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Investigations on the use of Lamb waves for de-icing purposes

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Abstract

The work at hand illustrates numerical and experimental investigations on the use of Lamb waves for detaching ice onto aerodynamic surfaces. The waves, generated through piezoelectric patches bonded onto the inner surface of the wing skin, cause a shear action at the ice/skin interface. The magnitude of the shear action is amplified at specific excitation frequencies (Lamb waves), corresponding to wave lengths commensurable with the skin thickness.

Theoretical models describing the shear transmission at the ice - structure interface were implemented to identify the main design parameters of the de-icing system, as the frequency of excitation, the dimension of the piezoelectric patches, their mechanic and electric features. On the basis of this information, a detailed finite element model of a square piece of structure (made of aluminum alloy) integrated with a piezo actuator on one face and with an ice layer on the other, was realized. At first, a normal mode analysis was carried out to identify the peaks of excitation; then a dynamic investigation was performed, this way estimating the effective shear at the interface with the ice and the ability of producing ice detachment at certain working conditions.

Finally, a test specimen was manufactured. The supporting structure was integrated with a piezo patch: to generate Lamb waves. The tests were performed in two steps: at first, the dynamic response of the structure with the ice was acquired for the entire bandwidth; then the structure was excited at some favorable peaks and the ice detachment level measured by comparing the current dynamic response at low frequency with the corresponding one in absence of ice.

1. INTRODUCTION

In the last decade the main Italian institutions and industry have shown a strong interest in developing technologies for increasing the reliability of Unmanned Air Vehicles in order to reach the same level of safety of those ones with pilots on board.

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In order to give support to the Italian industry CIRA defined its “Unmanned Air Vehicles” program to finalize research know-how towards the development of unmanned technology demonstrators. Within this framework the “Smart ON board System” (SMOS) project is aimed at developing ice protection system characterized by low weight and power consumption. A degradation of aircraft performance and safety due to ice accretions on aircraft structures is a major concern in the aircraft industry. The goal of the SMOS project will be reached coupling three different ice protection systems based on different technologies: an electrochemical one, a passive ice-phobic system, and a de-icing system realized by means of piezoelectric actuator. All these systems will be tested at the CIRA Icing Wind Tunnel on a demonstrator that will allow us to measure the power consumption of each one. In this paper we present the study about the de-icing system Lamb wave based.

2. DE-ICING SYSTEMS

A degradation of aircraft performance and safety due to ice accretions on aircraft structures is a major concern in the aircraft industry.

The build-up of ice on the leading edges of fixed wings causes an increase in drag, a decrease in lift, and altered moment characteristics of the aircraft. A number of de-icing methods are developed for removal of ice from aircraft wing structures. De-icing methods can be broadly classified as ground de-icing and in-flight de-icing. Ground de-icing is done when the flight is at rest by spraying glycol based chemicals, etc., for removal of ice. However, in-flight anti-icing is used to prevent ice accumulations when the flight is in air.

There are several methods of de-icing which include freezing point depressants, hot gas, electro-thermal, surface deformation, pneumatic impulse, electro-impulse systems, high frequency microwave, ultrasonic guided wave [1].

All of these are affected by drawbacks that limit their use during flight. Main issues concern the power consumption, the weight and the effectiveness. Further work is needed for improvement of predictions and the methods of removing ice from aircraft.

Hot gas systems have been the primary method employed to deice surfaces, but they have been left apart when engines became lighter and more efficient.

Thermal in-flight de-icing methods prevent accumulation of ice by keeping the surfaces at elevated temperatures. Normally thermal methods consume a very large amount of power and this represents the main drawback that engineers tend to overcome by introducing different types of de-icing methods.

Electrical methods also consume significant amount of power and can be too heavy. There is always a strong demand for de-icing techniques that are effective and at the same time, lightweight, low in power consumption, low maintenance and manufacturing costs, reliable operation, and offer little or no design change requirement and aero penalties [2].

Electro-thermal de-icer systems, being composed essentially by an electric heater, have very high power consumption, but benefit of their simplicity and of the very short response time in comparison with hot air or hot fluid systems.

Freezing point depressant de-icing systems, among other benefits mentioned before, provide operations with a low power demand, which is a big advantage, but these systems are less effective especially when the ice adhesive bond is greatest. Moreover these systems are not used in aircraft where the engine bleed air is used to supply air cabin because it can produce harmful vapours in the cabin.

High frequency microwave de-icing systems are effective when used in composite structures, so their use is limited to aircrafts or helicopters that present parts composed of these types of materials [3]. Also power consumption is an issue.

Recently surface deformation de-icing systems have been introduced where de-icing is performed not by the use of heat somehow transmitted to the structure, but making use of shear stress as de-bonding player [3]. For this class of systems the demand of power consumption is less compared to the wide family of de-icing systems making use of thermal energy. Nonetheless the main drawback that could limit their use and that must be kept under control is the perceived fatigue loading of the structure. Moreover all surface deformation systems have a minimum ice thickness that it can eject from the surface.

In addition to these drawbacks, pneumatic boots systems don't preserve the exact airfoil shape since the boots are bonded onto the exterior of the airfoil.

Vibratory de-icing systems benefits of low weight, their power requirements is similar to that of electro-impulse de-icing system, but they need special purpose amplifiers with large frequency bandwidths for the high frequencies of excitation.

Recently Palacios et al. [4] introduced a new approach using ultrasonic guided waves, Lamb waves, for de-bonding the accreted ice layer on helicopter blades.

De-icing systems that breaks the ice bonds by exceeding their adhesive strength using shear horizontal waves make use a novel non-thermal approach and are able to de-bond layers of ice under 3 mm thick.

Summarizing we can affirm that these latter systems show numerous advantages and are a promising technology to be employed for de-icing aircraft.

In the following table drawbacks and advantages of the different de-icing systems are summarized

Table 1 Drawbacks and advantages of different de-icing systems

De-icing System	Pros	Cons
Thermal	Effective	High consume of power
Electro-thermal	Simplicity, very short time response	High consume of power, too heavy
High frequency microwave	effective when used in composite structures	their use is limited, power consumption
Deformation de-icing systems family	Low power consumption	Perceived fatigue loading of the structure, minimum ice thickness that it can eject from the surface.
Pneumatic boots	Low power consumption	don't preserve the exact airfoil shape
Vibratory de-icing	Low weight	Need special purpose amplifiers with large frequency bandwidths for the high frequencies of excitation.
shear horizontal waves	Low power	able to de-bond layers of ice under 3 mm thick

In the present paper we present our activities regarding a de-icing system prototype to be used in "Unmanned Air Vehicles" program proposed by CIRA. The purpose of the concept is to detach a slice of ice accreted on an aeronautic structural element.

The work starts with an evaluation of the effectiveness of Lamb wave technology to produce the ice detaching from a structure. To this end we used finite element modeling of a plate made of aluminum in contact with a slice of ice accreted on a face, while on the opposite face of the panel a piezoelectric is bonded to induce Lamb waves to the structure. The horizontal shear generated by the Lamb wave was then estimated.

The work concludes with a summary of the activities presented and an outline of the future steps of the research.

3 THEORETICAL MODELLING

Lamb waves are guided waves which propagate in thin plates. Their energy decay ratio is proportional to $1/r$ in comparison to $1/r^2$ for a standard ultrasonic wave, where r is the distance from the source of the pulse [5]. These waves excited at high frequencies have short wave length so they are sensitive to structural changes and disturbances.

Lamb waves appear in a finite number of modes called symmetric and anti-symmetric. They are highly dispersive. Analytical mathematical models are difficult to obtain for general geometries.

The group velocity dispersion characteristics of a plate are important because the group velocity corresponds to the speed of mechanical energy propagation; while phase velocity dispersion curves indicate that the propagation speed of various Lamb wave modes varies with the frequency, and that multiple modes exist at any frequency.

We developed theoretical and numerical tools to identify conditions for which, by exciting the ice-structure system with a piezoelectric, it is possible to generate Lamb waves into the structure able to produce the ice detaching (Fig. 1).

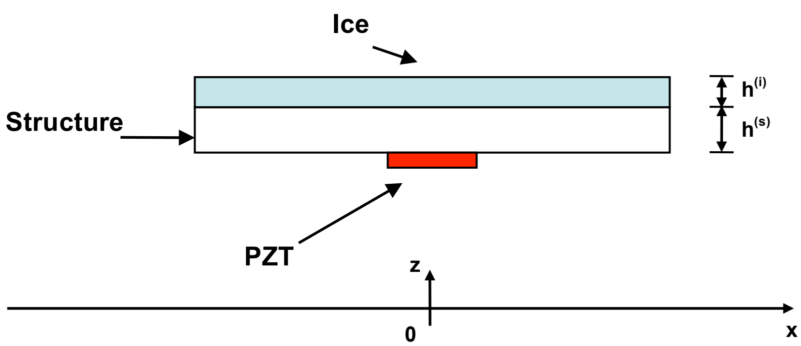

Figure 1. System composed of ice-structure-piezoelectric.

These models are based on the solution of the Cauchy-Navier equations of the type [3] [4]:

$$u_{x,y,z} = U_j e^{ik\left(x+\alpha_j z+ct\right)} \tag{1}$$

where x, y, z represent the displacement components u, U_j; k the wavenumber and α_j the jth eigenvalue. These latter in turn are expressed as a function of the frequency and dispersion velocity.

By imposing the boundary conditions (Eq. 2-9) we obtain a homogenous equation system which non zero solutions can be obtained for some couples frequency-dispersion velocity, for which Lamb waves are generated [6]. The obtained locus of points represents the dispersion curves, as depicted in Fig. 2. In the same picture two straight lines are reported: the working points of piezo of given dimension (red), and the working points of a piezo in resonance (green). The interseciont between the red line and the characteristics curves indicate the frequencies for which Lamb waves are excited.

$$\sum_{j=1}^{4}\left[\lambda^{(i)} + \alpha_j^{(i)} R_j^{(i)}\left(\lambda^{(i)} + 2G^{(i)}\right)\right] U_j^{(i)} e^{ik\alpha_j^{(i)} h^{(i)}} = 0$$
(σ_z=0 on ice free surface, z=$h^{(i)}$) (2)

$$\sum_{j=1}^{4} G^{(i)}\left[\alpha_j^{(i)} + R_j^{(i)}\right] U_j^{(i)} e^{ik\alpha_j^{(i)} h^{(i)}} = 0$$
(τ_{xz}=0 on ice free surface, z=$h^{(i)}$) (3)

$$\sum_{j=1}^{4} U_j^{(i)} - U_j^{(s)} e^{ik\alpha_j^{(s)} h^{(s)}} = 0$$
(horizontal displacement coincident at ice-structure interface) (4)

$$\sum_{j=1}^{4} U_j^{(i)} R_j^{(i)} - U_j^{(s)} R_j^{(s)} e^{ik\alpha_j^{(s)} h^{(s)}} = 0$$
(vertical displacement coincident at ice-structure interface) (5)

$$\sum_{j=1}^{4}\left[\lambda^{(i)} + \alpha_j^{(i)} R_j^{(i)}\left(\lambda^{(i)} + 2G^{(i)}\right)\right] U_j^{(i)} - \\ -\left[\lambda^{(s)} + \alpha_j^{(s)} R_j^{(s)}\left(\lambda^{(s)} + 2G^{(s)}\right)\right] U_j^{(s)} e^{ik\alpha_j^{(s)} h^{(s)}} = 0$$
(σ_z coincident at ice-structure interface) (6)

$$\sum_{j=1}^{4} G^{(i)}\left[\alpha_j^{(i)} + R_j^{(i)}\right] U_j^{(i)} - \\ - G^{(s)}\left[\alpha_j^{(s)} + R_j^{(s)}\right] U_j^{(s)} e^{ik\alpha_j^{(s)} h^{(s)}} = 0$$
(τ_{xz} coincident at ice-structure interface) (7)

$$\sum_{j=1}^{4}\left[\lambda^{(s)} + \alpha_j^{(s)} R_j^{(s)}\left(\lambda^{(s)} + 2G^{(s)}\right)\right] U_j^{(s)} = 0$$
(σ_z=0 on structure inner surface,, z=0) (8)

$$\sum_{j=1}^{4} ikG^{(s)}\left[\alpha_j^{(s)} + R_j^{(s)}\right] U_j^{(s)} e^{ikx} = \mathcal{F}\left[\tau(x)\right]$$
(τ_{xz} equal to the shear transmitted by the piezo through the adhesive layer) (9)

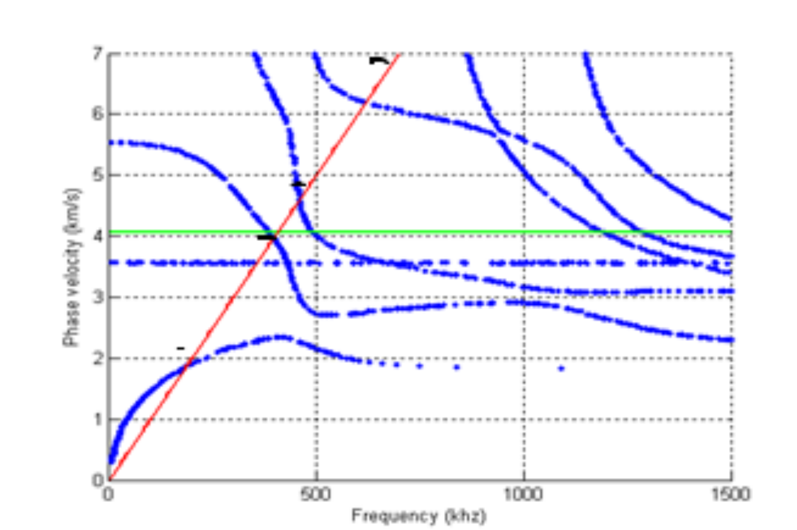

Figure 2. Characteristic curves (blue), working points of a piezo of a given length (red), working points of a piezo in resonance (green).

4 FE MODELLING

In addition to the theoretical model we developed a finite elements modeling of the same system structure-ice-piezo in order to evaluate the effectiveness of the Lamb wave technology to produce ice-detaching.

The FE model, depicted in Fig. 3 reproduces, with given constrain and symmetry conditions, a portion of a structure with a grid of piezo-actuator (Fig. 4). The wave length of the Lamb wave is comparable with the thickness of the structure (1.5 mm) and of the ice layer (2 mm).

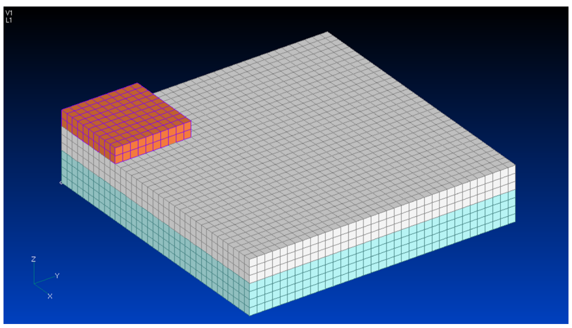

Figure 3. FE model of a portion of structure (grey) with a layer of ice on a face and a piezoelectric on the opposite face (red)

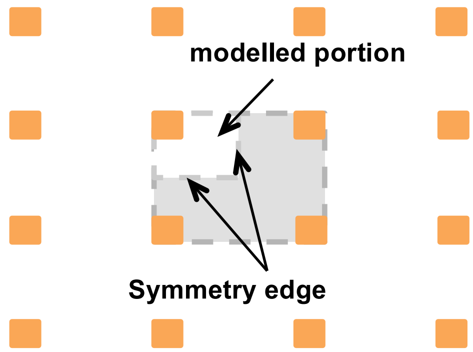

Figure 4. Modelled structure with a grid of piezoelectric

The FE model has been constructed taking into consideration for the structure, the ice layer and the piezoelectric actuator the parameters listed in the following Table 2.

Table 2 Main parameters for structure, ice layer and piezoelectric actuator

Structure	
Material	**7075 T6 Alluminum alloy**
Young modulus (GPa)	**90**
Poisson modulus	**0.33**
Density (kg/m^3)	**2750**
Dimensions (mm)	**60 x 60 x 1.6**
Ice layer	
Material	**Distilled water**
Young modulus (GPa)	**9.1**
Poisson modulus	**0.28**
Density (kg/m^3)	**920**
Dimensions (mm)	**20 x 20 x 3.5**
Piezo actuator	
Material	**Lead zirconate-**

	titanate
Young modulus (GPa) in x direction	**61.0**
Poisson modulus	**0.31**
Density (kg/m^3)	**8000**
d_{31} (C/N)	**280e-12**
N_{13} (m/s)	**1400**
e_{11}/e_0	**2740**
Dimensions (mm)	**20 x 20 x 1.0**

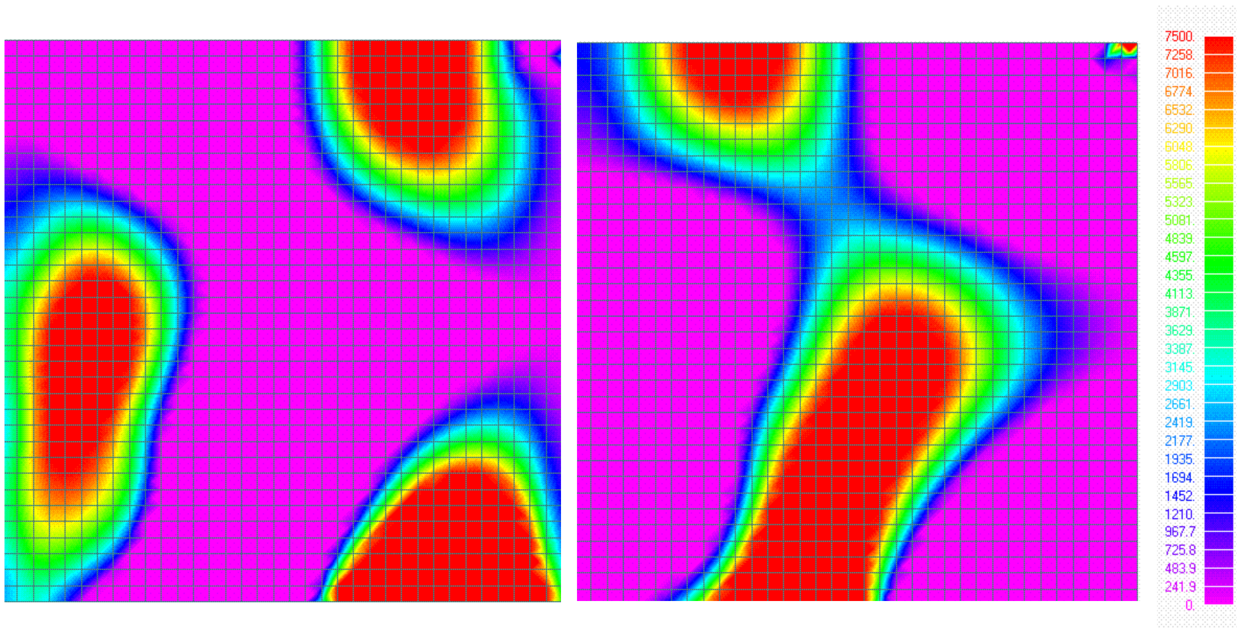

Figure 5. Shear *xz* to the interface ice-structure for two complementary oscillations.

The shear distribution to the ice-structure interface, resulting from the FE modeling, is depicted in the Fig. 5. The two pictures regard to complementary oscillations. The maximum value of 7500Pa, obtained for a unitary amplification, is present for a big portion of the area. While using an amplification of 200V we can obtain a shear of 1.5MPa able to produce the ice detaching, having supposed a perfect gluing between the piezo-actuator and the structure. This shear threshold has been defined by literature data and through a dedicated experimental campaign aimed at appreciating the ice adhesion strength [7] [8] [9].

5 EXPERIMENTAL ACTIVITY

An experimental activity has been performed in an environmental chamber to verify the ice detaching from an aluminum panel due to a piezo-actuator. We used the following test procedure.

We first acquired the dynamic response of the structure before freezing water on it and used it as clean reference. Then water has been frozen on the structure at -10 °C and the dynamic response with ice fully attached was taken at low level of excitation, to prevent from detachment and interface heating.

At the end we excited at high amplitude at specific frequencies to produce Lamb waves and obtain detaching. Moreover, the dynamic response and temperature were acquired at each instant to monitor dynamic response evolution with ice detachment and monitor the temperature level at the interface. From the comparison of the dynamic responses with the clean reference we noticed the ice detaching. In Fig. 6 are reported the top face and the bottom face of the structure with piezoelectric actuator and thermocouple bonded on the opposite faces. The piezo-actuator used to generate Lamb waves is bonded on the bottom face in correspondence of the ice layer and the thermocouple. In Fig. 6 is also possible to see removable the red edges used to contain water to be frozen.

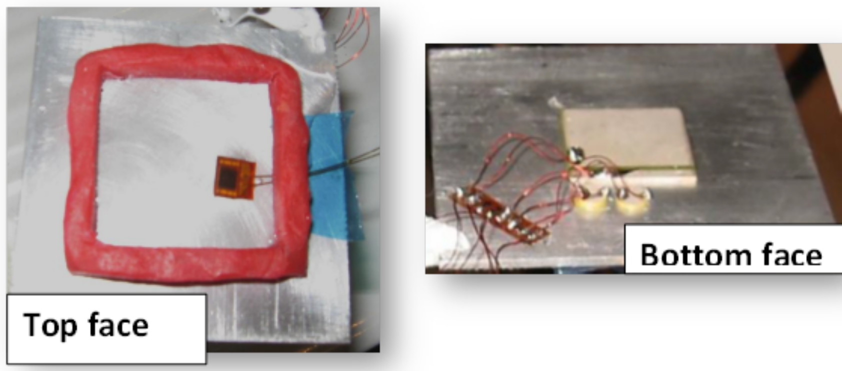

Figure 6. Thermocouple and removable edge (red) for water freezing on top face and piezoelectric on bottom face of the structure

The set up used to perform the experimental activities is composed of and environmental chamber to set the temperature at -10°C, an acquisition system, an oscilloscope, a pc, an amplifier and a signal generator as reported in Fig. 7 and Fig. 8.

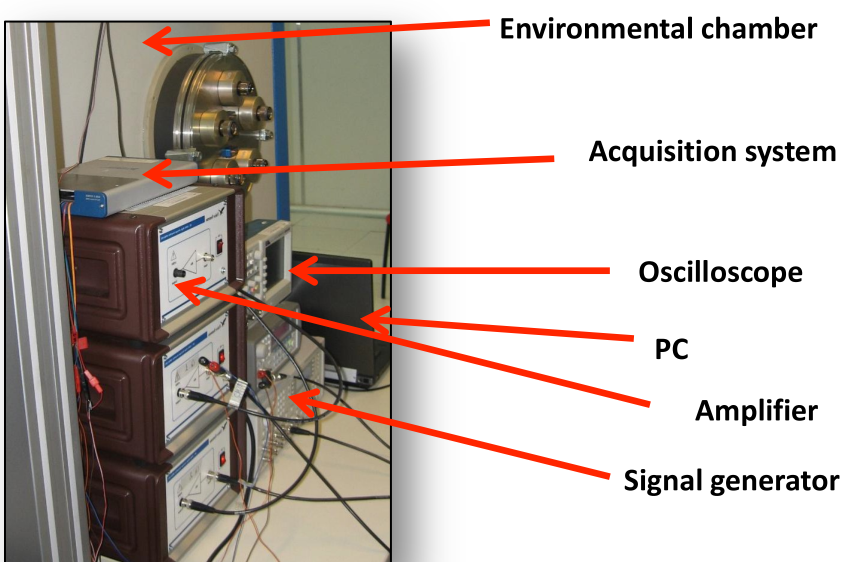

Figure 7. Test set-up

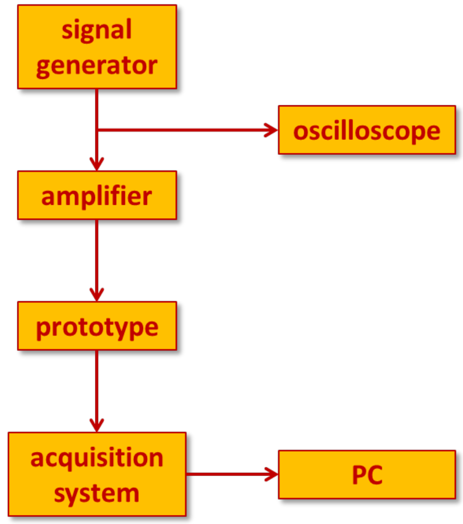

Figure 8. Flow-chart of the test activity

From the comparisons of the dynamic responses of the structure taken with ice layer on it, without ice and during excitation with lamb waves, we obtained the picture in Fig. 9, where we can see how the curves change from the presence of the ice layer and through the de-icing process: the blue curve in Fig. 9 during the excitation of the lamb waves approaches the target red curve taken without ice. In this case we excited at 26 KHz and used signal amplitude of 300Vpp.

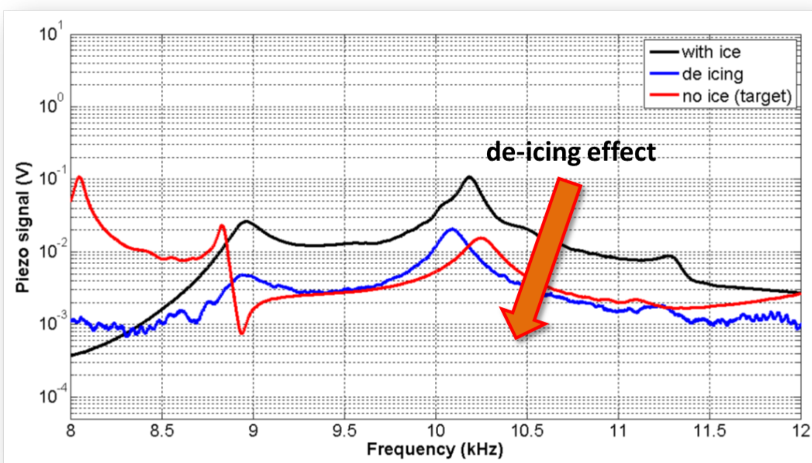

Figure 9. Dynamical responses comparison of the structure with ice, without ice and during the de-icing process

6 CONCLUSIONS AND FURTHER STEPS

In this work we have presented a conceptual design of a piezoelectric Lamb wave system to generate de-icing form an aeronautical structure. The analytic and numerical FE modeling approaches were adopted for predicting system ability to detach the ice.

A de-icing system prototype was manufactured and dedicated preliminary tests were organized, highlighting system de-icing effects. We compared the dynamical responses of the structure with and without ice accreted on it and during the de-icing process when the Lamb waves have been generated.

Further steps include the implementing the technology onto more realistic structural elements such plane structure with larger dimensions, structure with curvatures or isotropic and anisotropic materials Moreover, dedicated tests will be organized to enhance the TRL of the technology.

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