

ICE DETECTION: CORRELATION OF ICE ACCRETIONS AND DYNAMIC RESPONSES ON SMALL-SCALE AIRFOIL PROTOTYPES TESTED IN ICING WIND TUNNEL

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Abstract

New-generation aircraft will be based on electric or hybrid engines and will be regulated by stricter requirements on consumption. For these reasons, the development of innovative low power demanding ice detection and protection systems is needed. In fact, considering the above-mentioned requirements, conventional ice protection systems (IPSs) will soon be obsolete (they are based on hot air spilled from engines or require high-power consumption). In terms of energy savings, IPSs based on mechanical and thermo-mechanical concepts appear to be the most promising, particularly those based on ultrasonic guided waves, induced in the skin by piezoelectric actuators. The adoption of an ice detection system allows the activation of the protection system only in interested part of the wing at the most appropriate time, making the removal of the ice even more efficient. The current article investigates the capability of piezoelectrics of detecting ice by test in Icing Wind Tunnel (IWT). The dynamic behavior of an embedded prototype was investigated at different temperatures, without and with accreted ice. As expected, the comparison of the dynamic responses acquired under the same environmental conditions, reveals the presence of the ice.

Keywords: ICE, ICE DETECTION, IPS, PZT, IWT

1. General Introduction

This article investigates the functionality of a compact, low-power demanding ice detection system, based on piezoelectric technology in an Icing Wind Tunnel (IWT). An ice detection system based on piezoelectrics can make a pair with ice protection system (IPS) based on the same technology [1] - [5], looking for a system capable of recognizing and removing ice from the wings.

The current article investigates the above-mentioned system embedding a set of piezoelectric transducers into a small-scale airfoil demonstrator. In detail, they are bonded on the internal surface of the prototype. The idea of recognizing ice by piezoelectrics is based on their electro-mechanical behavior. They show mechanical deformations when electrically excited and exhibit electrical voltage when mechanically deformed. Therefore, piezoelectric actuators induce mechanical waves into the skin when excited with a cyclic electric signal. In this way, piezoelectric sensors, which exploit the opposite effect of the material, allow the measurement of the dynamic response of the prototype. Finally, the system allows the identification of the ice by comparing the dynamic responses acquired without and with accreted ice.

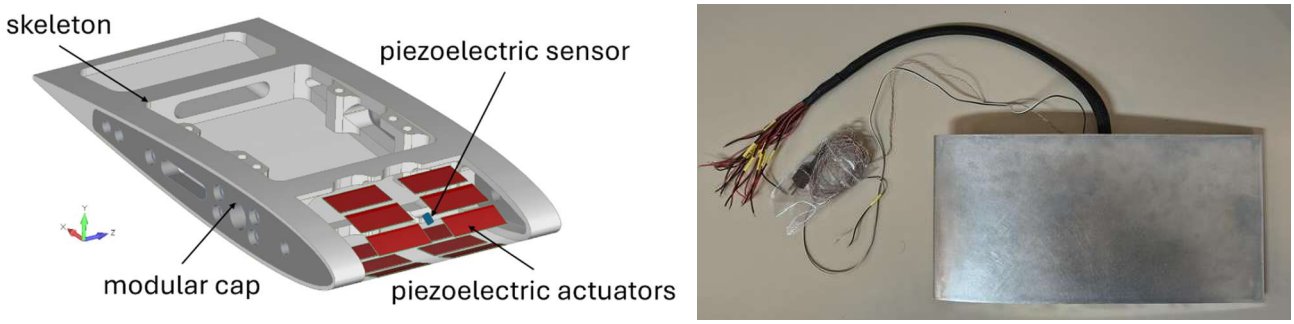
The description of the prototype is supplied in Section 2, that of IWT in Section 3. Methodologies are described in Section 4, followed by the description of test setup and the summary of test plan. Finally, the discussion of results is provided in Section 7.

2. Prototype

An aluminum demonstrator reproduces symmetrical 4° NACA series airfoil with a 310 mm chord and 150 mm span. The skin is 0.8 mm thick. The structure consists of two ribs, the front spar and the rear spar. They constituted a single component named skeleton. Finally, two modular caps were designed to allow inspection of the internal narrow room, in which actuators are bonded, as shown in Figure 1(a) [4],[6]. Thirteen piezoelectric transducers were bonded on the internal surface of the skin close to the LE. Twelve are used as actuators and have dimensions 35 x 18 x 0.5 mm along span, chord,

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and thickness respectively. They are made by piezoceramic P-51 (d_{31}=-186 x 10^{-12} m/V, S_{11}^{E}=16.7 x 10^{-12} m^2/N). The last one is a DuraAct P-876.SP1 (d_{31}=-180 x 10^{-12} m/V, S_{11}^{E}=16 x 10^{-12} m^2/N) and is considered as a sensor. The actuators are arranged in 6 rows along the chord, three rows on the upper surface of the skin and the other three on the lower. Each row is constituted by 2 actuators, as shown in Figure 1 (a). The piezoelectric sensor is bonded on the upper surface between the actuators of the closest row to the LE. The transducers were bonded with an epoxy structural adhesive [4],[6]. Figure 1 (b) shows the prototype after realization.



(a) digital mock-up (b) prototype

Figure 1 – Digital mock-up and prototype

3. Icing Wind Tunnel facility

The tests were carried out in the IWT of Fraunhofer IFAM. The facility allows the simulation of environmental conditions down to -30°C with a maximum wind speed of 95 m/s, with the chance to have the liquid water content (LWC) between 0.6 and 6 g/m^3 and the median volume diameter (MVD) of the droplets between 25 and 45 µm. The test chamber is a parallelepiped measuring 155 x 200 x 1000 mm in width, height and length respectively. The facility adheres to the standards of SAE ARP 5905.

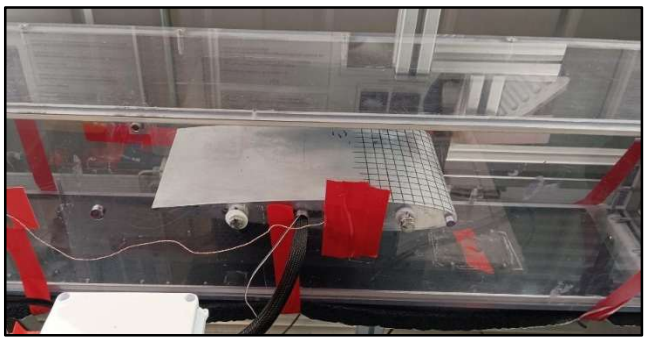
4. Methodologies

For each test, the chamber was cooled down to the desired temperature and then the water droplets were sprayed. The water droplets were ejected at a controlled temperature, size, and water content for the desired time through a specific nozzle. At the end of each test, the chamber was heated to defrost accreted ice and restore the initial conditions. The temperature of the test was measured by a temperature sensor positioned at the entrance (in the wind direction) of the chamber.

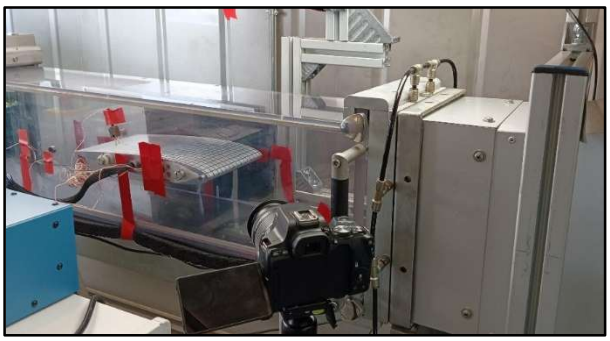
In each test, the piezoelectric actuators were excited with low-voltage sinusoidal signals while the transductions of the piezoelectric sensor and the thermocouple were processed and recorded. For each frequency between 10 and 50 kHz (considering a step of 50 Hz), the actuators were excited with a specific sub-signal, which was in turn induced, via the bonding layer, into the skin. The waves induced into the skin were intercepted by the piezoelectric sensor and transduced into an electrical signal acquired by the oscilloscope. The acquired signal contains the induced frequency and noise. The software processes the transduction of the sensor, which represents the response of the structure to the specific sub-signal, then the acquired signal is transformed from time-domain to frequency-domain via Fast Fourier Transform (FFT) and filtered to remove spectral content not correlated to the induced sub-signal. Then, the peak (maximum amplitude) of the transformed signal was stored. These operations were performed for each sub-signal (in a loop). A sheet which contains the peaks and their related frequencies was produced and graphed. The graphed values represent the dynamic response of the structure. Tests were carried out in different environmental conditions, first *without ice* and then *with ice* to compare the acquired responses.

5. Test Setup

The demonstrator was housed in the test chamber and screwed to the walls considering an angle of attack (α) of 0°C, as shown in Figure 2 (a). A digital camera was added to take a picture of ice shapes considered in tests, similarly to Figure 2 (b).



(a)



(b)

Figure 2 – Test configuration

The setup consisted of: NI PXIe-8840 controller, NI PXIe-5423 arbitrary waveform generator (AWG), and NI PXIe-5105 oscilloscope. Their main characteristics are summarized in Table 1. The generator and oscilloscope were managed via the controller using dedicated software developed in the NI LabVIEW environment, as described in section 4.

Table 1 – Main characteristics of instrumentation

ID	MODEL	MAXIMUM BANDWITH [MHz]	MAXIMUM SAMPLE RATE [MS/s]	CHANNELS	NOTE
Arbitrary Waveform Generator	NI PXIe-5423	40	up to 200	2	Generate signal to excite PZT actuators
Oscilloscope	NI PXIe-5105	60	60	8	Acquire signal of PZT sensor
Controller	NI PXIe-8840	/	/	/	Control AWG and Oscilloscope

6. Test Plan

Tests were carried out at three different temperatures, -4°, -10° and -20°C, at defined LWC and MVD. Table 2 summarizes the test conditions. The wind speed is set to 80 m/s. As mentioned before, two main kinds of test were made: measuring dynamic behavior of the prototype *with ice* and measuring dynamic behavior *without ice*; the two types of tests are carried out under the same environmental conditions for considering the *without ice* test as a reference.

Table 2 – Summary of the test conditions

TEST ID	TEMPERATURE* [°C]	LWC [g/m^3]	MVD [µm]	NOZZLE OPENING DURATION (ICING) [s]
1	-4	n.a.	n.a.	n.a.
2	-4	1.15	25	90
3	-10	n.a.	n.a.	n.a.
4	-10	1.15	25	90
5	-20	n.a.	n.a.	n.a.
6	-20	1.15	25	90

7	-20	1.15	25	120
8	-20	1.15	25	120

*icing wind tunnel static air temperature

Test 1 and Test 2 are carried out at -4°C, Test 3 and Test 4 at -10°C, Test 5 and Test 6 at -20°C. Differently, Test 7 and Test 8 are both carried out *with ice* at -20°C (so, their reference is Test 5) to test the sensibility of the detection.

7. Results

This section consists of two main parts: the first is focused on the test carried out with 90s ice accretions and the second with 120s ice accretions. The first part validates the capability, of a system based on piezoelectric technology, of recognizing ice accretions considering the dynamic responses. The second part reports the results of tests carried out on two similar ice accretions, which confirm the previous part and suggest good sensitivity of the system.
90s ice accretions are reported in Figure 3, they are used in Test 2, Test 4 and Test 6, respectively.



(a) ice accretion accreted at -4°C for test 2 (b) ice accretion accreted at -10°C for test 4 (c) ice accretion accreted at -20°C for test 6

Figure 3 – Ice accretions accreted for Test 2, Test 4 and Test 6

The dynamic behavior of the prototype at -4°C without and with ice (Test 1 and Test 2) is reported in Figure 4. The responses are very similar in the entirely investigated frequency domain; a particular superposition can be found in the range between 25000 e 30000 Hz. The marked similarity of the curves is explained considering that 1) the mass of ice is smaller than the mass of prototype 2) the piezoelectric sensor is far from most of ice. While it is possible to correlate the curves with each other, they are not the same. This difference, and so the fact that ice has modified the dynamic behavior of the profile, certainly confirms the chance of detecting ice with piezoelectric technology.

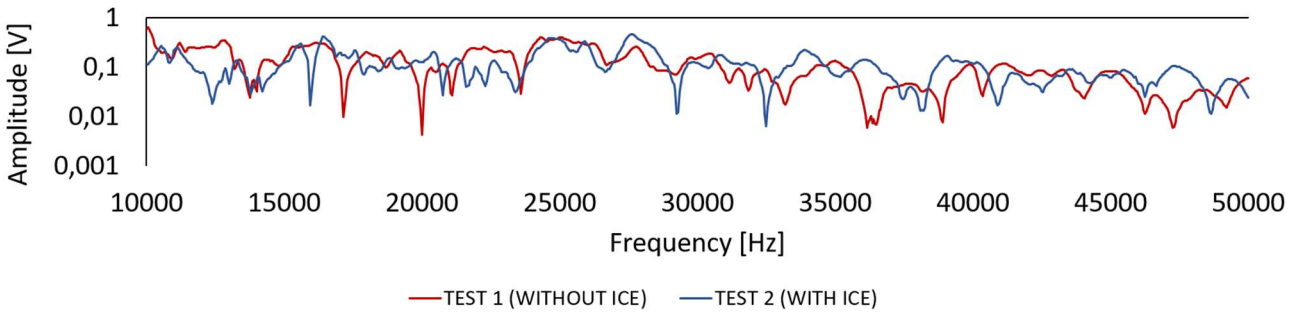


Figure 4 - Dynamic responses of the prototype at -4°C without and with ice (Test 1 vs Test 2) (y-axis is in logarithmic scale)

The test carried out at -10 and -20°C confirm further the above. In fact, the same considerations can be made by comparing Test 4 with Test 3 and Test 6 with Test 5. The dynamic behavior of the prototype *with ice* at -10°C is very similar to the behavior *without ice* at the same temperature (Figure 5). Similarly, at -20°C (Figure 6). In both cases, the dynamic response acquired in the test *with ice* is close to the response acquired in the test *without ice*; however, despite its little mass, ice has conditioned the acquired signal.

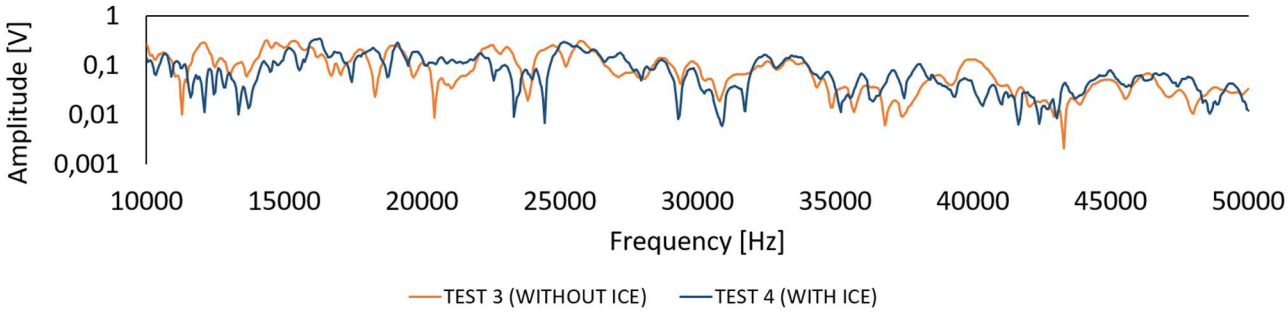


Figure 5 - Dynamic responses at -10°C without and with accreted ice, (Test 3 vs Test 4) (y-axis is in logarithmic scale)

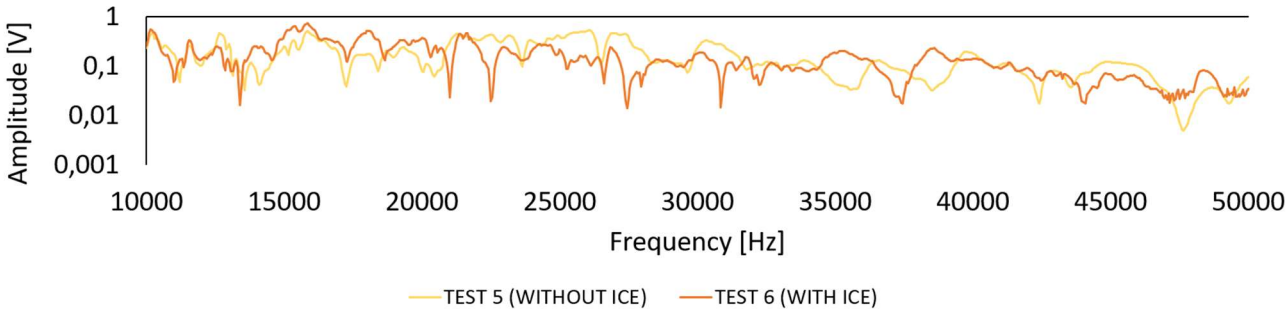
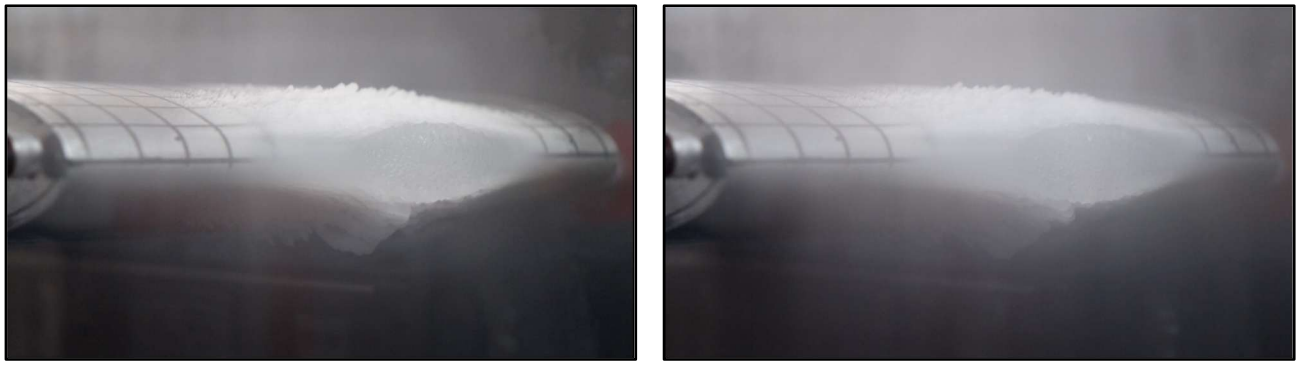


Figure 6 - Dynamic responses at -20°C without and with accreted ice, (Test 5 vs Test 6) (y-axis is in logarithmic scale)

Ice accretions for Test 7 and Test 8 (both at -20°C) are reported in Figure 7. As above mentioned, ice accretions of these tests were made in the same conditions to test the sensibility of the detection. The accretions appear very similar to each other. Despite this, different dynamic responses were expected. In fact, even though the chance of managing several parameters such as LWC, MVD, temperature and wind speed, ice growth is a stochastic process.



(a) ice accretion accreted at -20°C for test 7

(b) ice accretion accreted at -20°C for test 8

Figure 7 - Ice accretions accreted for Test 7 and Test 8

The dynamic responses of the prototype at -20°C, with the two above-mentioned ice accretions, are reported in Figure 8. In addition, in the same figure, the behavior of the prototype *without ice,* at the same temperature, is reported. The responses of Test 7 and Test 8 (*with ice* tests) demonstrate that a little difference between the ice accretions can be captured by the dynamic responses. In fact, they are very similar to each other. Moreover, the similarity between the two responses *with ice* is greater than their similarity with response *without ice*, in according with the marked similarity between the ice accretions.

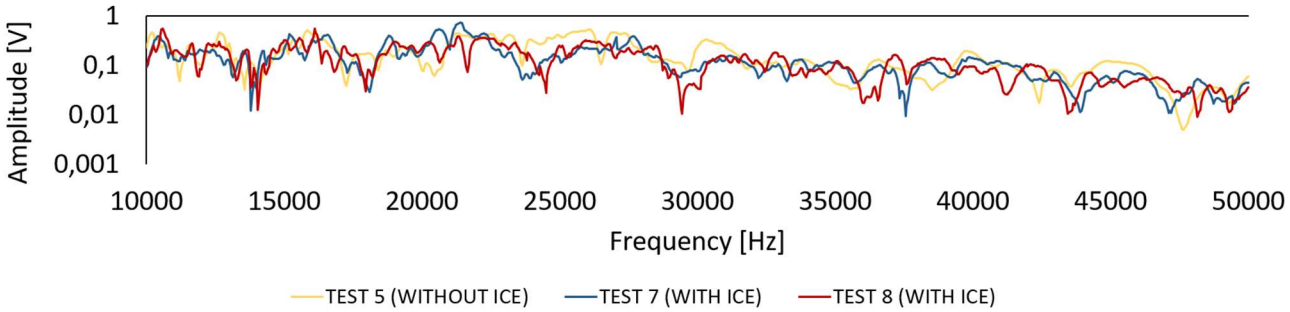


Figure 8 - Dynamic responses at -20°C without and with accreted ice, (Test 7 vs Test 8) (y-axis is in logarithmic scale)

8. Conclusions

The present article investigated the feasibility of identifying ice accretions on wing surface by piezoelectric technology, testing small-scale prototypes in Icing Wind Tunnel. First, the compact ice detection system investigated proves to be a low power consuming system, considering that the maximum amplitude of the exciting signals was 2V. Then, the tests showed the capability of the system of identifying ice accretions. In detail, by comparing the dynamic response of the structure and accreted ice with a specific baseline. Finally, the sensibility of the system was successfully investigated.

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References

[1] Daniliuk V, Pamfilov E, Daniliuk A, and Xu Y. Feasibility Study of Ultrasonic De-Icing Technique for Aircraft Wing Ice Protection, *Proceedings of International Conference on Aviamechanical Engineering and Transport (AviaENT 2019)*, Irkutsk, Vol.188, 2019

[2] Shi Z, Kang Z, Xie Q, Tian Y, Zhao Y and Zhang J. Ultrasonic Deicing Efficiency Prediction and Validation for a Flat Deicing System. *Applied Sciences*, Vol. 10, No. 19, p. 6640, 2020

[3] Shi Z, Zhao Y, Ma C and Zhang J. Parametric Study of Ultrasonic De-Icing Method on a Plate with Coating. *Coatings*. Vol. 10, No. 7, p. 631, 2020

[4] Mangiacrapa L, Klaas T, Pellone L, Piscitelli F, Rehfeld N, Mingione G, Amoroso F, Concilio A and Ameduri S. Wind Tunnel Tests on a Piezo-Based Ice Protection System. *Actuators*, Vol. 15, No. 2 p. 102, 2026

[5] Zhang Y, Zhang H, Yi X, Wu B, Guan X and Xiong J. Analysis method and experimental study of ice accumulation detection signal based on Lamb waves. *Chinese Journal of Aeronautics*, Vol. 37, No. 8, pp. 388-403, 2024

[6] Mangiacrapa L, Piscitelli F, Rehfeld N, Amoroso F, Mingione G and Ameduri S. Realization of Icing Wind Tunnel demonstrators for the characterization of a hybrid Ice Protection System. *Proceedings of AIAA Aviation Forum and ASCEND 2025,* Las Vegas, AIAA 2025-3525, 2025

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