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ULTRASONIC DE-ICING SYSTEM DESIGN METHODS BASED ON RESONANCE AND IMPEDANCE MATCHING

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Abstract

Systems and components safety of aircraft will encounter the threats under the environment that ice accumulation occur on the impact surface of the airplane. Our objective is to investigate an efficient de-icing method by introducing piezoelectric actuators onto the in-flight aircraft to overcome the ice hazards. Two design methods for ultrasonic de-icing system with different applications are researched in this paper. Simulation of resonant frequency and impedance for a single isotropic plate and piezoelectric ceramics, as well as the analysis of combined de-icing configurations with piezoelectric actuators at its impedance lows, are the main research items. The results achieved during the verification experiments for ice removal prove the feasibility of the ultrasonic de-icing method with the lower power consumption than the thermal method.

Keywords: Piezoelectric Actuator, Resonant, Impedance Matching, Ultrasonic De-icing System

1. Introduction

During the aviation at a high altitude of aircraft, ice accumulation will arise on the impact surface when aircraft flying through a cloud layer that contains supercooled water particles in the frozen atmosphere. Accumulated ice will change the geometric shape of the aircraft, which can decrease the lift coefficient and increase the drag of the aircraft [1]. It is necessary to develop effective technologies to prevent the formation of ice and remove the ice when ice accumulation occurs to eliminate flight safety hazards. In recent years different types of anti/de-icing methods include thermal, mechanical or coating methods have been studied by many researchers [2]-[3]. And among them, the heat de-icing method has been successfully applied in the aviation industry because of its significant anti/de-icing effect. However, under the demands for green energy and efficient energy utilization of transportation, the thermal method has limitations on anti/de-icing purpose of future vehicles due to its high weight and large power consumption [4]. Mechanical de-icing methods have caught people’s attention in recent years due to the development of varied equipment, mechanical structures and automotive materials [5]-[7]. But the risks of structure damage under instantaneous impact force (for electro-impulsive separation system), electromagnetic interference on instruments (for electro-magnetic impulse de-icer) and material durability during multiple large deformation conditions (for pneumatic impulse ice protection method) limit the widespread use on aircraft. Therefore it is necessary to develop a light and low-energy usage method for ice removing. And the ideas of using piezoelectric actuators to drive the structures to achieve the de-icing aims have been investigated in the past 20 years.

For the research of the principle of ultrasonic de-icing method: Ramanathan et al. [8] introduced the horizontal shear waves excited by piezoelectric materials on the flat aluminum plate for de-icing purpose. Motivating effects on the leading edge of airfoil wing excited by different sizes of piezoelectric ceramic pieces were studied by Venna et al. [7][9], and a de-icing method using one single piezoelectric actuator to stimulate enough shear stress was proposed through simulation analysis and experimental verification. Palacios et al. [10]-[11] conducted the proof-of-concept de-icing experiments on aluminum plate and leading edge structure of wing inside the wind tunnel with ice accretion atmospheric conditions respectively, on those structures piezoelectric exciting materials were attached by specific adhesive. A new de-icing idea was proposed by Lin et al. [12], which aimed to excite the structures at their resonance frequency point to get sufficient vibration intensity for ice-removing. For the research on the theoretical mechanism of ultrasonic de-icing and the icebreaking mechanism: Kalkowski et al. [13]-[14] investigate the capability of ultrasonic structural wave actuated by piezoelectric structure to delaminate the surface accretions, and treat plaster instead of ice as the surface accretions to verify the feasibility of this ultrasonic removing method. Marc et al. [15]-[16] focus on the ice fracture propagation mechanisms under the action of electro-mechanical resonant vibration through numerical analysis and FEM (finite element method) simulation. Meanwhile, Valerie et al. [17] reveal the ice fracture initiation mechanisms with piezoelectric actuators in the electro-mechanical resonant ice protection system. Rouset et al. [18] compare the stress and strain of plate with extensional and flexural mode respectively to highlight the vibration mode selection criteria during the detail design process of the piezoelectric ice protection system. In other research directions, FEM simulation of the ultrasonic ice protection system on a flat plate and wind turbine blades, as well as the size and array design of the piezoelectric actuator, also have obtained considerable findings [19]-[20].

For the ultrasonic de-icing investigations achieved by many scholars, mainly attentions are paid on actuators utilization with set dimensions on the target de-icing structures to conduct the simulation analysis or ice removing tests [7]-[9]. Some researches focused on the whole constructions including exciting elements and target de-icing parts and tried to demonstrate the delamination of accumulated ice under the effects of ultrasonic excitation at the resonance frequency vibration points with the lowest system impedance. However, the selection criteria of piezoelectric actuators were not clear, and the method focused on the final whole system resonance vibration seemed more accidental for the detail design processes of the ultrasonic de-icing system.

In terms of the effect of structural resonance, larger vibration amplitude can be made on the plate structure when shocked at its natural frequency. Meanwhile, the maximum motivating effect of piezoelectric actuators will be induced at the resonant frequency of ceramic, and optimal energy conversion efficiency of the whole de-icing system including actuators and plate configuration will be guaranteed at the smallest impedance point. In terms of the mechanical properties of ice under different experimental results [21]-[22], the maximum shear strength of ice in the frozen environment is around 1.7 MPa and that of impact ice in the icing wind tunnel is 1 MPa, whereas the tension strength of refrigerated ice is about 274 MPa [5]. Since the strength of the bonds created by accumulated ice is always smaller and weaker in shear than in tension or in compression, much more power will have economized if using the shear stress as the key force for de-icing purposes. Therefore, we combine the advantages of structural resonance, low electrical impedance, and increased shear stress to study the specific de-icing system design process through simulation and experimental methods. And the research approach discussed in this paper is aimed to build a clear path on structure de-icing purpose excited by piezoelectric actuators at its resonant frequency and impedance lows, and aimed to research detailed numerical design process to provide a reference for subsequent engineering de-icing applications.

2. Methodology and Experimental Setup

2.1 Basic Theories of Structural Dynamic Analysis

The finite element method (FEM) employed in this paper focus on structural dynamic analysis, such as modal analysis and harmonic response analysis. Some basic theories of structural dynamic analysis are introduced in this section.

When introducing the inertial force into system, the motion control equation of a multiple-degree-of-freedom system according to the d'Alembert's principle can be expressed as:

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=[F] \tag{1}$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix.

The mass matrix, damping matrix and stiffness matrix can be expressed as:

$$[M]=\iiint_V \rho[N]^T[N]dV \quad [C]=\iiint_V c[N]^T[N]dV \quad [K]=\iiint_V [B]^T D[B]dV \tag{2}$$

where $[N]^T$ is the shape function matrix, $[B]^T$ is the position coordinate matrix, D is the elastic constant matrix related to element materials.

For modal analysis, the following equation is applied to calculate the eigenvalue problem:

$$\left([K]-\omega^2[M]\right)[\delta_0]=0 \tag{3}$$

For harmonic response analysis, mode superposition method is employed to calculate the dynamics response under input load on structure:

$$[\delta_0]_i^T[M][\delta_0]_i\ddot{y}_i+[\delta_0]_i^T[C][\delta_0]_i\dot{y}_i+[\delta_0]_i^T[C][\delta_0]_i y_i=[\delta_0]_i^T[F] \tag{4}$$

Piezoelectric actuators are selected as input exciting source, so the input load for dynamic analysis can be defined as:

$$\begin{aligned} T_{ij} &= c_{ijkl}^E S_{kl} - e_{kij} E_K \\ D_i &= e_{kij} S_{kl} - \varepsilon_{ij}^S E_j \end{aligned} \tag{5}$$

where S is the strain vector, D_i is the electric displacement vector (C/m^2), E is the applied external electric field vector (V/m), T is the stress vector (N/m^2).

2.2 Design Process and Steps

Two research approaches can be conducted for clarifying the research content of this paper: piezoelectric actuator based method for feasibility study and de-icing target structure-based method for practical research. Characteristics of structure with accumulated ice should be treated as known conditions for ice protection system design, so the target structure-based method should be considered according to the demand for actual use. But to take full advantage of existing piezoelectric ceramics in the lab, as well as considering the consistency in the aims of these two research approaches, the piezoelectric actuator based method with aluminum plate is chosen to be elaborated in the simulation section to conduct the feasibility study of this new design path for the ultrasonic de-icing system. Meanwhile, other research cases also be studied in the numerical section. Based on the above illustration, parameters of piezoelectric ceramic are treated as the design input of overall ultrasonic de-icing structure and are set as constants.

The development of the proposed ultrasonic de-icing method involves the following steps, and the first and second items can be adjusted in sequence according to different design aims:

- Simulation and measurement of the impedance of piezoelectric ceramics are conducted at the beginning of the design process to determine the detail ultrasonic resonance frequency with impedance lows.
- The size of a flat aluminum plate is designed according to the resonance frequency data of ceramic via the simulation method. Meanwhile, the vibration mode of the plate at the resonance frequency should guarantee the favorable excitation condition of piezoelectric actuators.
- Simulation analysis of coupled finite element model including plate and piezoelectric actuators with ice layer attached on plate surface is carried out by commercial software ANSYS® respectively. FEM calculation without ice layer would emphasize the natural vibration circumstances of the whole system near the resonance frequency determined by piezoelectric ceramics, while shear stress between ice layer and aluminum plate is considered for the simulation analysis of FEM when ice layer is bonded on the surface of the metal substrate.
- The proof-of-concept experiment with the ultrasonic de-icing system is implemented in the icing environment with minus temperature to validate the feasibility of the ultrasonic de-icing method.

In order to establish a clear expression of the scientific approach, the overall research purpose including the details above is presented in the schematic diagram shown in Fig.1.

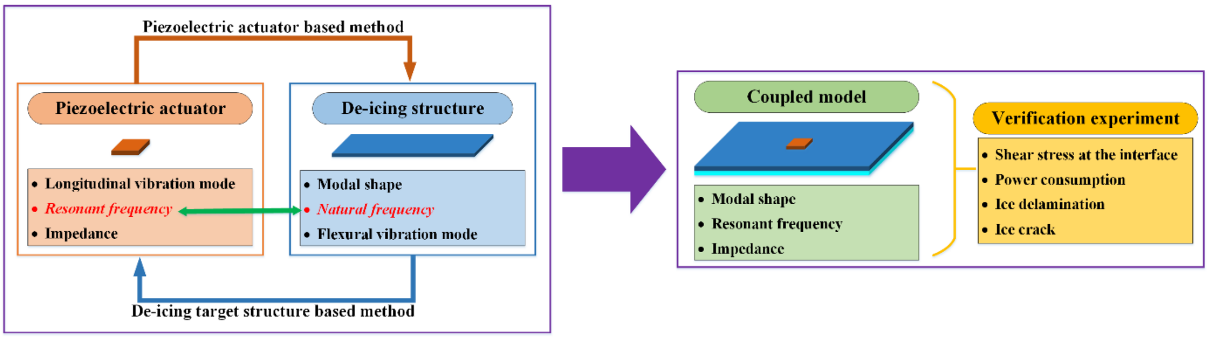


Figure 1 –Research framework of the ultrasonic de-icing system design methods.

2.3 Numerical Simulation Model

A de-icing prediction model was determined by the certain configurations designed in the above sections employing mechanical simulation software ANSYS®. Five piezoelectric actuators and an ice-layer were set to mount on both sides of the aluminum plate. PZT (lead zirconate titanate) actuators were bonded at the central position of the aluminum substrate. A little space between two actuators is 0.002m to fulfill the convenience of the ceramics bonding process in the actual experiment preparation. The range of ice-layer was slightly smaller than that of the plate, each edge of ice-layer leave 0.002m clearance from the edge of the plate. Because the variation of ice thickness has little effect on an adhesive fracture [13], so the thickness of the ice layer is set to 0.001m. The metal plate and ice-layer were modeled with 8-node 3D quadratic isotropic elements, while the piezoelectric ceramics were modeled with 8-node 3D quadratic coupled-field isotropic elements. The bonding connection between ice-layer, plate and actuators was modeled with 3D node-to-surface contact/target elements. Considering the actual structure size, to ensure the calculation accuracy and calculation efficiency, the mesh size of the finite element model is set to 0.001m. Detail summary of elements for FEM model building are shown in Tab.1.

Table 1 – Elements used in FEM model.

Component	Element type	Parameters concerned
Ice	Solid 185	Displacements, Stress, Strain
Plate	Solid 185	Displacements, Stress, Strain
Piezo-actuators	Solid 5	Displacements, Voltage, Current or Charge
Interface	Targe170 & Conta175	“Contact-target” pair: for connection

In terms of specific piezoelectric actuators arrangement design, a detailed model with one single piezoelectric ceramic excitation was used for the first time, and the actuator was bonded in the middle of an aluminum plate. The maximum shear stress at the interface between the ice layer and the substrate calculated by the simulation method is 2.26 MPa. Due to this small shear stress, the ice layer could not be effectively removed in the actual experimental process. Therefore, to ensure a better excitation effect for de-icing in the specific research of this paper, the arrangement of multiple piezoelectric elements form is chosen as the research target in detailed design process. De-icing evaluation and feasibility of the system driven with specific voltage during simulation are illustrated by comparing the shear stress level obtained during the analysis process with the adhesive strength data obtained in the published experiments [21].

The details of the finite element model are shown in Fig. 2. Information of the materials of the ice layer and aluminum plate are shown in Tab. 2 and the material parameter matrixes of the piezoelectric actuator are shown in *Eq. (6)*. The material information of the composite plate are: ρ=2000kg/m^3, EX=50GPa, EY=8GPa, EZ=8GPa, GXY=5GPa, GXZ=5GPa, GYZ=3.846GPa, PRXY=0.3, PRXZ=0.3, PRYZ=0.4. And the composite plate is made of five layers of biaxial glass fiber reinforced composite material.

Table 2 – Material parameters of ice and aluminum.

Material	Density/kg·m^{-3}	Young's modulus/Pa	Poisson's ratio
Ice	919.7	9.33×10^{9}	0.325
Aluminum	2780	7.05×10^{10}	0.33

$$
\begin{aligned}
&\rho = 7600\ kg\cdot m^{-3}\\
&\varepsilon = \begin{bmatrix} 7.9688 & 0 & 0 \\ & 7.9688 & 0 \\ & & 5.3125 \end{bmatrix} \times 10^{-9}\ F\cdot m^{-1}\\
&c = \begin{bmatrix} 14.9 & 8.11 & 8.11 & 0 & 0 & 0 \\ & 14.9 & 8.11 & 0 & 0 & 0 \\ & & 13.2 & 0 & 0 & 0 \\ & & & 3.13 & 0 & 0 \\ & & & & 3.13 & 0 \\ & & & & & 3.4 \end{bmatrix} \times 10^{10}\ N\cdot m^{-2}\\
&e = \begin{bmatrix} 0 & 0 & -4.1 \\ 0 & 0 & -4.1 \\ 0 & 0 & 14 \\ 0 & 10.3 & 0 \\ 10.3 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} C\cdot m^{-2}
\end{aligned} \tag{6}
$$

where ρ is the density of piezoelectric actuator, ε is the dielectric constant matrix, c is the elastic coefficient matrix, and e is the piezoelectric coefficient matrix.

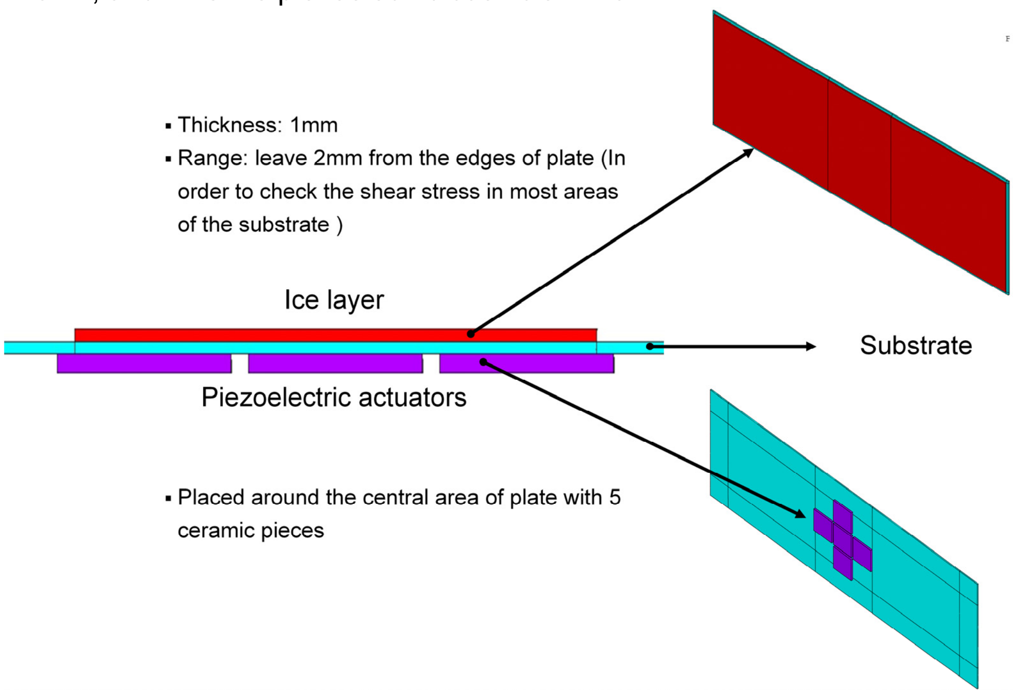


Figure 2 – The detail finite element model for de-icing simulation.

2.4 Experimental Setup

An impedance analyzer was selected to investigate the electrical properties of these actuators. Piezoelectric ceramic with the size of 20×20×1.5 mm and material type of PZT-8 is selected as the targeted piezoelectric element of the overall ultrasonic system due to its high resonant frequency and better electromechanical coupling properties. This type of ceramic was tested by impedance analyzer with the sweep frequency ranging from 1 kHz to 500 kHz to get the response curve of impedance vs. frequency. Comparison between numerical and experimental results are discussed in next section to validate the consistency of calculation and measurement.

To validate the feasibility of the ultrasonic de-icing method, the corresponding experiment with the ultrasonic de-icing system designed in this article is conducted in an icing environment with temperature as -23℃. A specific experimental support platform was designed for a variety of structural test requirements, on which the whole coupled de-icing structure was fixed under the clamped boundary condition of four sides. To achieve the ideal boundary conditions of the plate, four edges of this substrate were tightly compressed by the clamp aluminum plate and fastening bolt, leaving the remaining region of the plate around the position on where the piezoelectric actuator was attached as the designed target test area. The excitation signal was generated by an excitation source and finally applied to the electrodes of the actuators. The schematic diagram of the overall de-icing platform is shown in Fig. 3.

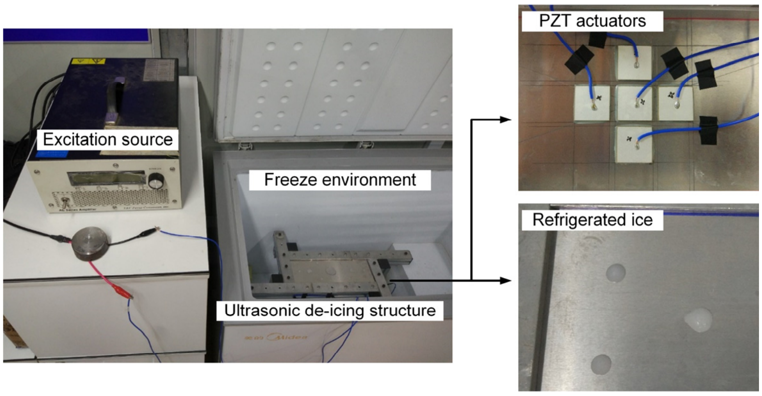


Figure 3 – Schematic diagram of the overall ultrasonic de-icing test platform.

Small refrigerated ice is generated using injectors and pure water. All small ice points were frozen on the surface of the substrate plate in a freezing environment of the refrigerator with the temperature of -23℃ for about 3 hours to achieve the fully freezing condition. Due to the higher mechanical characteristics in tensional and shear strengths of refrigerated frozen ice than these of impact ice in wind tunnel, the successful ice-removing results in validation experiments of this article will also provide evidence for the de-icing feasibility of the designed ice protection system on actual impact ice of aircraft.

3. Results and Discussions

3.1 Impedance Analysis of Piezoelectric Ceramics

Piezoelectric ceramic with the size of 20×20×1.5 mm and material type of PZT-8 is selected as an example to verify the consistency between the calculated results and the experimental results. Meanwhile, these results also can be treated as a design input for piezoelectric actuator based method in section 3.2 and 3.3.

According to the derivation of impedance, impedance of piezoelectric ceramic is defined in *Eq. (7)*:

$$Z = \frac{1}{Y} = \frac{V}{j\omega \sum Q_i} = \frac{V}{j \cdot 2\pi f \cdot \sum Q_i} \tag{7}$$

where ω is the circular frequency (rad/s), f is the frequency (Hz), $\sum Q_i$ is the nodal charge on the ceramic (C), which can be obtained from the software, and Y is the admittance of PZT piece (S), Z is the impedance of PZT piece (Ω).

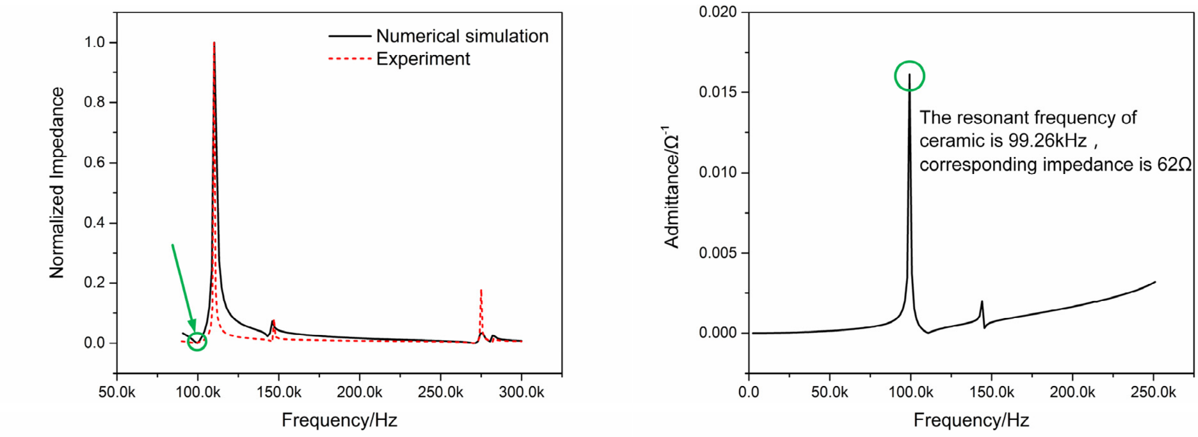


Figure 4 – Impedance results and the determination of the resonant frequency of ceramic. (Left) A comparison of impedance results of actuator between simulation analysis and experimental data, the resonance frequency can be obtained at the point marked with a green circle. (Right) The admittance results of actuators, meanwhile the resonance frequency of piezoelectric ceramic can be found easily at the point with the maximum value of admittance.

Harmonic response simulation of piezoelectric ceramic with longitudinal vibration mode was carried out to calculate the frequency response curve of impedance through the expression in *Eq. (7)*. A comparison of impedance results between simulation analysis and experimental measurement is shown in Fig. 4. Good agreement between calculated and experimental results is proved. It can be found that the lowest impedance 62Ω is achieved at 99.26 kHz from the frequency response curve of admittance, which is the resonance frequency of the d_{33} piezoelectric ceramic. The resonance frequency obtained in this section would be treated as design input of plate size design in next section.

3.2 Numerical Results under the Piezoelectric Actuator Based Method

Detailed simulation analysis of piezoelectric actuators, aluminum substrate and the coupled FEM model are conducted through mechanical analysis software to check the impedance of ceramics, vibration condition of the plate and shear stress at the interface between ice and substrate respectively. Because of the reversibility of the execution process of these two different design methods, piezoelectric actuator based method with aluminum plate is mainly adopted to elaborate on the specific design process.

Larger vibration intensity of structure can be obtained when the structure is excited at its one natural frequency. So finite element modal analysis for a single aluminum plate structure on which the actuators are bonded is carried out to design the dimension and configuration to obtain the one natural frequency of plate, which will match the resonant frequency of the ceramic that discussed in section 3.1. According to the research results of Marc et al. [16], the initiation of ice layer delamination is mainly due to the out-of-plane components of vibration mode and the flexural modes are suitable to initiate fractures inside ice layer. So out-of-plane flexural vibration mode of plate is obtained with this one natural frequency. Under this vibration frequency, shear stress excited by the structure will exceed the required adhesion strength of ice and induce the delamination of ice on the target de-icing area.

To make more regular vibration mode for investigation, piezoelectric actuators were arranged to be bonded at the central area of the plate. So the modal shape of the plate at the specific natural frequency of the structure is the target vibration mode for further de-icing purposes. In this specific vibration mode, namely flexural mode, the deformation of the plate was in the thickness direction, which is the same direction of piezoelectric actuator vibration. Furthermore, the mechanical strain at the central position of the plate should be larger in this vibration mode shape. Under these requirements, a 300×100×1 mm steel plate was designed under this piezoelectric actuator based method for aluminum substrate. The detailed vibration mode is shown in Fig. 5.

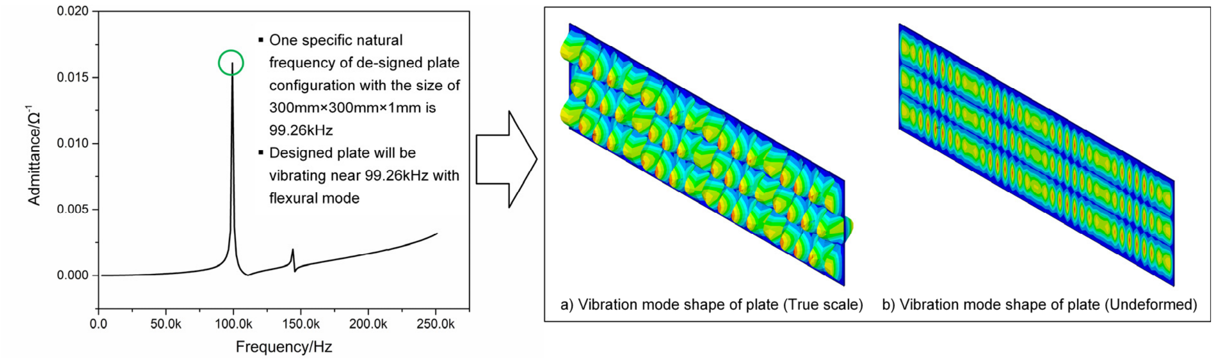


Figure 5 – The detail vibration mode of the plate at its one natural frequency near the resonant frequency of piezoelectric actuators.

After determining the size of piezoelectric ceramic and plate, de-icing prediction model without ice-layer was simulated for the detailed vibration condition and mode shape of the coupled structure before the shear stress simulation. According to the theory of structure dynamics, the change of structure mass will alter the natural frequency of the whole model. So one different natural frequency of the coupled structure will be obtained when the plate is attached by piezoelectric actuators. The specific vibration conditions of structure with the frequency near the original resonant frequency of actuator are simulated to confirm each mode shape of these is the flexural mode. Two mode shapes of the prediction model without the ice layer under the frequency close to the resonant frequency of actuators and substrate are select and shown in Fig.6. As previously described above, the corresponding structural vibration modes at these two frequencies are all out-of-plane flexural vibration mode.

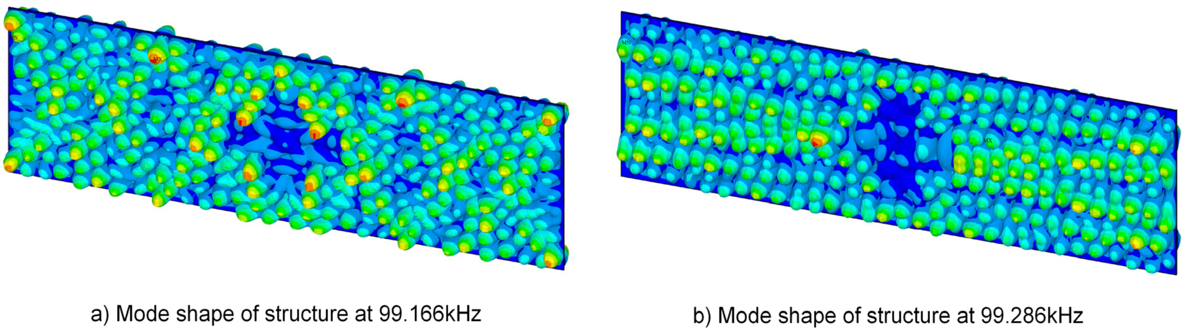


Figure 6 – Two mode shapes of the model under the frequency close to 99.26 kHz.

In addition to the structural resonance consideration, the impedance characteristics of this electromechanical coupling structure need to be evaluated through simulation method, which was the same method used for impedance analysis of piezoelectric actuators. A frequency of 107.24 kHz, corresponding to a point having a maximal admittance and near structural frequencies calculated above, was treated as a target driving frequency.
Therefore, for the de-icing system design method proposed in the paper, a total of five frequencies were involved as the excitation frequency of subsequent de-icing process:

- **Frequency 1**: Resonance frequency of piezoelectric ceramics.
- **Frequency 2**: One natural frequency of the single plate close to Frequency 1.
- **Frequency 3&4**: Two natural frequencies of the electromechanical coupling structure including piezoelectric ceramics and plate, closing to Frequency 1&2.
- **Frequency 5**: One frequency corresponding to a point having a maximal admittance of the electromechanical coupling structure including piezoelectric ceramics and plate, and near Frequency 1&2.

For a plate with the material of glass fiber reinforced composite (GFRP), design method introduced above also can be carried out on this structure. The piezoelectric ceramics of the same size of 20×20×1.5 mm and material type of PZT-8 as the previous section were still selected as the targeted piezoelectric element in the simulation of this section. And the resonance frequency of actuator was set as the input design parameter for the dimension designing of composite plate. And the composite plate was made of five layers of biaxial glass fiber reinforced composite material. So the plate with the size of 300×120×2 mm was designed based on the above design method to match the resonance frequency of the PZT actuators. Five frequencies for excitation purposes were also resolved according to the methods for determining each frequency. The calculation results of the two different structures are summarized as shown in the following Tab.3.

Table 3 – Material parameters of ice and aluminum.

Material of plate	Size of plate /mm	Size of actuators /mm	Frequency /kHz				
			1	2	3	4	5
Aluminum	300×100×1	20×20×1.5	99.260	99.275	99.166	99.286	107.240
GFRP	300×120×2	20×20×1.5	99.260	99.245	99.105	99.241	104.800

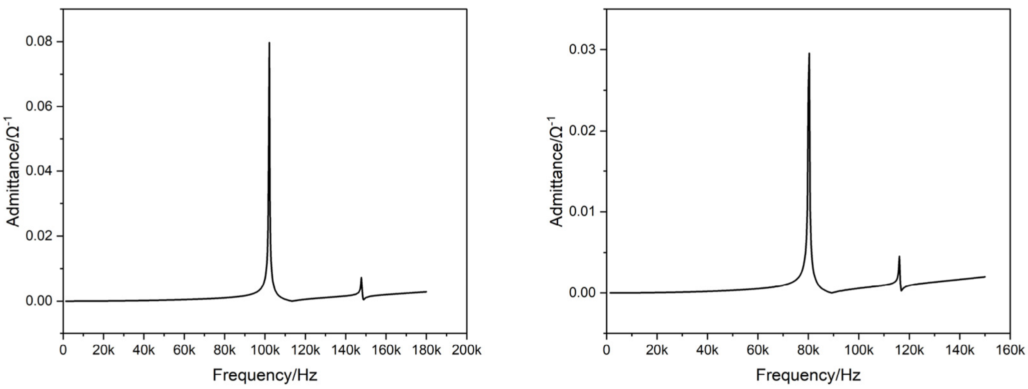
3.3 Numerical Results under the De-icing Target Structure-based Method

When applying the design method on the actual de-icing structure with the unchanged configuration, the resonant frequency should be guaranteed by designing the piezoelectric ceramic, so as to get the desired performance to induce the required vibration and shear stress on the substrate. This method introduced in this paper is called the de-icing target structure-based method.

An aluminum plate with the size of 300×150×1 mm and a composite plate with the dimension of 300×200×2 mm were chosen as the target de-icing structure. All the materials used in this section are all have the same material information exhibited in the above sections. The material of the piezoelectric ceramic remains unchanged, and the corresponding resonance frequency and natural frequency are matched by adjusting the size of the piezoelectric actuators. So the actuators with the size of 19.5×19.5×1 mm and 24.8×24.8×2 mm are determined for metal plate and composite plate respectively. The admittance results of each actuator mentioned above are shown in Fig. 7, and the calculation results of the two different structures are summarized as shown in the following Tab. 4.

Table 4 – Material parameters of ice and aluminum.

Material of plate	Size of plate /mm	Size of actuators /mm	Frequency /kHz				
			1	2	3	4	5
Aluminum	300×150×1	19.5×19.5×1	101.950	101.966	101.834	102.077	112.900
GFRP	300×200×2	24.8×24.8×2	80.342	80.334	80.243	80.507	91.500



a) Actuators with the size of 19.5×19.5×1mm

b) Actuators with the size of 24.8×24.8×2mm

Figure 7 – Admittance results of actuators with the size of 19.5×19.5×1 mm and 24.8×24.8×2 mm.

3.4 De-icing Feasibility Calculation Results

Structure deformation and stress, which are the main factors of mechanical vibration de-icing method, are generated when the voltage is applied on both sides of the piezoelectric ceramics. So feasibility calculations for ice-removal are carried out for each de-icing system designed in section 3.2 and section 3.3 to evaluate the vibration conditions (displacement on the structures) and stress status. Detailed information of different de-icing systems are shown in Tab.5. Simulations of vibration condition without/with 1mm thickness ice-layer attached onto the surface of plate were conducted under five excitation frequencies. Finite element simulation models used in this section are introduced in section 2.3. The voltage applied onto the surface of actuators were 300V for each cases. Clamped boundary conditions were set at four sides of plate, meanwhile free boundary conditions were guaranteed at four edges of ice layer when it exists. Central point of the top surface of plate, which was also the central point of interface between ice and plate, was select as the data extraction point for de-icing evaluation.

Table 5 – Detailed information of different de-icing systems.

De-icing system	Material of plate	Material of actuators	Size of plate /mm	Size of actuators /mm
System 1	Aluminum	PZT-8	300×100×1	20×20×1.5
System 2	GFRP	PZT-8	300×120×2	20×20×1.5
System 3	Aluminum	PZT-8	300×150×1	19.5×19.5×1
System 4	GFRP	PZT-8	300×200×2	24.8×24.8×2

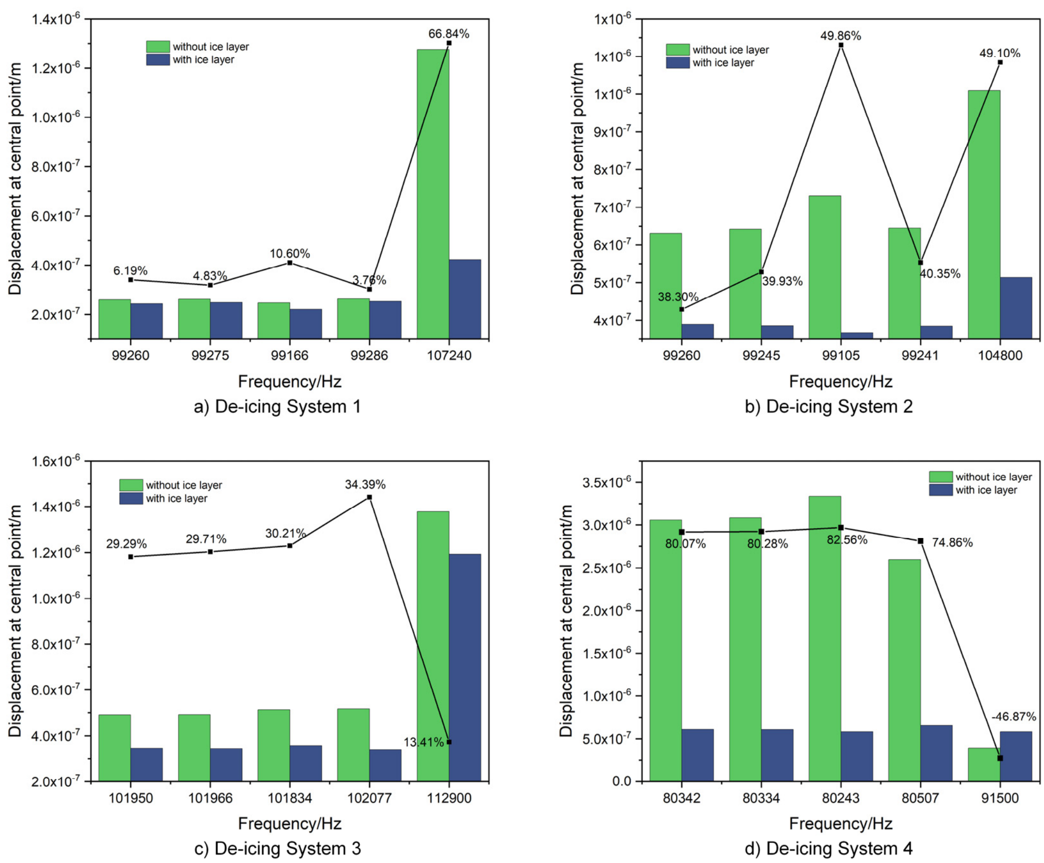


Figure 8 – The displacement under the exciting of different frequencies.

The displacement under the exciting of different frequencies are shown in Fig. 8. Shown that the displacement of the structure is larger at Frequency 5 than that at other four frequencies on system 1-3. This is because, when exciting the structure at the frequency with lower impedance, the coupled system will has a better electromechanical conversion efficiency. That's the reason that many scholars will find the minimum impedance frequency of coupling structures in their studies. But the actual icing state and the ice removing process are difficult to accurately predict, the distribution of ice layers on the actual structure surface is unregulated, so the minimum impedance frequency is hard to be determined for actual de-icing application. Better vibration conditions also be excited when focusing on other four frequencies, and similar vibration amplitude levels provide support for actual de-icing aims by use of frequency sweeping function.

Due to the irregularity of ice-distribution, in this article, the coupled model including plate and actuators was treated as a single electromechanical actuators, as well as the ice layer was considered as the load. So the vibration conditions of the model without ice layer were regarded as the output response of the driver in the no-load state, meanwhile the output response of the actuators in the load state were checked when ice layer appears onto the surface of plate. The attenuation degree of 1mm ice layer on the structure vibration output are also shown in Fig. 8. Shown that maximum attenuation level can be found at different frequencies. This result is also caused by the change of structural impedance characteristics caused by ice. Relatively small attenuation also indicates the feasibility of de-icing at the other four frequencies.

Total shear stress at the interface between ice and plate at central point are shown in Fig. 9(a) and the maximum shear stress obtained with 1mm thickness ice-layer with the voltage of 300V for five exciting frequencies are shown in Fig. 9(b). The results demonstrate that by applying the voltage of 300V, the maximum shear stress obtained with 1mm thickness ice-layer exceeds the required adhesion strength of refrigeration ice (1.7 MPa). This means that the delamination of ice on the plate can be achieved if required power is imposed on actuators under the specific natural frequency of coupled de-icing configuration. Meanwhile, the particular exciting frequency of the whole de-icing structure is near the resonance frequency of piezoelectric ceramic used in this model as the actuators.

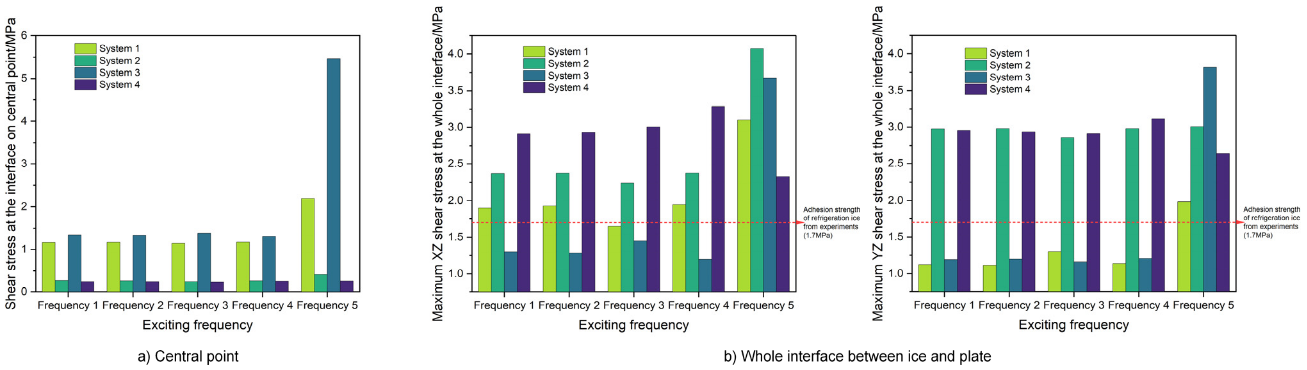


Figure 9 – Shear stress at the interface between ice and plate.

3.5 Experiment Validation

According to the results discussed in above section, designed de-icing system under the piezoelectric actuator based method with aluminum plate was determined as the sample to perform verification experiment in the cold icing laboratory environment discussed in section 2.4. Small refrigerated ice is generated using injectors and pure water. The detailed position of small ice points are marked on the displacement nephogram of the plate and are shown in Fig. 10. The piezoelectric ceramics are excited at the frequency which has been simulated in section 3.2 and 3.3. In order to execute the experimental validation of the de-icing method in the ultrasonic frequency range, the input load power is applied from 0 to 50W. The de-icing results recorded during experiments are shown in Fig. 11 and Tab. 6.

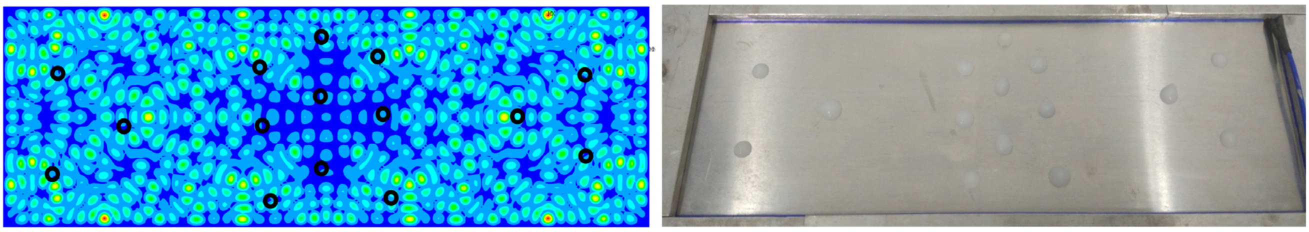


Figure 10 – The detail position of small ice points on the plate.

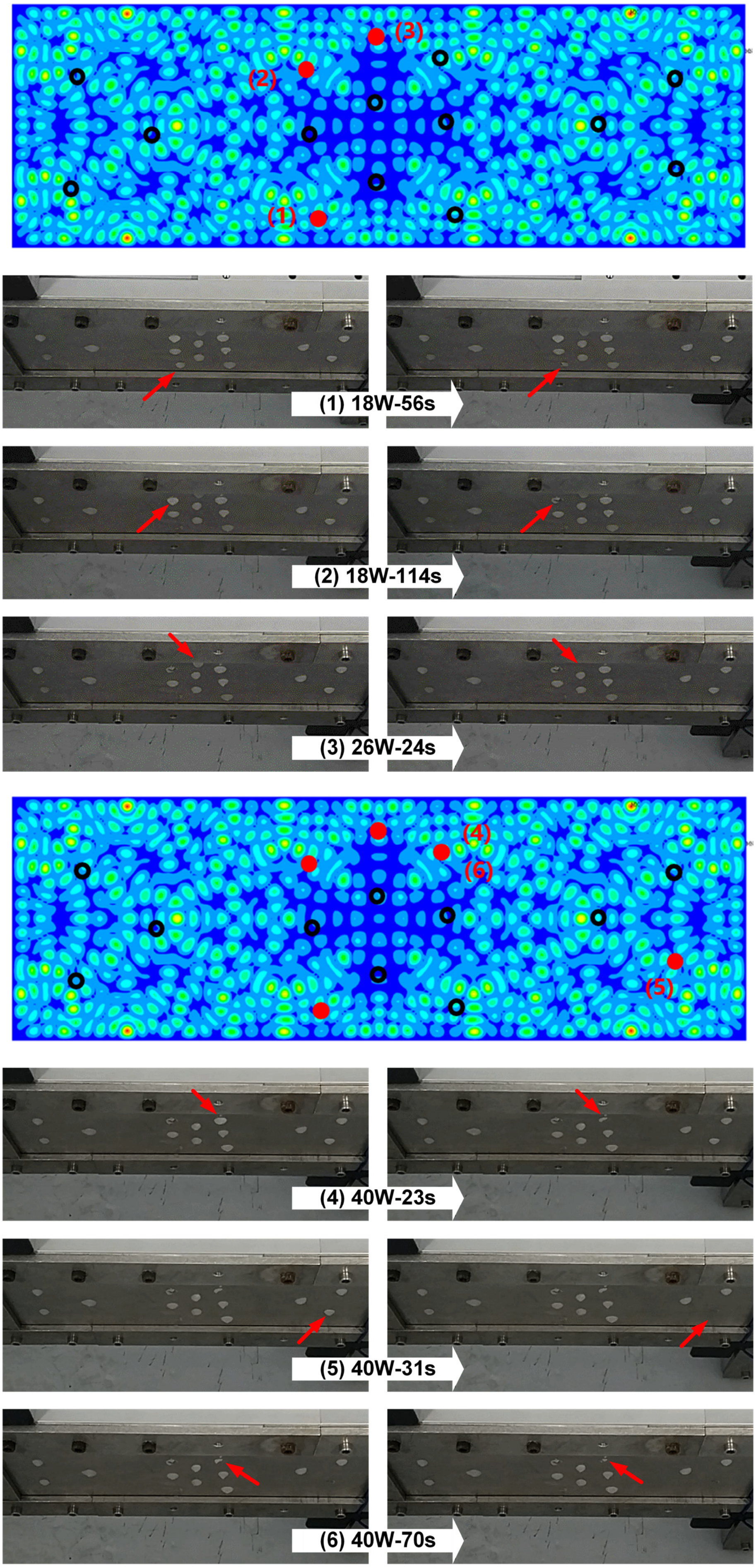


Figure 11 – De-icing results recorded during experiments.

After turning on the excitation source and increasing the input power on actuators, ice points located near the five actuators would be delaminated from the substrate firstly, which can be seen in case 1~4. These points are all bonded at the position with bigger displacement, it also means bigger shear stress at the interface of ice and substrate. This conclusion could be obtained when comparing the displacement nephogram of ice with the shear stress nephogram of ice. Since the larger displacement will cause larger shear stress, stronger vibration and displacement need to be applied to induce bigger shear stress for de-icing purposes. By continually increasing the load power on PZT ceramics, another ice point that away from the area of the actuator is removed (case 5). And the shedding of small pieces of residual ice in the previous ice-removing area also can be seen in case 6. The maximum overall energy utilization for the cases with ice delamination or break (case1-6) is 1.79 W/cm^2, which is 54.1% lower than the thermal method (3.9 W/cm^2) [11].

Table 6 – De-icing results recorded during experiments.

Case ID	Exciting frequency/Hz	Load power /W	De-icing time/s	Energy utilization/ kW·cm^{-2}
1	100	18	56	0.8
2	99	18	114	0.8
3	102	26	24	1.07
4	107	40	23	1.79
5	107	40	31	1.79
6	107	40	70	1.79
7	107	50	300	2.23

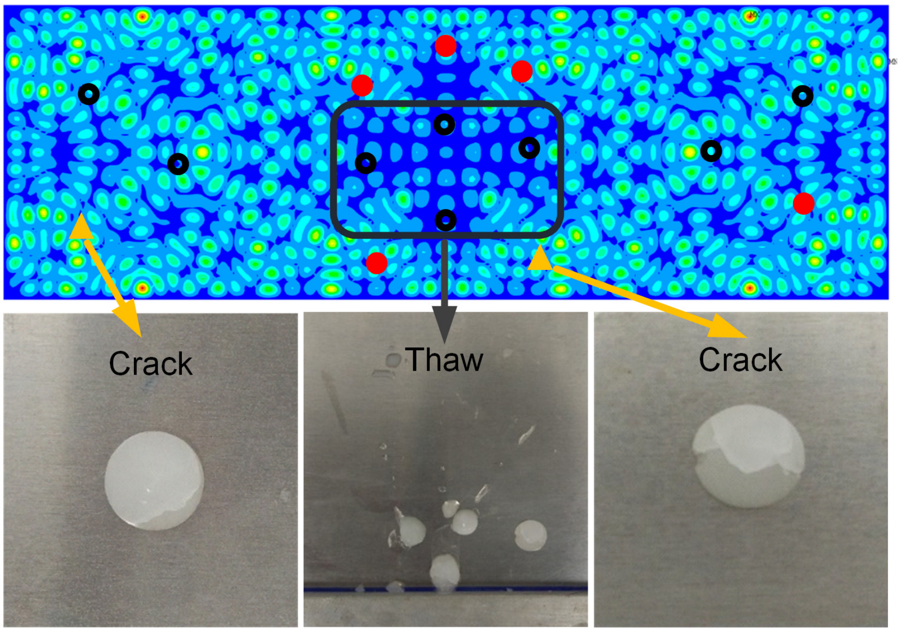


Figure 12 – Cracks and thaw of ice after a long operation time under the power of 50W.

With a longer exciting time as 108s and a higher load power of 50W, ice points located above the actuators are melted due to the heat generated by piezoelectric actuators. Meanwhile, some cracks are observed inside the ice which is not delaminated from the plate. These results are shown in Fig. 12, as the cracks have arisen in certain areas with high major stress and small shear stress. It is worth noting that the heat generated during the experiment is beneficial for de-icing, but also harmful to the functional quality of actuators. Therefore the case of heat produced during the experiment needs further investigation regarding the requirements of actuators lifetime safety and de-icing.

4. Conclusions

Based on the resonance frequency of the piezoelectric ceramics and the resonance vibration of the structure, a detailed design idea and method for the ultrasonic de-icing system designing process are proposed and described in this paper. Detailed numerical and experimental researches are implemented in this work, and satisfactory ice delamination and internal cracks are observed during the experimental investigation, the technical feasibility of this ultrasonic de-icing method is verified. Systematic summary of conclusions described in this article are shown below:

- Matching of the resonance frequency of the piezoelectric actuators and the specific frequency of the base structure is the core focus of this design method. The structural design, material selection, and arrangement design of the related actuators can be studied in more detail based on the core design focus proposed in the paper.
- Five frequencies discussed in this paper all have the abilities to induce ice removing in actual situations. And actual de-icing aims by use of frequency sweeping function is an efficient ice protection method when considering the irregularity of ice-distribution.
- Satisfactory ice delamination and internal cracks are observed during the experimental investigation, the technical feasibility of this ultrasonic de-icing method is verified. Meanwhile, the maximum overall energy utilization for the cases with ice delamination or break is 1.79 W/cm^2, which is 54.1% lower than the thermal method (3.9 W/cm^2).
- When applying this method on the actual de-icing structure with the unchanged configuration, by paying more attention to the piezoelectric material itself as well as the frequency matching between piezoelectric actuator and structure in future studies, the features of the whole dynamic de-icing system, such as the response frequency of the actuator and the damping of the structure, can be fully considered in the de-icing method to achieve the optimal de-icing result with less power consumption as possible.
- Changes in temperature affect the de-icing effect and structural vibration. The temperature rise phenomenon is beneficial to the actual de-icing process but harms the life of the driving ceramics. So further researches are necessary for reasonably managing the heat generated during the de-icing process regarding the lifetime of actuators and de-icing needs, as well as the optimal layout of piezo-actuators to enhance the de-icing effect.

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6. Copyright Issues

7. Archiving

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9. Copyright Statement

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