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Sine-Sweep actuation of piezoceramic patches in deicing aircraft wing leading edge

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Abstract - **The work reported in this paper presents experimental research on sine sweep frequency-controlled Lead Zirconate Titanate (PZT) piezoceramic patches to de-ice a typical leading edge of an aircraft wing. The PZTs are excited in d_{31} mode to induce vibration so that induced out-of-plane shear stresses to shear off the deposited ice. The modular concept of leading-edge curved profile in the aircraft wings between the cross ribs can be effectively utilized to implement this electromechanical excitation for de-icing. Experimental vibratory deicing is effective at resonance frequencies first at twist (torsion modes) and subsequently at bending modes. This process ensures higher out-of-plane shear stresses that are more than the adhesive shear strength of ice on an aluminum surface typically 1.5 MPa. An innovative new concept of Sine sweep frequency-controlled excitation method is found to be the best since it excites the bending and twist modes and takes care of the time variant aircraft wing leading edge with ice. The ratio of area of PZT to total wing area is only 1.8%. The power consumed by this electromechanical excitation is of the order of 0.35 kW/m^2 in comparison to 10 kW/m^2 deicing by Electro-Thermal method. This method is also environment compatible in contrast to the conventional chemical method that contaminates the ground water. The results indicate a possibility of potential applications of the PZTs in deicing as they can be used both as ice thickness detecting sensors as well as actuators for deicing.**

***Index Terms*:** Deicing, PZT, wing leading edge, shear mode, electromechanical frequency-controlled vibration.

INTRODUCTION

Airplane's performance is severely affected by the variation in lift characteristics at the leading edge. The ice deposited on the leading edge degrades lift generating capability. Ice deposited near the leading edge of an aircraft wing (stagnation point.) changes the profile of upper surface and lower surface, thus seriously affecting the lift-to drag ratio performance characteristics. Pneumatic de-icing, Electro thermal de-icing, chemical methods [1], electro-vibratory de-icing [2,3] and anti-icing [6,10] are currently used for de-icing as various options. Anti-icing as well as de-icing with chemical liquids seriously affect the aircraft performance, as the coating may shear off at speeds higher Mach numbers of 0.3. Chemical methods [1] used for de-icing seeps into ground water that can possibly contaminate the drinking water. The power consumed by Electro-thermal de-icing is of the order about of 40 kW leading to high power consumption. Pneumatic bladders also consume same levels of power. The adhesive shear strength of ice is found to be the critical parameter in electro-mechanical deicing techniques and effective implementations. Ice thickness, temperature of substrate material in addition to the adhesive shear strength of ice is a parameter that needs to be considered during selection of electromechanical deicing methods. The de bond stress greater than Aluminum-ice adhesive bond shear strength (1.5 MPa) can be achieved by PZT. The ice alone tensile strength of varies between 8 MPa to 10 MPa that depends on the ambient temperatures which is an order higher than the ice-Aluminum interface bond strength. The advancement in De-icing techniques [8,9] emphasize the application of various techniques including thermal, vibration and chemical methods. The PZT patches are used to excite the structures in ultrasonic frequency for de-icing [7]. The piezoceramic patches can be used for actuation [4,5] of structures both in axial, bending and torsional vibration modes. The excitations generated by the PZTs can induce higher shear stress that can de bond the ice layer from the substrate. In this paper, PZT patches are used to demonstrate experimentally the de-icing capabilities in the shear (torsion) and bending modes of the leading edge of an aircraft wing.

EXPERIMENTAL STUDIES

Figure 1 shows a typical aircraft leading edge segment. The wingspan length of 1050 mm with chord width of 1000m confirming to NACA0020 with Aluminum alloy material is used. The modular span of each segment is about 350mm. The thickness of the aero foil was chosen as 1.1 mm. PZT-5H (Sparkler Ceramics, Pune, India) patches of dimensions 50mm X 50mm X 0.5mm and 50mmx25mmx0.5mm were spaced equally and located closer to the leading edge near the least curvature region for the numerical study. There were two sets of PZT patches mounted on the underside of the suction and pressure surfaces as shown in Figure 2.

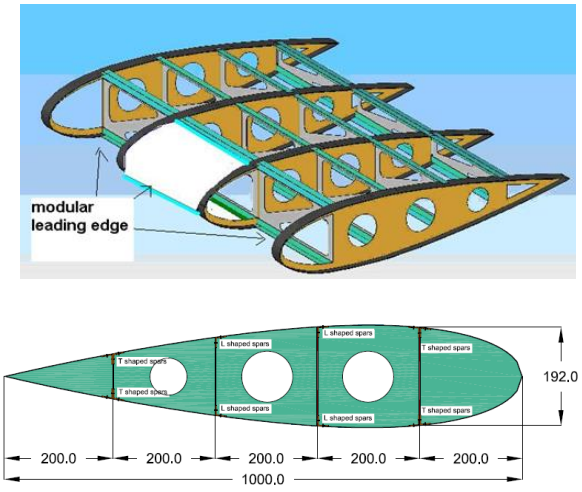


Figure 1: Modular airfoil leading edge



Figure 2 : Aircraft Leading edge module with PZT piezoceramic patches.

The piezoceramic patches need to excite the relevant modes (bending, twisting/torsion) to break the ice bond efficiently with least power consumption as compared to other existing techniques. An experimental study is performed with the ice thickness of 3mm. The shear modes that have sufficient energy to break the ice can be used for de-icing as the ice is weak in tension and shear.

The dynamic charactistics along with natural frequencies of the modular leading edge of the airfoil were measured using expermiental modal enalysis (EMA) as shown in Figure 3. Instrumented impulse hammer PCB (Piezotronics, USA) 086 C03, PCB acclerometer 352A21 in association with conditioning amplifier PCB-480A and National Instruments NI-6009 DAQ system were used to obtain the time response and frequency response function (FRF) of the leading edge module as shown in Figures 4 and 5 respectively. The high ampitude associated natural frequencies of the local modes of the leading edge 132.18Hz, 416.56 Hz 701.56 Hz, 740.6 Hz, 904.37Hz, 1329.69 Hz will be useful in deicing with sinesweep excitation of PZT patches. There will be minor shift in these natural frequencies due to the mass effect of 3mm ice layer as the system becomes time variant with reference to dynamic characteristics of the global modes and local modes of the aircraft wing and leading edge module respectively.

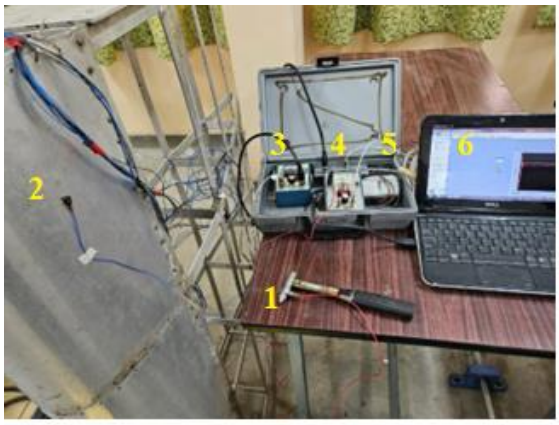


Figure 3: Experimental modal analysis measurement set up (*1: Impulse hammer, 2: Accelerometer, 3: Charge amplifier , 4: Condition Amplfier, 5: DAQ system, 6: NI-LabView Interface***)**

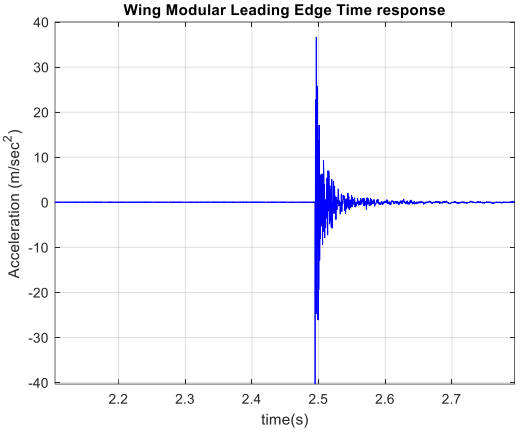


Figure 4: . Time Response at Leading edge of the airfoil wing model.

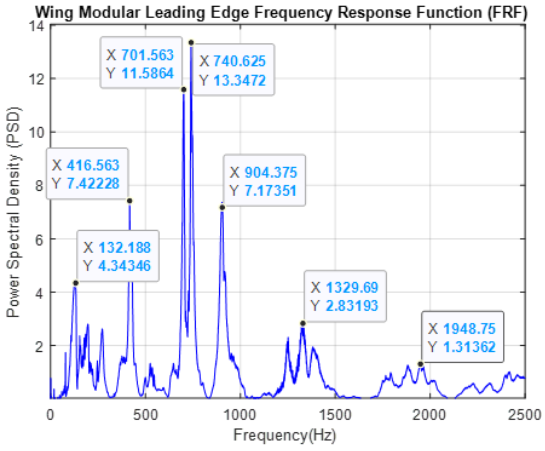


Figure 5: . Time Frequency Response Functiom (FRF) at Leading edge of the airfoil wing model.

The modular leading edges are fixed in between the cross ribs of the aircraft wing. The model mount positions in the freezer box (5'x5x'3') are shown schematically in the Figure 6.

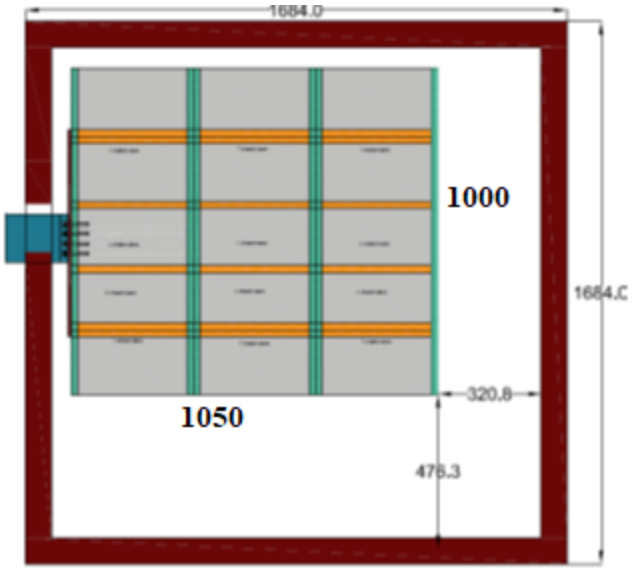


Figure 6: NACA-0020 airfoil and wing in deice chamber (dimensions in mm)

The temperature of -20 degree Celsius is constantly maintained the deep-freezer. The temperature of the wing surface area was always measured using a thermocouple. Cooled water was sprayed on the wing surface. Blue coloring pigment has been added to distinguish water with base Aluminium substrate. The sprayer nozzle was directed horizontal to the wing leading edge as shown in the Figure 7. An ice thickness less than 1.5mm cannot be removed with optimal power ratio from PZT actuation. Typical ice thickness of 3mm is the threshold where the conventional de-icing systems gets activated. Hence, an ice thickness of 3 mm was achieved by cumulative five sprays in a span of every 2 minutes. Ice thickness greater than 3mm is advantageous to be easily removed due to inertia effect of the deposited ice under vibration.



Figure 7: water spray for ice formation (ICE spray process - https://youtu.be/CgEasGLG16M)

The PZT power amplifiers and the signal generator are used to actuate the PZT patches with voltage of 100V and the details are shown in Figure 8. The out of plane shear stresses developed at the leading-edge help to de-ice.

A sine-sweep frequency controlled wave signal in the range 50-2000 Hz as observed in the FRF (Figure 5) was fed to PZT amplifier with actuation voltage of 100V. The sine sweep control of frequency is most necessary as the dynamic characteristics of the leading edge are time variant as the de bonded ice changes the modal parameters specifically Natural frequencies and the associated ice-Aluminium shear and de bond stresses due to mass change from de-icing.



Figure 8 : Deicing Chamber with Instruments

RESULTS AND DISCUSSIONS

Thus, piezo actuated vibration of leading edge base substrate with the resonance frequencies in bending , shear (twist) modes (50-2000 Hz, sine sweep excitation) create out-plane shear stresses that are greater than the adhesive shear strength of ice will help to break the ice-Aluminium substrate interface. As the ice de-bonds from Aluminium substrate the mass effect of 3mm ice gets reduced with marginal increase in the natural frequencies, however the sine sweep actuation of PZTs will actively take care of de-icing which will be advantageous in time variant system. In the first 90 seconds the de-bond stresses build up to reach the maximum stresses to de-ice.

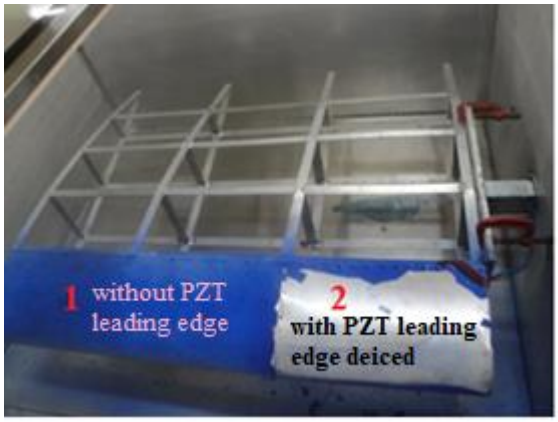


Figure 9. Deiced wing model leading edge (Leading Edge de-icing Process - https://youtu.be/N1r5dnHtW7s)

The de-bond stress developed during the process between 90-240 seconds initiates microcracks. The de-icing process took about 240 seconds as shown in the Figure 9 also can be observed in the video link provided. The de-ice time can be reduced with increased voltage to 200V maximum. The local shear modes of the leading edge initiate cracks and the bending modes dislodge the ice from the surface. In actual aircraft the global modes of the wing (bending and twisting) associated with airflow will further reduce the time to de-ice. The residual ice at the junctions of the edges at the support of cross ribs will not seriously affect the lift characteristics of the wing.

CONCLUSIONS

The piezocermaic (PZT) patches can be effectively used to deice the leading edge of the aircraft wings. The higher strain zones of a particular mode (bending or twist/shear) can be used to create high substrate ice bond stresses (σ_{xz}, σ_{yz}) so that deicing can be successfully achieved. the local modes of the leading edge particularly shear modes were found to be effective in deicing. The leading edges are modular in construction and can accommodate the PZTs. The local modes of the leading edge in the range 50Hz-2000Hz efectively help to deice. The leading edge of the wing is under vibration for a duration less than 240 seconds will not influence any of the subsystems of the aircraft wing. The fatigue induced stresses at the leading edges are not a concern as the stress to remove ice is of the order of 1.5 MPa which is very much lower than the yield strength of the Aluminum substrate. The weight of PZT patches is 140gm/m of leading edge , area of PZT/total wing area being 1.8% and the power consumed 0.35 kW/m^2, in comparision to 10 kW/m^2 by Electro-Thermal methods. The studies reported in this experiment are with refrigerated ice which has ice-Aluminum interface bond stress of the order 1.5 MPa as compared to 1 MPa for the naturally accredited ice formed in actual environment. Thus the power consumed for the practical applications in actual aircrafts will be still lesser in comparison to laboratory demonstrated leading edge of aircraft wing with refrigeratd ice. The PZTs will have difficulty to remove ice from steel surface as the Young's modulus of Steel is almost three times as that of PZT affecting the actuation authority.

The sucessful demonstration of sine-sweep excited PZTs to de-ice the leading edge of the aircraft wing has potential practical applications as it consumes less power and envornment friendly.

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