Numerical Simulation and Experiment of the Piezoelectric De-Icing System

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Keywords: piezoelectric de-icing system; finite elements analysis; de-icing experiment; energy saving

Abstract. An energy-saving de-icing technology of aircrafts with high efficiency and energy saving is discussed, which is based on the inverse piezoelectric effect. The finite elements analysis model of a testing skin is developed to analyze the natural modes and harmonic response by the software ANSYS, which proves the feasibility to remove ice by piezoelectric ceramic actuators in theory. Furthermore, the piezoelectric de-icing experiments are performed, in which the ice can be removed successfully in the voltage 650V and frequency 1530Hz. The technology has notable energy saving effect since the power consumption is no more than 32.5W, which is much less than other electrical de-icing systems. The results show that it is worth doing the research into the piezoelectric de-icing technology for its promising future in the application.

Introduction

Aircraft icing denotes that super cooled water on the aircrafts freezes. Icing will not only increase the weight of the aircraft, but also change the aerodynamic shape of the aircraft, which severely affects the lift generating ability of the aircrafts and results in the resistance increase and stability deterioration [1]. Much de-icing technology has been developed and developing to solve the icing problem. The hot air anti/de-icing system is widely used in aircrafts, but it exhausts large power of engines. The electro-thermal anti/de-icing system requires 26kW, and the electro-impulse de-icing system requires 3kW [2]. Piezoelectric de-icing, a new de-icing technology, recently is proposed to apply to the aircrafts. This system has such characters as simple structure, less energy consumption and convenient maintenance, which indicates good application prospect in the future [3, 4]. Thus, the piezoelectric de-icing system will be studied by numerical simulation and experiments in this paper.

Summary of Piezoelectric De-Icing System

Piezoelectric de-icing system is one of mechanical de-icing systems, which means the ice is moved by eternal mechanical force. However, the tensile force to remove ice adhered on the aircrafts is different from the shear force, because the adhesive tensile strength is larger than the shear strength. That’s to say, it is more effective to use the de-icing methods to destroy the adhesive shear strength of the ice by shear force. The piezoelectric de-icing technology, which is based on the inverse piezoelectric effect, is discussed to generate such shear stress [5, 6].

Finite Element Analysis of the Piezoelectric De-Icing System

The Numerical Simulation of Testing Skin without Piezoelectric Ceramics

The finite element analysis of the piezoelectric de-icing system is performed by the software ANSYS [7], which is verified by the following experiments. The shear stress and the modal modes are calculated of the testing skin model by modal analysis and harmonic analysis. Thus, the position of the piezoelectric ceramics can be determined by the calculated results as well as driving frequency.

The wing of NACA 0030 is used in this work. The model of the wing leading edge is simplified in Fig.1. The length of the wing chord is 0.3m, while the airfoil thickness 0.3m and the skin thickness 2mm. The physical parameters of the skin are as follows. The density of the skin is $2.78\times10^{3}\,kg/m^{3}$, the elastic module is 70.5GPa, and the Poisson's ratio is 0.33. The element type of Solid 45 is used to divide the skin model. The freedom of the nodes on the edge of the testing skin is constrained because the model is simplified as the edge is fixed by other clampers. The modes and the natural frequency are obtained by modal analysis. When the electrical excitation frequency applied to the testing skin is equal to the natural frequency, the amplitude of the vibration of the skin reaches the peak value in theory, which is the key of this experiment to confirm the design driving frequency and installation position of the piezoelectric ceramic. Generally speaking, the higher natural frequency is, the more complex the mode is. However, the energy decays seriously as the frequency increases, so the top 10 modes are calculated. The sixth mode is shown as an example in Fig.2, which illustrates the maximum deformation position. It means that the piezoelectric ceramics can be fixed as x=0.09，y=0.11，z=±0.3 and x=0.18，y=0.148，z=±0.3 in this mode.

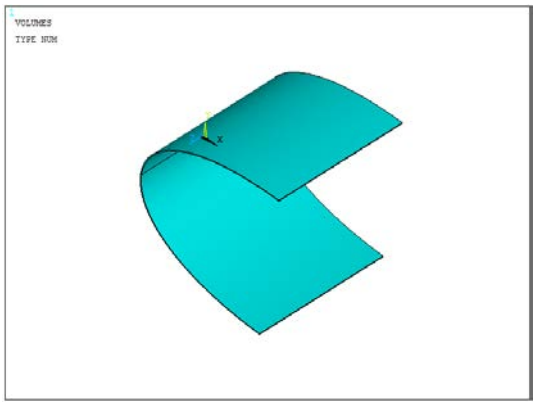

Fig.1 The model of Wing Edge

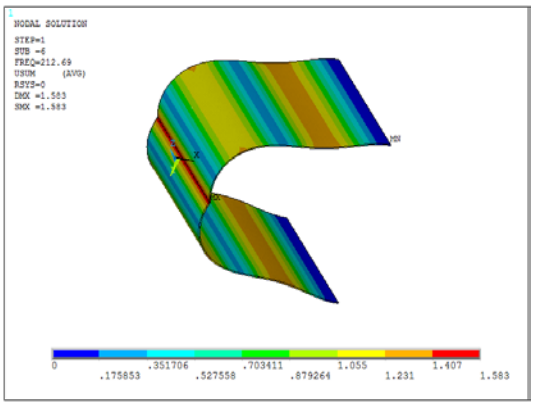

Fig.2 The Sixth Mode of the Wing Edge Model

The Numerical Simulation of Testing Skin with Piezoelectric Ceramics

Two pieces of piezoelectric ceramic are chosen to fix on the testing skin in the maximum deformation as mentioned above. The analysis model of the testing skin with piezoelectric ceramics is developed. The physical parameters of the piezoelectric ceramic are as follows,

$$\rho_P = 7.6\times10^{3}, \qquad \varepsilon^{S} = \begin{bmatrix} 7.9688 & 0 & 0 \\ & 7.9688 & 0 \\ & & 5.3125 \end{bmatrix}\times10^{-9},$$

$$\boldsymbol{c}^{E} = \begin{bmatrix} 14.9 & 8.11 & 8.11 & 0 & 0 & 0 \\ & 14.9 & 8.11 & 0 & 0 & 0 \\ & & 13.2 & 0 & 0 & 0 \\ & & & 3.13 & 0 & 0 \\ & & & & 3.13 & 0 \\ & & & & & 3.4 \end{bmatrix}\times10^{10}, \qquad \boldsymbol{e} = \begin{bmatrix} 0 & 0 & -4.1 \\ 0 & 0 & -4.1 \\ 0 & 0 & 14 \\ 0 & 10.3 & 0 \\ 10.3 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

where ρ_p, ε^S, c^E, e are the density, dielectric constant matrix, elastic coefficient matrix in short circuit, and piezoelectric constant matrix, respectively.

The coupling element type is Solid 5 for the piezoelectric ceramics and Solid 45 for testing skin. The freedom of the nodes on the testing edge is constrained too. However, the deformation position of the testing skin with piezoelectric ceramic differs a little from the skin without those. The position of the ceramics adjusts to the model with ceramics in modal analysis. Thus, the final position is confirmed to fix the piezoelectric drivers. The harmonic analysis is carried out with the frequency from 0 to 6000Hz and the excitation voltage 320V. The nodal stress is obtained in Fig.3 with the natural frequency 1600 Hz in general postprocessor. And response stress varying with

frequency is illustrated in Fig.4 in time postprocessor. If the excitation frequency is 1600 Hz, the maximum stress of the nodes along XZ direction is 3.42MPa, the stress along YZ direction is 3.42MPa, and the stress along XY direction is 4.74MPa. Once the ice adhesive shear strength reaches 2MPa, this force can remove the ice adhered to the skin, which means it is feasible to design this piezoelectric de-icing system as this calculation model [4]. Therefore, the experiment is carried out to verify this calculation.

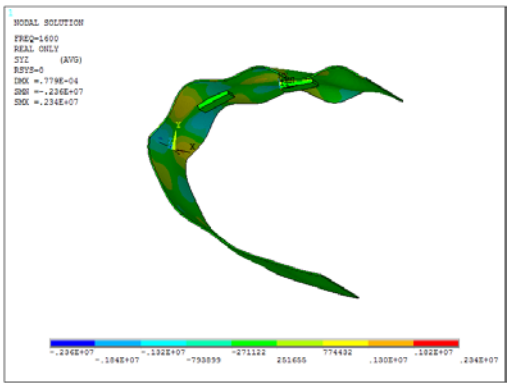

Fig.3 The shear stress along YZ direction in the 1600Hz

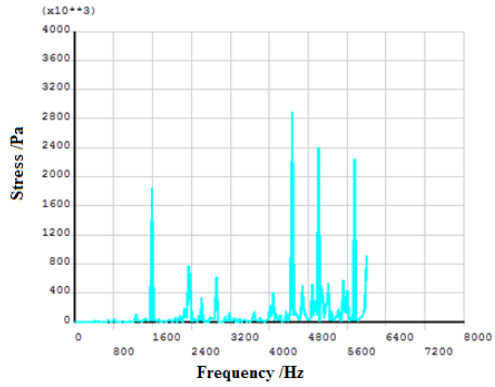

Fig.4 The shear stress vs. frequency along YZ direction

Piezoelectric De-Icing Experiments

Experimental Equipment

The testing skin with piezoelectric ceramics is fabricated as below. The signal generator, power amplifier, piezoelectric sensor, oscilloscope and refrigerator are required to this de-icing system. Firstly, the water is prayed on the testing skin which is put in the refrigerator in the temperature -15 centigrade degree. The discharge circuit is connected to the signal generator which is to generate the sinuous signals with excitation frequency. The signal is amplified by the power amplifier up to 1000 V. When the ice is prepared, the circuit is excited to piezoelectric ceramics. The piezoelectric sensor and the oscilloscope record the de-icing frequency and the vibration amplitude.

Experimental Results

Firstly, testing skin without ice is excited by the input voltage. The resonance frequencies can be read from the oscilloscope by comparing waveforms. The vibration amplitude can reach peak values when the excitation frequency is 1530Hz, 4320Hz, 4830Hz, 5920Hz, respectively. Then, de-icing experiment is performed in the refrigerator. Water is prayed on the testing skin to freeze. The ice can successfully be removed with the discharge voltage 650V and the peak current 0.1A in Fig.5. Compared with the calculation frequency 1600Hz, the relative error is less than 10%. Meanwhile, the power exhaust is no more than 32.5W, which is far from that of the electro-thermal de-icing system and electro-impulse de-icing system.

a. Before de-icing b. After de-icing

Fig.5 Piezoelectric de-icing experiment

Conclusion

The feasibility of the piezoelectric de-icing technology is intensively discussed by numerical analysis and experiments. The ice can be successfully removed in driving voltage 650V and excitation frequency 1530Hz which agrees well with the calculated results. From this study, this de-icing system shows the advantages as simply structure, low energy consumption, less noise, good maintenance, etc. With the high demand of low energy consumption, light weight and no pollution of the aircrafts, this technology will broadcast widely in the future, which also be applied to de-icing of wind turbine and dust removal.

Acknowledgment

This research is funded by College Students Innovation Project of Shanghai University of Engineering Science.

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