ELECTRO-MECHANICAL DE-ICING SYSTEM FOR A NON-ROTATING STRUCTURE OF SMALL AND MEDIUM SIZED HELICOPTERS

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Abstract

There is a high demand for de-icing systems with low energy consumption for small and medium sized helicopters. De-icing systems based on the electro-mechanical principle appear to be particularly energy efficient since they take advantage of structural resonance frequencies. However, this approach has its limitations in terms of structural conformity, operational aspects and environmental conditions. This paper investigates the design process of such an electro-mechanical de-icing system as well as its performance on a real helicopter structure during realistic icing conditions in a laboratory environment. A special focus is on the non-consideration of an ice layer during the design process. The optimized system is subsequently confirmed by experimental results that will help to bring the approach further towards industrial applications.

1. INTRODUCTION AND BACKGROUND

Icing on aircraft is a serious hazard for aviation and is of particular importance for the vertical flight industry, which operates mainly in the air layers where there is a high risk of icing. As a result, helicopters without active de-icing systems cannot be operated in critical conditions.

For large helicopters, ice protection systems already exist, which are mainly based on electro-thermal principles. However, thermal de-icing systems have a relatively low efficiency, therefore high electrical power is required to remove an accumulated ice layer. A down-scaling of these existing systems to small and medium-sized helicopters is not economically feasible, as the required amount of energy would lead to a considerable increase in weight and thus a significant reduction of payload.

Therefore, a novel de-icing system based on resonant excitation of the structure in the low-frequency range is investigated within the scope of this research. The main advantage of this de-icing principle can be found in its energy efficiency potential, since only the structural damping has to be overcome in the case of resonant excitation [1–3].

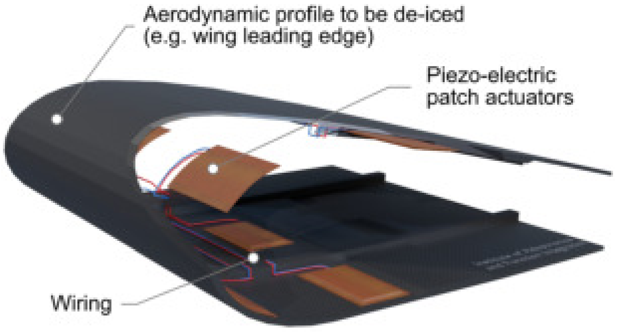

Figure 1: Basic architecture of an electro-mechanical de-icing system

2. ELECTRO-MECHANICAL DE-ICING SYSTEM FOR HELICOPTERS

The electro-mechanical de-icing (EMDI) system, also classified as low-frequency de-icing (LFDI) system, uses actuators to excite a structure to resonance vibration [4–7]. The actuators are typically attached to the inside of the structure, so that they are protected from environmental influences but also do not affect the aerodynamic shape of the structure (see Figure 1). During the de-icing process, the actuators are driven with an oscillating voltage, which results in a stimulated vibration of the structure by the constant alternation of contraction and expansion of the actuators and consequently the surface deforms. If this activation is carried out with natural frequencies of the structure, resonance occurs and strong deformations can be achieved despite low energy consumption [7]. The oscillating deformation of the structures surface consequently leads to stresses in an ice layer as well as in the interphase between an ice layer and the surface of the component. When the stresses exceed critical tensile and shear stresses the cohesion in the ice layer or the adhesion between

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surface and ice fails, which consequently leads to cracks, delamination and ice shedding [8]. Two main failure mechanisms of an accumulated ice layer have been observed in the past. These are cracks in the ice due to normal stresses in the ice layer as well as delaminations due to shear stresses in the boundary layer between ice and structural surface. Which one of the two mechanisms eventually is responsible for ice removal, depends on different influencing factors and has not been clearly distinguished yet, since both mechanisms often interact with each other [3]. Likewise these critical tensile and shear stresses initiating failure are very dependent on the prevailing ice conditions (ice type and thickness, surrounding temperature, etc.) as well as on the structure itself (roughness of surface, thermal conductivity, stiffness, etc.). While lower temperatures increase the tensile strength, a growth in ice-layer thickness decreases its strength, which can be explained by a Weibull distribution of defects in a brittle material like ice [9].

At temperatures below 0°C, water undergoes a phase change from liquid to solid form and becomes ice. Water droplets floating freely in the air do not necessarily freeze immediately when the temperature falls below freezing point, but remain in a liquid state even at very low temperatures. The occurrence of these supercooled droplets is due to the trouble-free droplet formation in the atmosphere. Only when they are shocked, i.e. if they collide with an aircraft, the phase transition takes place. Then, the supercooled droplets immediately change to ice and freeze on the aircraft surface. This leads to rapid ice build-up on the circulated surface. In addition to the accumulated weight on the aircraft, ice build-up on aerodynamic profiles leads to an increase in drag and a reduction in lift [10, 11].

In order to identify the relevant areas and structures of a helicopter that are particularly affected by icing when flying through a cloud at temperatures below freezing point, a complete helicopter was iced in a wind tunnel at the beginning of the research project. The identification of particularly ice-prone areas was subsequently compared to the requirements for the electro-mechanical de-icing system. In de-icing systems based on the electro-mechanical principle, which take advantage of structural resonances, the design of the system is very much dependent on the helicopter structure to be de-iced. In addition to geometric boundary conditions, operational criteria like vibration decoupling, transparency of the windshield, influence on flight characteristics, etc. must also be considered in the design of the system.

It should be emphasized that systems based on the electro-mechanical principle, unlike anti-icing systems, can only be operated as de-icing systems. The electro-mechanical de-icing principle requires a certain ice layer thickness and thus a certain stiffness discontinuity in the boundary layer between the ice accretion and the structure in order to generate a mechanical stress that exceeds strength limits. Ultimately, only a sufficiently high mechanical stress leads to delamination or cracking of the ice layer. These constraints must be considered when designing the electro-mechanical de-icing system.

3. DESIGN OF THE DE-ICING SYSTEM

In order to design an effective de-icing system based on the electro-mechanical operating principle with resonant structure excitation, it is important to know exactly the vibration behavior of the structure to be de-iced. Of particular interest are natural frequencies at which high curvatures and thus high strains are present in the ice-critical region, the level of structural damping, possible nonlinearities and the coupling to surrounding structures.

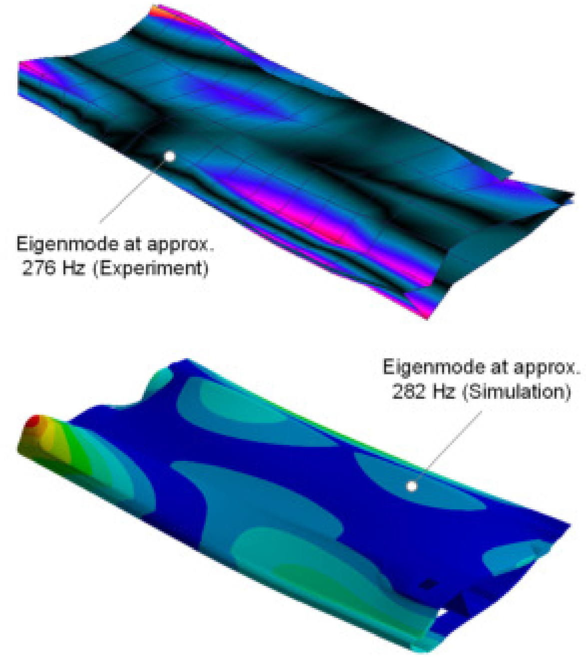

Figure 2: Comparison of experimental (top) and numerical (bottom) eigenmode and their eigenfrequencies with antinodes distributed over the entire structure

For the investigations in this work, a representative structural component of a helicopter is used. In order to determine the vibration behavior, an experimental modal analysis provides the required information to validate the numerical model of the structure. Nonlinearities were not observed during the experiments. The damping is of an order of magnitude expected for technical structures in the investigated frequency range. The boundary conditions were approximated as closely as possible to the real connection of the structure, which resulted in a one-sided fixed clamping. The dynamics of the boundary condition was thus neglected. Figure 2 shows a typical eigenmode derived from the

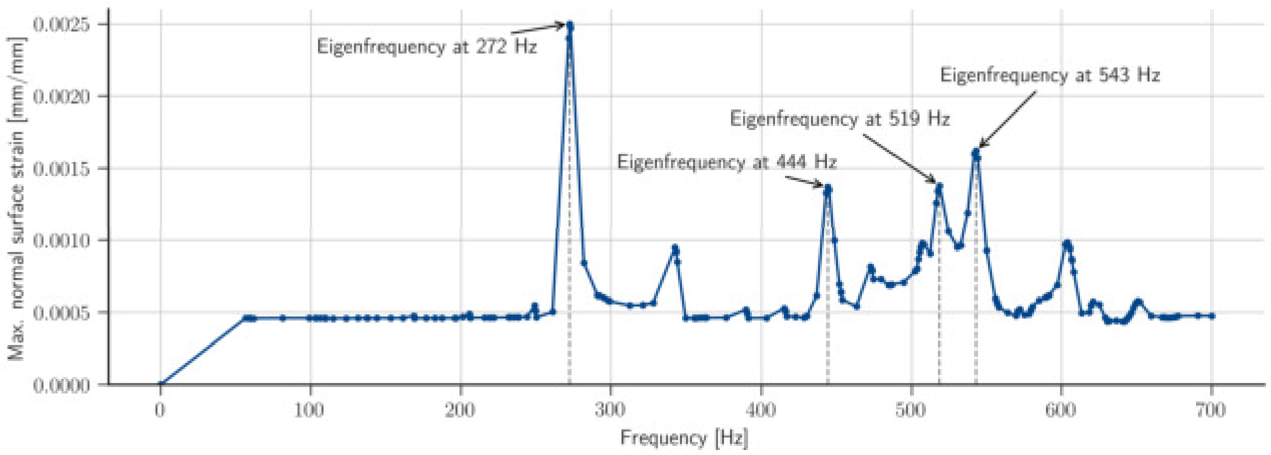

Figure 3: Selection of eigenmodes with high normal surface strains of elements located in the ice-prone area based on a frequency response analysis in the numerical model of the structure for a specific actuator configuration

experimental modal analysis (top) carried out using phase separation methods after excitation with an impact hammer. The comparison with the numerical results (Figure 2 bottom) shows a good agreement, especially towards the front edge of the profile (front edge in pictures), which is particularly prone to icing. This match between numerical model and experiment is especially valid for the low-frequency range. At higher frequencies and thus increased modal density, the deviations between calculated and experimentally determined values also become larger.

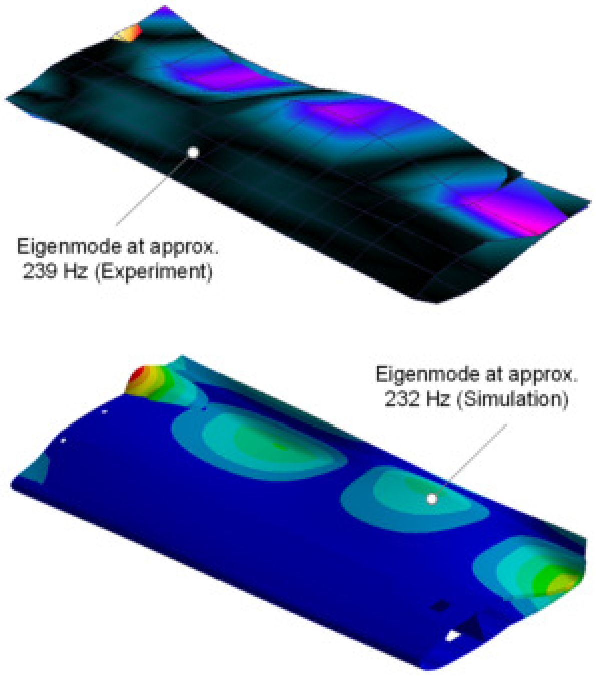

Figure 4: Comparison of experimental (top) and numerical (bottom) eigenmode and their eigenfrequencies with antinodes concentrating on the rear of the structure

The calibrated numerical model is consequently used to design the de-icing system for the representative structure. The main design objective is to find optimal positions of the piezo-ceramic patch actuators in such a way that the eigenmodes, which can generate particularly high stresses in the interface between ice and structural surface, get excited with as much energy as possible. This implies that, the generalized excitation for these modes is close to one with a given actuator configuration.

From the results generated by icing of an entire helicopter in an ice wind tunnel, the ice-prone areas of the structure at hand were identified. These concentrate along the front edge of the structure and consequently will be used for the optimization of the de-icing system. In contrast to Figure 2, Figure 4 shows an eigenmode, whose antinodes are concentrated along the rear edge of the structure. Likewise a good correlation between calculated and experimental results can be observed. But since the critical surface is located on the opposite side, it is visually obvious that this eigenmode will not be of superior importance for the de-icing system. Eigenmodes, which produce large curvatures and thus high strains in the area along the front edge, are of special interest.

However, since not only an individual but rather the interaction of several eigenmodes finally leads to de-icing, the controllability of all eigenmodes involved must be considered when designing the actuator layout. Therefore, an optimum must be found when designing the actuator positioning in order to maximally excite all eigenmodes involved. The main parameters are the number of actuators, their positions and the phase relation between each of the single actuators.

Figure 3 shows exemplarily the surface maximum normal strains in the selected area over an excitation frequency range from 0-700 Hz based on a numerical simulation. As it can be seen, there are several frequencies, which result in particularly high strains for this actuator configuration and excitation concept.

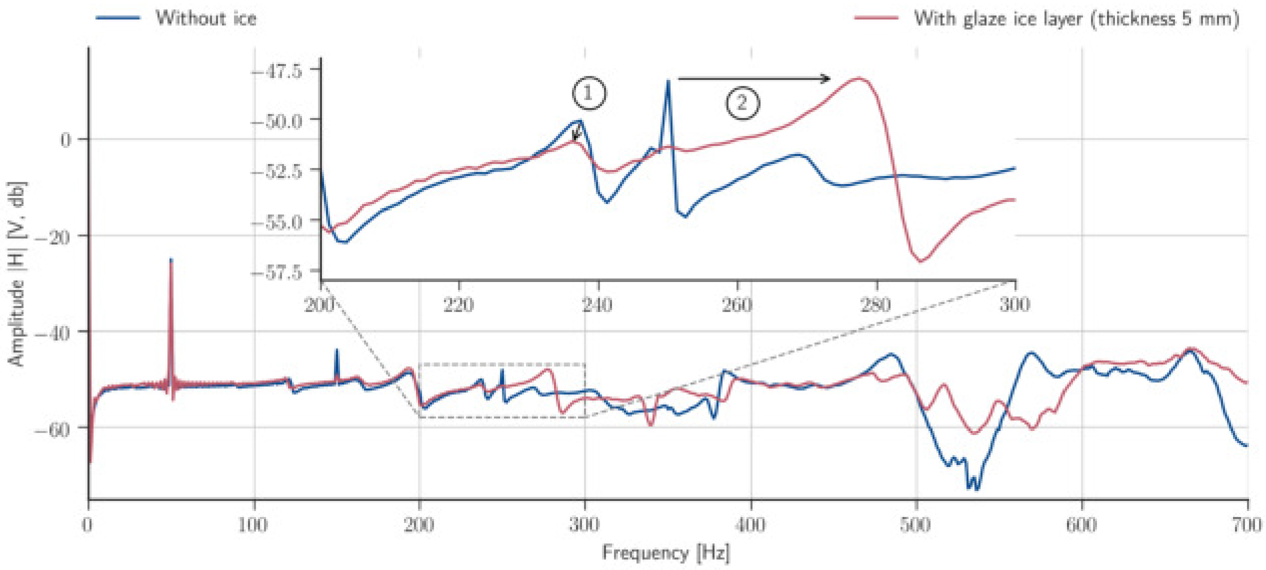

Figure 5: Amplitude of the frequency response function for one patch actuator pair attached to the surface of the structure and influence of a 5 mm glaze ice layer on the frequency response

When comparing Figure 2 with Figure 3, it becomes obvious that modes, which also have visually detectable amplitudes in the de-icing area (in contrast to other modes as in Figure 4), also produce high strains in the relevant surface areas. The discrepancy in the frequencies mainly results from the additional weight of the actuators that were necessarily integrated during the frequency response analysis in contrast to the modal analysis in Figure 2. When optimizing the de-icing systems towards high strains, it is important to consider that the strains and thus stresses in the structure do not exceed the material strength.

In this work not only the maximum values of the strains are evaluated, but especially the 95%-quantile is evaluated, thus singularities of the numerical calculation can be eliminated. This procedure further ensures that the strain values, which should finally lead to de-icing, are distributed over a large area or several locations rather than concentrated on only a few numeric elements.

A major limitation of this numerical optimization approach, which uses surface strains as design criterion, is that it does not take into account the ice layer on the structure. The difficulties to determine the mechanical properties of ice as they depend on a high number of factors, such as type of ice, temperature, ice layer thickness or surface condition of substrate, are the major reason to choose this approach. Otherwise, many parameters and their characteristics would have to be considered during the parameter study. Furthermore, even if the ice layer is taken into account, it cannot be predicted whether the behavior reflects reality, thus the results must also be validated in the experiment. Therefore, and additionally to save resources, this approach of neglecting an ice layer and using the surface normal strains only as decisive criterion seems acceptable for the time being.

In addition, also the ice layer itself very much influences the vibration behavior of the structure. Figure 5 shows the frequency response function for one patch actuator pair on the structure with and without an ice layer from experiment. It becomes clear, that a glaze ice layer of 5 mm thickness has a significant influence on the vibration behavior of the structure. In the enlarged part in Figure 5 two main effects are assumed to be likely to occur as a result of an attached ice layer. On the one hand the height of the amplitude response can be reduced (Pos. 1 in Figure 5), on the other hand natural frequencies shift to higher or lower frequencies (Pos. 2 in Figure 5). Additionally, completely new eigenmodes can also be created. These effects can be explained by the direct influence of an ice layer on the generalized masses, the structural damping and the stiffness of the structure.

Again, these correlations are very much dependent on the type and thickness of the ice and the ambient conditions. Therefore, it seems once again justified to consider only the surface strains for the theoretical design of the actuator positions of the de-icing system and to neglect an attached ice layer. After completion of the design optimization, the functionality of the de-icing system will be examined on the basis of experimental investigations in the following.

4. EXPERIMENTAL CHARACTERIZATION OF DE-ICING SYSTEM

The design of the de-icing system is transferred to a real helicopter structure and its performance evaluated in a de-icing test facility (see Figure 6). The

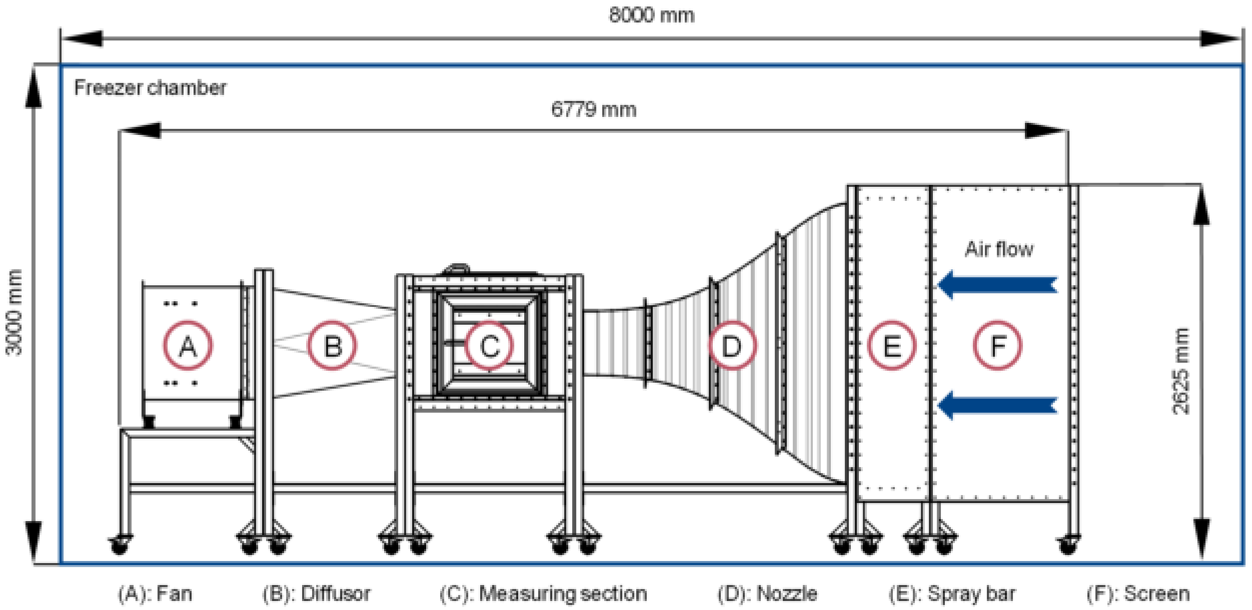

Figure 6: De-icing test facility of the Institute of Adaptronics and Funktion Integration (iAF) at the Technische Universität Braunschweig (TU BS)

Institute of Adaptronics and Function Integration (iAF) at the Technische Universität Braunschweig (TU BS) operates an open type wind tunnel (Eiffel-type) for this purpose, which is placed in a large freezer chamber. At the inlet of the wind tunnel nozzle there is a spray bar device which allows a fine droplet mist to be introduced into the air flow. These droplets supercool on their way to the structure and form a layer of ice when they impinge on its surface. This enables the realistic generation of ice layers on test specimens and a subsequently testing of the functionality of de-icing systems. The measuring section of the de-icing test-facility has a cross-section of 400 x 400 mm and the conditions can be varied within the ranges given in Table 1.

Table 1: Range of variation of ice-conditions in the iAF (TU BS) de-icing test facility

Parameter	**Min.**	**Max.**	**Unit**
Temperature	-20	0	[°C]
Liquid Water Content (LWC)	0.1	1.4	[g/m^3]
Median volume diameter (MVD)	50	90	[µm]
Airspeed	0	40	[m/s]

By changing the individual parameters from Table 1, different types of ice as well as ice layer thicknesses can be created on a test structure (Figure 7).

Glaze ice is of particular interest in structures, which have aerodynamic functions, as the growth rate of this type of ice can become considerably high, which is associated with a significant increase in weight and drag as well as a decrease in lift, as the shape of the ice has a strong negative influence on the aerodynamic performance around the leading edge of the profile [12]. Therefore, the performance of the de-icing system was especially investigated for glaze ice conditions at -5°C.

The test structure was fixed on one side of the test section for the de-icing experiments. For integration reasons, the piezo-ceramic patch actuators were placed on the outside of the structure, since accessibility on the inside was severely restricted and thus would require specially designed and manufactured actuators. This was also taken into account during the design phase of the system. For future investigations, however, it is planned to integrate the actuators to the inner side of the structure so that they will be protected against environmental influences such as erosion.

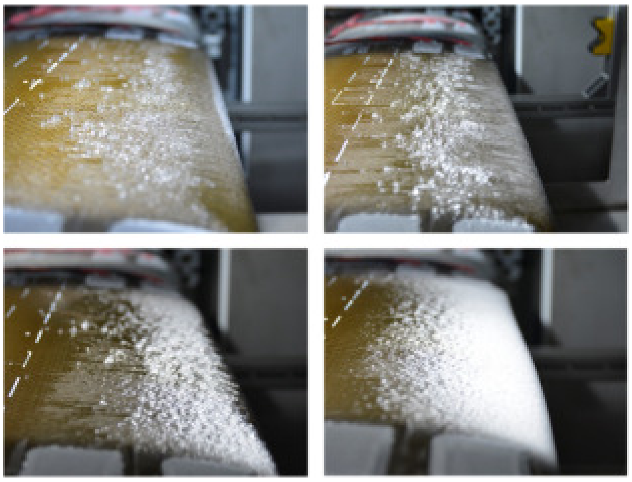

Figure 7: Different types of ice on the test structure (top: glaze ice with different thicknesses, bottom: mixed ice (left) and rime ice (right))

A total of 16 DuraAct actuators (P-876.A15) were placed on the structure. The specifications of the actuators considered during the design phase are shown in Table 2.

Table 2: Specifications of piezo-ceramic patch actuators (DuraAct P-876.A15) used for this research

Parameter	**Value**	**Unit**
Operating voltage range	-250 to 1000	[V]
Blocking force	775	[N]
Min. bending radius	70	[mm]
Electrical capacitance	45 (±20 %)	[nF]
Piezo-ceramic height	500	[µm]
Dimensions	61 × 35 × 0.8	[mm]

After attaching the actuators to the surface of the structure, they were additionally coated with a protective layer to prevent moisture from penetrating the actuators, what might cause failure of the piezo-ceramic material.

Due to limitations in the hardware equipment, not all the actuators could be operated up to the high frequency range of 2 kHz within their full operating voltage range at once during the experiments. Therefore all 16 actuators are controlled for the low frequency range up to 1.3 kHz and only 8 actuators in the higher frequency range, thus they can still be supplied with sufficient energy. Furthermore, the phase relation between the actuators is changed to optimize the performance of the system. Half of the active actuators are always operated with 180° phase shift to each other. During the tests, the actuators are driven by a linear sine sweep in the specified frequency range. The sweep time was varied between 60 and 120 s, as the amount of energy, which excites the structure at a certain frequency is directly dependent on the sweep rate [13]. However, since extremely long sweep times are not feasible during testing, an optimum sweep rate has to be found.

The results of the de-icing experiments are shown in Table 3 as well as in Figure 8 and Figure 9. As it can be seen in the figures for an ice layer thickness of 4 and 5 mm, delamination, cracks and partial de-icing could be achieved. Table 3 also shows that there is a certain ice layer thickness which is beneficial for the performance of the electro-mechanical de-icing system.

Below an ice layer thickness of 3 mm, the cohesion and thus the stiffness of the ice layer is so low that the high strain on the surface of the structure does not exceed the critical strengths in terms of adhesion and cohesion and thus de-icing does not occur. The same applies to an ice layer thickness that exceeds a limit value, for the current hardware set-up this is 7 mm. This can be explained by the fact that the stiffness of the ice layer is so high that the actuators are restricted in their expansion and thus the critical stresses in the boundary layer or in the ice are also no longer exceeded. Furthermore, the structural damping and generalized masses increase with an increasing ice layer thickness, which leads to smaller amplitudes of the structural vibrations for the same amount of input energy. This behavior was also confirmed by [3].

Table 3: Limits of the de-icing system for the test structure and glaze ice at -5°C

Ice layer thickness	**Results**	
	phase relation (a)	phase relation (b)
≤ 2 mm	(/)	(-)
3 mm	(++) at ≈270, 700 Hz	(-)
4 mm	(++) at ≈260 Hz	(+++) at ≈1.5 kHz
5 mm	(+) at ≈1.1 kHz	(+++) at ≈1.5 kHz
6 mm	(+) at ≈1.3 kHz	(/)
≥ 7 mm	(/)	(/)

(+) Delamination, (++) Delamination and cracks, (+++) Partial de-icing, (/) No observation, (-) No data,

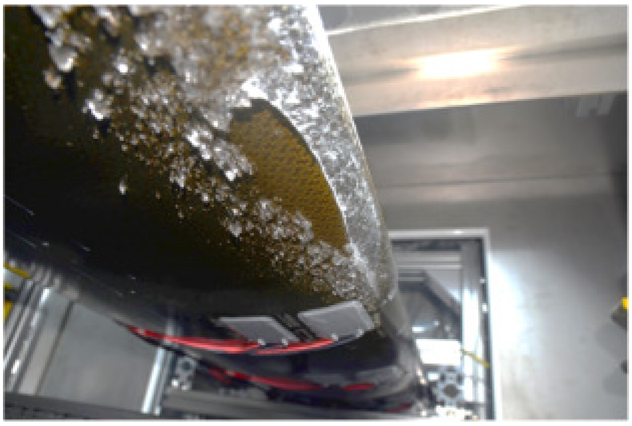

Figure 8: Partial de-icing on the test structure for a 5 mm thick glaze ice layer

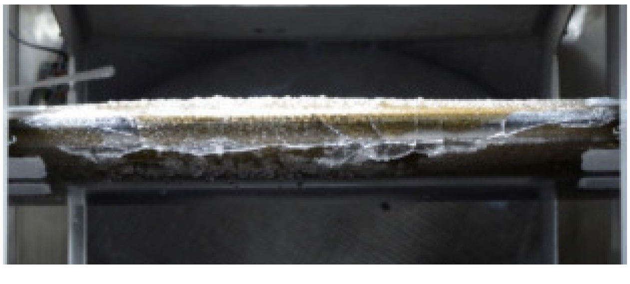

Figure 9: Delaminations, cracks and partial de-icing on the test structure for a 4 mm thick glaze ice layer

Experiments at lower temperatures and the predominance of a rime ice layer have confirmed the assumption that the de-icing system cannot be used reliably under these conditions. This can be explained by the fact that in the case of rime ice, typically no coherent ice layer is formed on the surface of the structure and thus no critical stresses can be generated in the ice layer.

Another conclusion that can be drawn from the results is that defined natural frequencies play a role in de-icing, as assumed in the design. Thus it is shown that the development of delamination and cracks only occurs at specific frequencies in all tests. If those frequencies are known, only those specific ones have to be excited for successful de-icing. What has to be taken into account is the influence of different ice layers on these frequencies, as shown in Section 3 of this paper. Therefore, a sensor system is necessary that recognizes the consequent frequency shift due to an ice layer. Hence, the de-icing system can be operated at the optimum operating points and a sweep over a very wide frequency range, as used in the experiments of this paper, can be omitted. Thus additional energy can be saved. However, this adaptive behavior of the system to the respective icing condition significantly increases the complexity.

5. CONCLUSIONS AND FURTHER RESEARCH

This paper investigates the applicability of a de-icing system based on the electro-mechanical principle for small helicopters. In particular, the boundary conditions to be considered when using this system were revealed. For example, electro-mechanical de-icing can only be used where a certain ice layer thickness can be tolerated, actuators can be installed and vibrations of the structure are allowed. Furthermore, restrictions regarding the type and thickness of ice were identified.

Furthermore this work shows that in the design process based on numerical calculations the actuator position as well as the phase relation between the actuators can be optimized even when neglecting a modelled ice layer. Disregarding an ice layer reduces the effort of the calculations considerably, as the parameter diversity regarding the mechanical properties of the ice and the interaction with the substrate surface would increase significantly. Apart from the ice layer, it is important that the entire structure, including the correct boundary conditions, is considered in the design of the system, since these have a large influence on the vibration behavior and the structural damping.

In order to optimize the vibration behavior of a structure for this de-icing system, it is crucial to consider the parameters already in the structural design of the component. Nevertheless, the system is potentially suitable as a retrofitting option for existing structural components, which could be shown in this research. However, this only applies as long as other functions such as aerodynamic ones are not disturbed.

A major shortcoming of the presented investigations is the insufficient power electronics that were available for the experiments. Therefore, the experimental results can be used as an indication for the limits of the de-icing system, but a definite estimation can only be given if in future experiments all of the installed actuators can be controlled in their full power range. Investigations regarding the energy consumption of the de-icing system can likewise only produce meaningful results if all actuators can be controlled in their full voltage range over all frequencies. These still open questions shall be answered in the upcoming investigations so that the hypothesis of the low energy consumption of electro-mechanical de-icing systems compared to conventional systems can be confirmed, which makes them especially interesting for small and medium sized helicopters.

Nevertheless, it could be shown for the first time that the idea of electro-mechanical de-icing is also suitable for high stiffness carbon fiber composite components.

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