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Investigation of the Design of a Piezoelectric Deicing System Based on Extension Resonant Modes

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ABSTRACT

Extension modes have proven to provide sufficient ice-interface shear stresses, exceeding the adhesion strength of ice to the substrate and ensuring instantaneous ice delamination. A proposed proof of concept involves the utilization of lightweight piezoelectric actuators for deicing the leading edges of aircraft with minimal power requirements. This deicing method induces vibrations into the structure by activating its inherent extension resonant frequencies, thereby creating sufficient stress levels to fracture the ice and delaminate it from the surface. The deicing mechanism depends strongly on the chosen excitation mode, which depends on the actuator placement. Hard and soft piezoelectric actuators were used to excite extensional modes to generate shear stresses at the interface leading edge/ice great enough to delaminate the ice. Deicing was demonstrated with a power input density of 0.074 W/cm^2 for a surface ratio of 0.07 hard piezoelectric actuators per cm^2 .

This contribution discusses a design rule for the piezoelectric actuators positioning for the excitation of extensional modes supported with experimentations.

Keywords: deicing, extension mode, hard piezoelectric actuator, soft piezoelectric actuator, fracture mechanism.

1. INTRODUCTION

The transition towards "More Electric Aircraft" (MEA) signifies a fundamental shift in aircraft design philosophy, aiming to replace traditional hydraulic and pneumatic systems with electromechanical counterparts [1], [2]. This initiative is driven by several factors, including the pursuit of enhanced efficiency, reduced maintenance requirements, and decreased environmental impact [3], [4]. In conventional aircraft, hydraulic and pneumatic systems are commonly utilized for various functions such as actuation, control surfaces, landing gear operation, and deicing. However, these systems have several drawbacks, including high weight, complex maintenance procedures, and susceptibility to leakage and failure.

The adoption of electromechanical systems in MEA offers several advantages. Firstly, electromechanical systems typically have lower weight compared to their hydraulic and pneumatic counterparts, contributing to overall fuel efficiency and reduced emissions. Additionally, electromechanical systems often require less maintenance, leading to lower operational costs and increased aircraft availability.

The avionic piezoelectric deicing system represents a promising alternative for ice protection in MEA. Piezoelectric materials exhibit the ability to convert electrical energy into mechanical vibrations, which can be used to disrupt and remove ice accretion on aircraft surfaces. Compared to traditional deicing methods, piezoelectric deicing systems offer several advantages, including lower energy consumption, faster response times, and reduced weight and complexity.

In this contribution, a proof of concept of a deicing system utilizing lightweight piezoelectric actuators with minimal power requirement is proposed. First, a numerical model is proposed for positioning piezoelectric actuators and choosing the proper resonance mode, followed by experimental validation. Then, an extended model based on the same methodology is subsequently developed. Finally, a comparison between hard and soft PZT actuators for deicing is conducted.

2. PIEZOELECTRIC DEICING SYSTEM OPERATING PRINCIPLE

The piezoelectric deicing system's operational principle involves generating microscopic mechanical vibrations through the converse effect, also known as the reverse piezoelectric effect. These electromechanical vibrations, depending on the resonance mode, induce a stress field that triggers cohesive fractures within the ice, adhesive fracture at the interface between the leading edge and the ice, or a combination of both [5]. Two configurations for applying piezoelectric actuators have been outlined in the literature. The first configuration employs Langevin transducers, chosen for their simple installation using bolts and reduced risk of mechanical failure due to their prestressed structure, enabling them to withstand higher stresses during operation. However, the use of prestressed PZT ceramics, primarily intended to activate structural flexural modes, may, in optimal scenarios, lead to some ice delamination [6]. Since we are interested only in extensional modes, this configuration won't be used in this contribution. The second configuration involves piezoelectric patches that can be glued to the mechanical structure, has been more extensively tested in literature, and appears to hold greater promise (Figure 1). In order to excite only a specific mode, a properly designed sinusoidal voltage generator should be used [7].

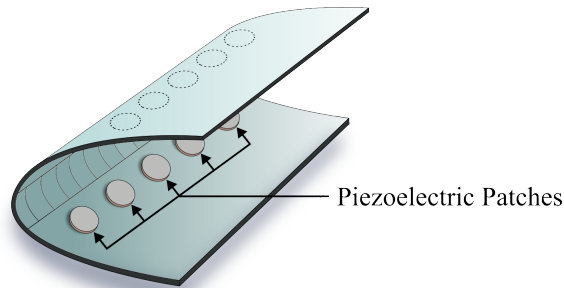


Figure 1 Configuration of a piezoelectric de-icing system with piezoelectric patches.

3. ICE PROPERTIES

Extensive work to experimentally determine the cohesive strength within the ice and its adhesive strength to different materials has been conducted by multiple authors [8], [9], [10], [11], [12], [13], [14]. These investigations revealed that refrigerated glaze ice's expected adhesive shear strength range is estimated to fall between 0.24 MPa and 1.7 MPa. Experimental measurements indicated that the average adhesive shear strength of freezer ice to steel at -10 °C was 1.5 MPa, with the maximum value reaching 1.66 MPa [15]. Additionally, the cohesive tensile strength was observed to range between 0.6 MPa and 3 MPa [16], [17], [18].

TABLE I
GLAZE ICE PROPERTIES

Glaze ice	
Young's modulus (E)	9.3 GPa
Poisson's ratio (ν)	0.325
Density (ρ)	900 kg/m ³
Cohesive strength	[0.6 - 3] MPa
Adhesive strength	[0.24 - 1.7] MPa

4. FINITE ELEMENT ANALYSES

A 150 mm × 50 mm × 1.5mm aluminum plate with only one round hard PZT (PIC181) actuator placed in the middle was initially modeled numerically in 3D using the finite element software COMSOL (Figure 2). Its impedance was computed and compared to the measured one (Figure 3). The sample is in free boundary conditions. The round shape of piezoelectric ceramic was chosen since it suffers less stress on the edges than a rectangular shape [19].

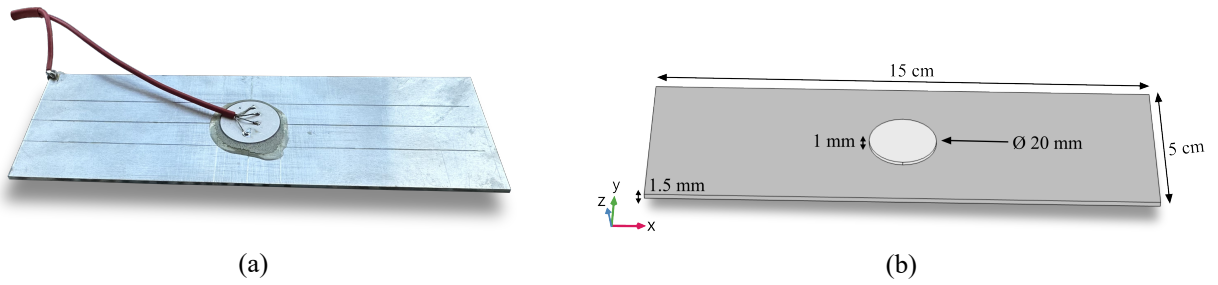


Figure 2 3D finite element modeling and reel image of the plate.

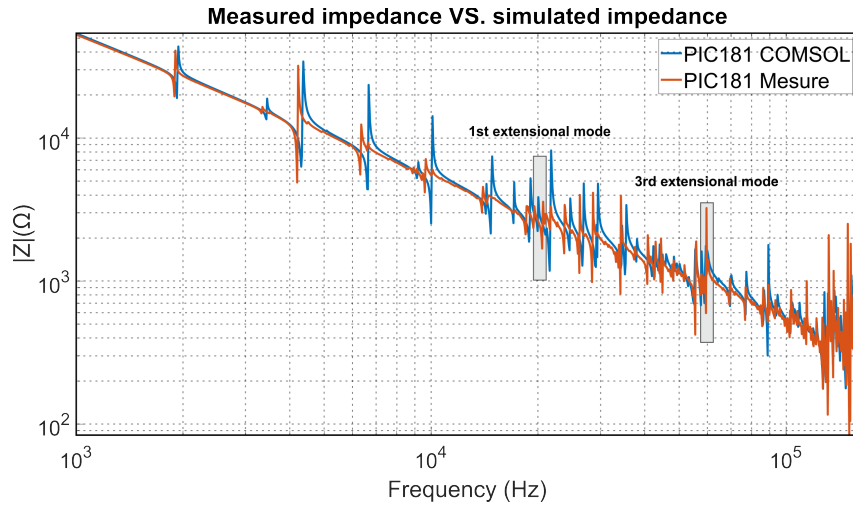


Figure 3 Measured impedance vs. simulated impedance of the structure.

For this configuration, only the fundamental extensional mode and its odd harmonics will manifest in the plate [20]. To visualize only the extension modes dans les simulations COMSOL, zero displacements are enforced along the y and z axes. According to simulations, the first extensional mode (fundamental) is identified at approximately 20 kHz (Figure 3 and Figure 4). However, when the displacement is set to be free on the three axes, the extensional mode will be coupled with flexural modes and other parasitic modes, making it difficult to be observable around 20 kHz (Figure 4-b). On the other hand, when driving the piezoelectric actuator at the 3rd extensional mode which is spotted around 60 kHz (Figure 3 et Figure 5), the extensional mode is still dominant even when displacement is set to be free on the three axis (Figure 5-b). Also, the stress level obtained (mainly shear stress) is much higher than the 1st extensional mode.

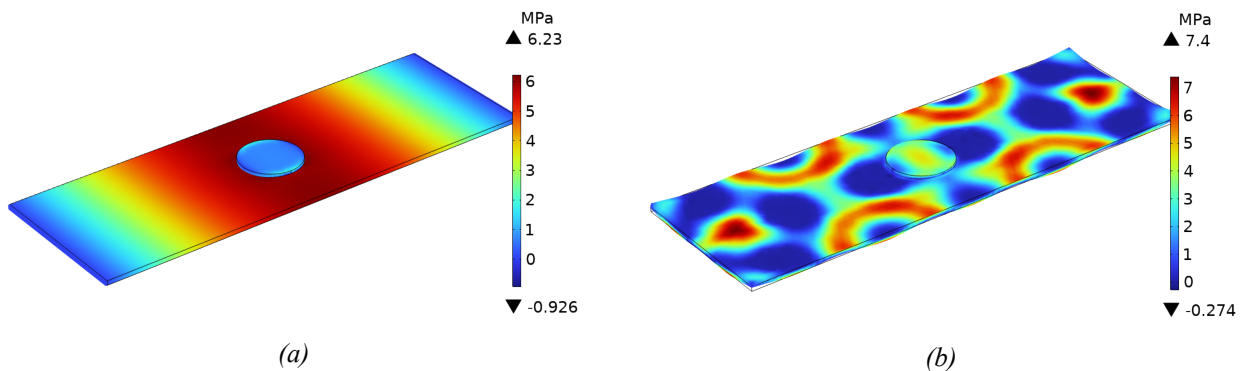


Figure 4 Shear stress levels at the 1st extension mode at 20 kHz: (a) zero displacements imposed on the y and z axis, (b) free displacement on the x, y and z axis.

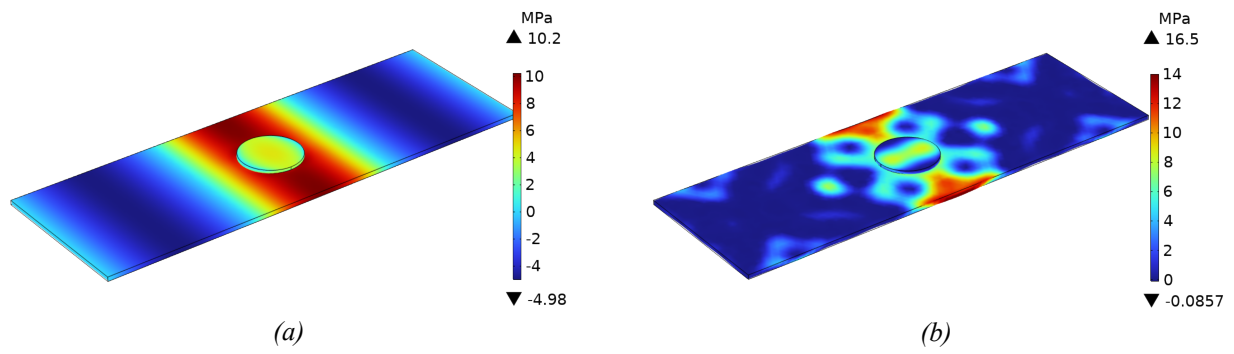


Figure 5 Shear stress levels at the 3rd extension mode at 59 kHz: (a) zero displacements imposed on the y and z axis, (b) free displacement on the x, y and z axis.

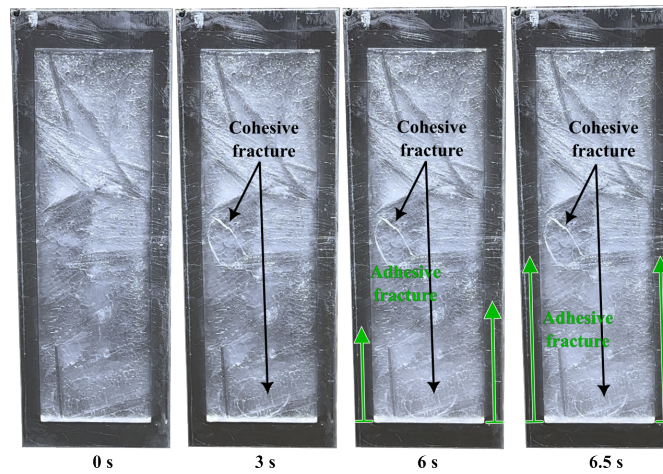


Figure 6 Cohesive fractures and propagation of adhesive fracture at the 3rd extension mode.

To increase the stress level at the third extensional mode, two additional ceramics were attached to the plate at the peaks and valleys of the extensional wave and in opposition to the one in the middle. Simulation results show a shear stress level approximately three times higher for the 3rd mode than when only one actuator is used (Figure 7). Consequently, during experimental tests for the third mode, we observe multiple cohesive fractures initially induced by parasitic modes, followed by adhesive fractures, leading to complete ice debonding. These three stages occur at 200 V within approximately 5 seconds, as illustrated in Figure 8.

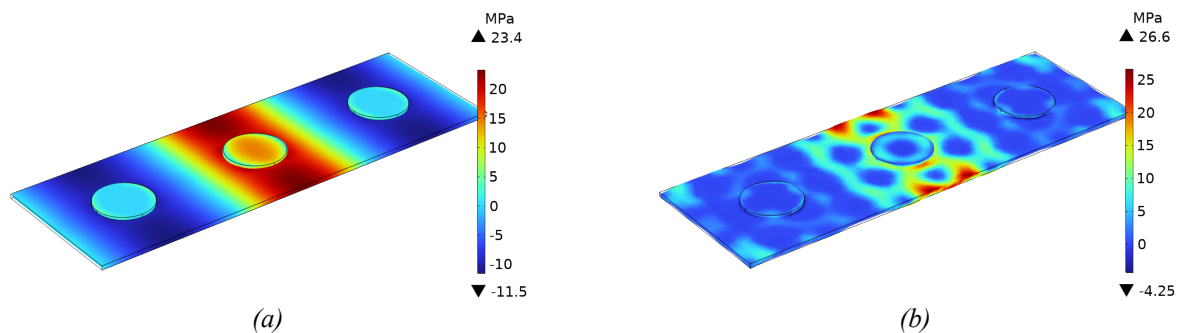


Figure 7 Shear stress levels at the 3rd extension mode at 59 kHz with 3 actuators: (a) zero displacements imposed on the y and z axis, (b) free displacement on the x, y and z axis.

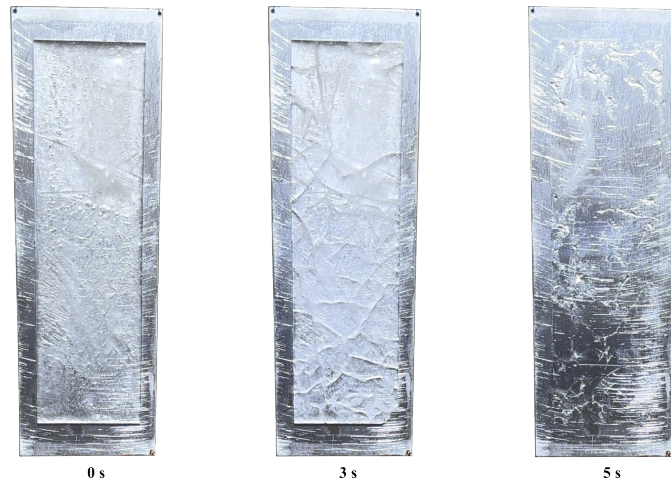


Figure 8 Experimental result of deicing at the 3rd extension mode of the plate.

5. EXTENDED DEICING MODEL

a. Free boundary condition

After confirming the accuracy of the numerical model for the small plate through experimental validation, an extended deicing model was developed. This model consisted of a larger aluminum plate measuring 350 mm × 250 mm × 1.5 mm, equipped with 20 hard PZT actuators identical to those used previously. The same approach was employed for both driving and positioning the actuators. As depicted in Figure 10, the actuators were positioned to enhance the 7th extension mode at 55 kHz (Figure 9), thereby generating sufficient stress to fracture and delaminate the ice. An instantaneous fracture and delamination of 2 mm-thick-ice occurred at this frequency with a power input density of 74 mW/cm² and a surface ratio of 0.07 piezoelectric actuators per cm².

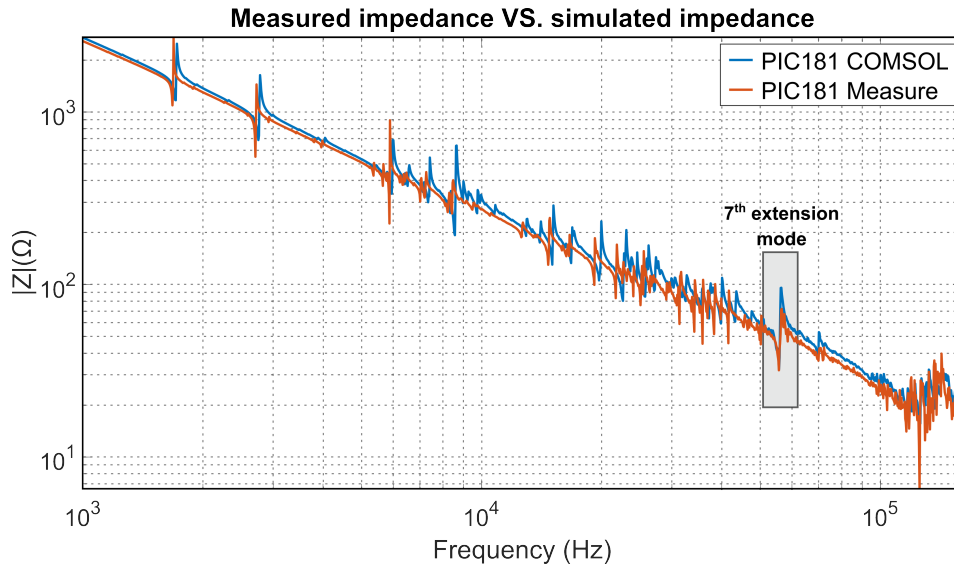


Figure 9 Measured impedance vs. simulated impedance of the extended model.

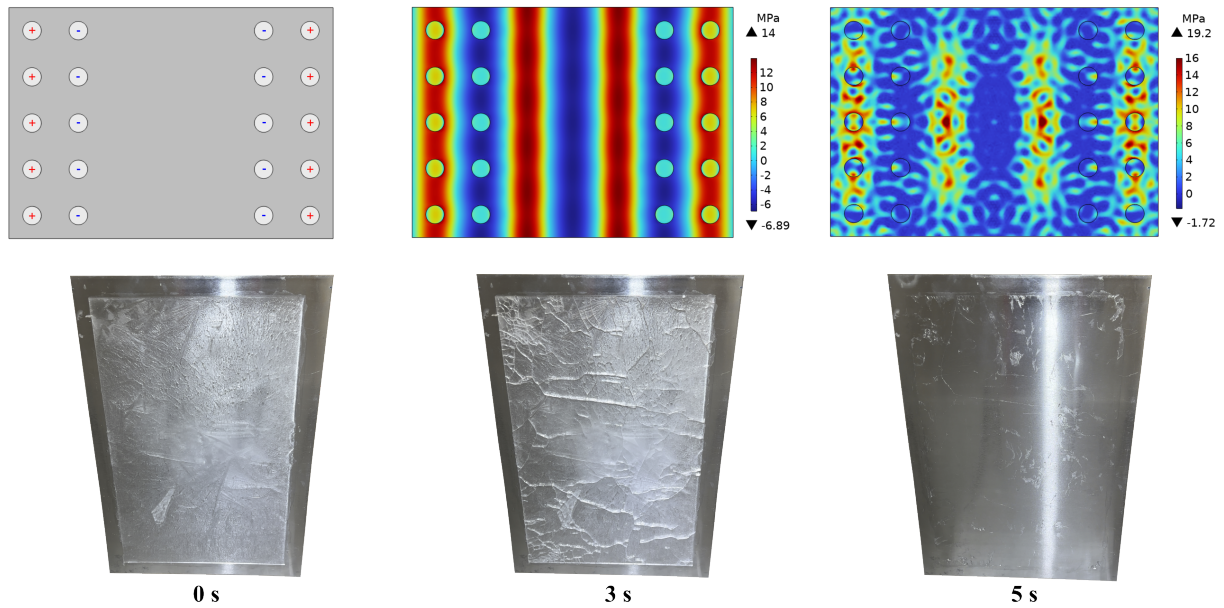


Figure 10 Simulation result of the 7th extension mode and its corresponding experimentation results.

b. Fixed boundary condition

For the configuration with fixed boundary conditions, an aluminum plate of the same dimensions as in the case of free boundary conditions was used, along with the same number of actuators. However, since the two ends of the plate along its length are clamped, corresponding to nodes of displacement of the extension wave, the actuators must be shifted by one-quarter of the wavelength (2.5 cm) on each side, as illustrated in Figure 12. The 7th extension mode remains around 55 kHz, with the same impedance value (30 Ω) as in the case of free boundary conditions (see Figure 11 and Figure 9). At this frequency, the shear stress level is approximately 30% higher at certain points for the same power level. Experimentation for this case has not been conducted since, according to simulations, complete deicing is expected, similar to the free boundary case.

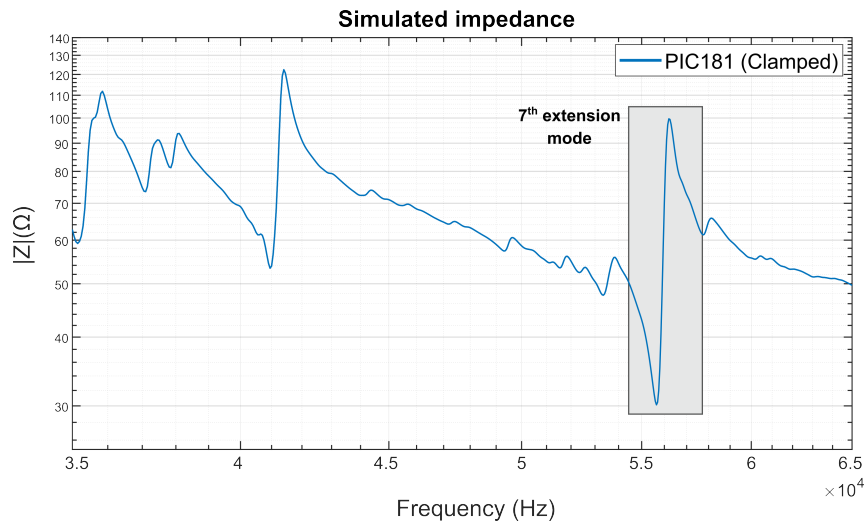


Figure 11 simulated impedance of the clamped configuration.

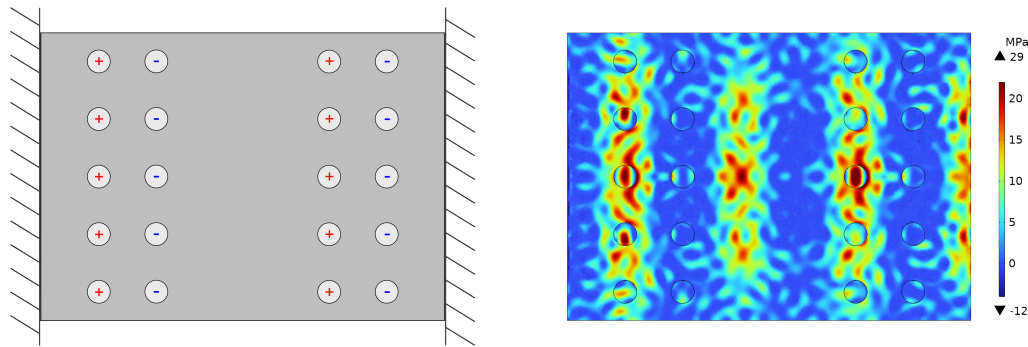


Figure 12 Simulation result of the 7th extension mode of the clamped configuration.

6. CONCLUSION

This paper has explored a novel electromechanical deicing approach based on utilizing extension modes with piezoelectric actuators. Deicing was achieved by harnessing structural extension modes to generate sufficient shear stress for ice detachment and complete deicing. COMSOL finite element simulations were utilized to identify the optimal excitation mode and placement of piezoelectric actuators. Experimental results demonstrated successful deicing with a power input density of 0.074 W/cm² and a ratio of 0.07 piezoelectric actuators per cm². Compared to other deicing and anti-icing methods currently employed in certain aircraft, such as the hot air bleed system or electrothermal system, the piezoelectric deicing system offers significantly lower power consumption. Compared to other deicing and anti-icing solutions already employed in some aircraft, such as the hot air bleed system or electrothermal system, the piezoelectric deicing system is much more economical in terms of power consumption. Research indicates that the specific power needed for ice protection with a hot air bleed system could reach up to 420 kW for an Airbus A320, equivalent to 25 kW/m² [21]. Similarly, protecting the wings of a Boeing 787 with electrothermal deicing requires between 45 kW and 75 kW, resulting in an estimated power requirement of 3.61 kW/m² [22].

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