023.
- [13] EUROCAE, "Minimum Operational Performance Standard for Inflight Icing Detection Systems," European Aviation Safety Agency, ED-103A, 2017.