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LIPCA in the Development of Shape Changing Aerial Vehicle

MdRejwanul Haque[1], Bodiuzzaman Jony[2], Md. Mobassir Hossain[3], Debanan Bhadra[4], Kh. Nusaiba Hafiz[5], Md. Abdus Salam[6]
[1-6]Aeronautical Engineering Department, MIST, Bangladesh.
E-mail:rejwan.xy@gmail.com[1], jonyzaman08@gmail.com[2], irtezarahman@yahoo.com[3], diptotheone@gmail.com[4], nusaibasnigdha@gmail.com[5], head@ae.mist.ac.bd[6]

Abstract

The Light Weight Piezo-Composite Curved Actuator (LIPCA) is a smart material having one or more properties that can be altered by an external stimulus in order to meet specific requirements or conditions. Now-a-days, properties of smart materials especially Piezo Composite Materials are extensively used in the aerospace industry to overcome various constraints, especially to develop shape changing aerial vehicle.A piezoelectric stack actuator is assembled using multiple layers ofpiezoelectric materials which are placed in series and wired in parallel. Piezoelectric stack actuators have been widely usedin many applications ranging from fuel injection systemsto vibration cancellation in disk drives. Aside from being compact insize, they are capable of nanometer resolution in displacement, have high stiffness, provide excellent operating bandwidth and high force output. Application of voltage regulates the shape changing i.e. whether the actuator should expand or contract.This shape changing technology mostly known as morphing wing and flapping wing technologies provide expanded functionality in piloted and robotic aircraft providing various mission requirements as well as increasing the role of aviation in both military and civilian applications. This study will provide a thorough analysis of how LIPCA can be used in the development of shape changing aerial vehicle and finally demonstrates the development of morphing wings.

Keywords: PZT actuators, LIPCA, Wing Morphing.

1. Introduction

Smart materials are used vastly now a days. With the advancement of the material science it is becoming very possible now to apply the mechanism of smart materials such as LIPCA in various aspects like aerial vehicle. With the help of the LIPCA morphing wings can be developed which can be referred as the next generation of wings and aerial vehicle. In recent years, considerable interest has directed toward application of smart (adaptive) structures to control the static and dynamic responses for rotary and fixed wing aircraft. In this paper, the particulars of morphing wing and Piezo Electric (PZT) actuators are provided. This paperreveals background study of morphing wing on section 2, review of morphing wing technology on section 3, review of PZT on section 4, composite plate using embedded PZT on section 5, morphing wing using LIPCAis proposed on section 6, a brief study of LIPCA application is described on section 7, a brief of shape changing tailing boundaries on section 8, estimation of actuation displacement in section 9 and conclusion on section 10.

2. Background study of morphing wing

The idea of seamless wing morphing was not widely investigated without advance materials and computer technology made seamless variable wing geometry a possibility until the 21st century. The primitive idea of morphing wing came from the idea of Wing Warping called a technique for roll (rotation around the aircraft's longitudinal axis) controlled by many early aircraft, which was first used and planned the Wright brothers.The technique was a system of pulleys and cables to rotate the trailing edges of the wings in opposite directions. This approach is similar to that used to trim the performance of a paper airplane by curling the paper at the back of its wings [1].From bird the initial motivation for modern wing morphing came largely from, such as the swift, which shapes birds wings according to the present phase of flight. According to the 'Defense Advanced Research Projects Agency' a morphing aircraft to be an 'adaptable, time variant airframe, whose changes in geometry influence aerodynamic performance'[2]. Present day's aircrafts incorporate features which significantly change the geometry of the wings to influence their aerodynamic properties, namely flaps and slats. The big challenge for wing morphing is the choice of material for the wing skin for an aircraft with which is more complex than that for aircraft with rigid wings, due to the need for the material which can stretch elastically in multiple directions. From tests we observed thermoplastic polyurethanes and copolyester elastomers performed better than woven materials, requiring less force and being able to exhibit greater strain without permanent deformation, making them ideal materials for using them to wing morphing[3].Materials such as shape memory alloys, shape memory polymers and piezo crystals are just some of the materials that can be used as actuators in shape changing materials [4].They possess a different blend of actuation stress, strain and speed, and depending on the application some will be more suited than others. The Primitive advantage of a morphing platform would be the increased cost effectiveness of aircraft through eliminating the need for multiple, expensive, mission specific aircraft.

3. Review of wing morphing technology

A number of different methods of actuation can be utilized for 'morphing' morphing wings, be they hydraulic, pneumatic or electric. Another alternative, and one that has become increasingly popular given the desire for simplicity in order to minimize costs, weight and space taken up by the actuator, is the use of a Shape Memory Alloy (SMA), or Smart Alloy. An ideal example of such a material is LIPCA, a memory alloy which displays a piezoelectric effect (an electric current induced will cause a change in shape and vice versa). PZT has a further benefit of being very fast to react to an induced current, allowing very quick precise actuation, an absolute must in the world of aircraft control [5].

4. A Review of PZT

Piezo-actuators like stacks, benders, tubes, rings make use of the deformation of electro-active PZT-ceramics which are ferroelectric in nature when an electric field is applied. This deformation can be used to produce motions and forces. PZT stands for lead (Pb) zirconium (Zr) Titanate (Ti) [6]. Piezo actuators were used before specially for the purpose of quasi-static precision positioning but it has developed an interest in the field of smart materials.In the piezoelectric effect, electro-mechanical interactions and the conversion of energy take place. It relates the electric field to the mechanical deformation in the piezo electric material. Piezoelectric ceramic materials are polar materials. The ceramic contains net external electric dipole moment which are the outcome of the arrangement of electric dipoles inside the crystal[7]. Without an applied electric field the individual electric dipoles in the ceramic material become casually positioned in the shown in Fig. 1. At this condition this material gets un-polarized and gradually it turns to para electric in nature. The specialty of piezo electricity becomes absent as a result of that.

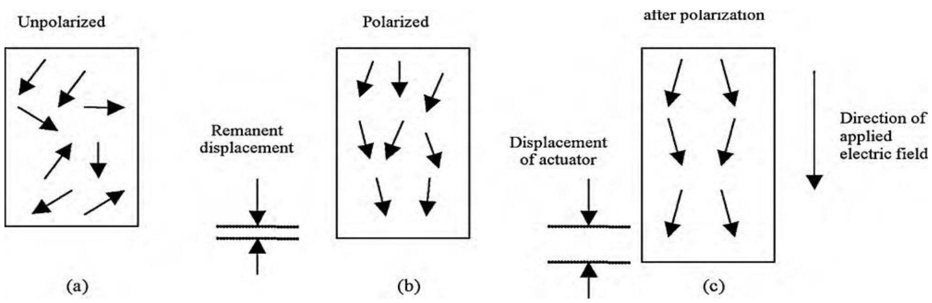


Fig. 1. Behavior of PZT

When an electric field is applied to the ceramic material the electric dipoles become arranged close to the applied electric field. As a result polarization takes place and it is shown is Fig. 1. (b). When the applied electric field is removed there will be some remnant displacement. As a result when the electric field is applied again, the ceramic material as well as the actuator extends. It is shown in fig 1(c)[7].A PZT actuator can be driving using voltage, charge, capacitor insertion. But there is a problem regarding hysteresis and creep. Hysteresis is the reason of the polarization of microscopic particles [7, 8]. Creep occurs when the remnant polarization continues to change after the applied signal reaches its final value[9]. To avoid the hysteresis there are three processes.

(a) Voltage driving method:It is simple but it is less efficient for the disadvantages of hysteresis and creep. This causes precise positioning when the actuator is used [12].Using the voltage driving method, the Tokin model AE0505D16 piezoelectric stack actuator was experimented by a 10 Hz, 0-100 v sine wave input. A large amount of hysteresis was noticed [7]. Hysteresis can be reduced by operating a piezo electric actuator by keeping the amplitude and frequency of the applied voltage constant and very small [11]. However it creates the lack of actuators efficiency of deformation over a long range. Creep hampers the positioning of an actuator. A lesscreepcurve

wasobtainedbydrivingaTokinmodelAE0505D16piezoelectricstackactuatorusinga100Vstepinput.Thestepinputwasappliedat10s [7].
(b) Charge driven:A charge input to drive the actuator is used to reduce the effects of hysteresis. Jouaneh [8, 13], Newcomb [7, 14] and Comstock [15] had implemented this. An experiment was conducted using Tokin model AE0505D16 piezoelectric stack actuator was experimented by a 10 Hz, 0-100 V sine wave input and almost linear graph was observed [7].
(c) Capacitor insertion method:It is a better process and more efficient. In this state, capacitors in series are connected with piezoelectric actuators [16, 17]. An experiment of capacitor insertion method using Tokin model AE0505D16 piezoelectric stack actuator was conducted [7] and the results are observed. There is little hysteresis in this process. However, Bazghaleh [10, 18] proposedthe digital charge amplifier increases accuracy by reducing hysteresis. It consists of a voltage amplifier, digital to analog converter (DAC), analog to digital converter (ADC) and digital signal processor (DSP).

5. Composite plate with embedded PZT actuators

A simply supported composite plate can be composed of [0/90/0]S graphite/epoxy layers with PZT actuators placed at the top and bottom surfaces of the plate. The poling directions of the two PZT wafers are opposite, so that the plate can produce a bending moment [19]. An experiment conducted by Sahng Min Lim shows that if 200 N m−2 pressure is over the plate and an electric field is applied such that the plate recovers its original shape. The dimension of the composite plate was 0.254 m×0.254 m, with the thickness of the PZT layer at 0.254 mm. The thickness of each graphite/epoxy layer is 0.138 mm. Material properties of the graphite/epoxy are summarized in table-1.

Table 1. Material properties

Properties	PZT G1195 Piezoceramic	T300/976 Graphite/epoxy
$\boldsymbol{E_{11}}$(GPa)	63	150
$\boldsymbol{E_{22}}$(GPa)	63	9
$\boldsymbol{v_{12}}$(GPa)	0.3	0.3
$\boldsymbol{G_{12}}$(GPa)	24.2	7.1
$\boldsymbol{d_{31}(10^{-10}\ m\ V^{-1}})$	2.54	0
$\boldsymbol{d_{31}(10^{-10}\ m\ V^{-1}})$	2.54	0

The equivalent coefficient of thermal expansion (CTE)s are calculated from Thermal analogy [20].Fig. 2.shows the deformed shapes of the composite plate after applying 200 N m−2 pressures over the plate and applying 15 or 27 V to the PZT layers. Fig. 5.shows the displacement of the plate along its centerline for 0, 15, and 27 V after applying the pressure.

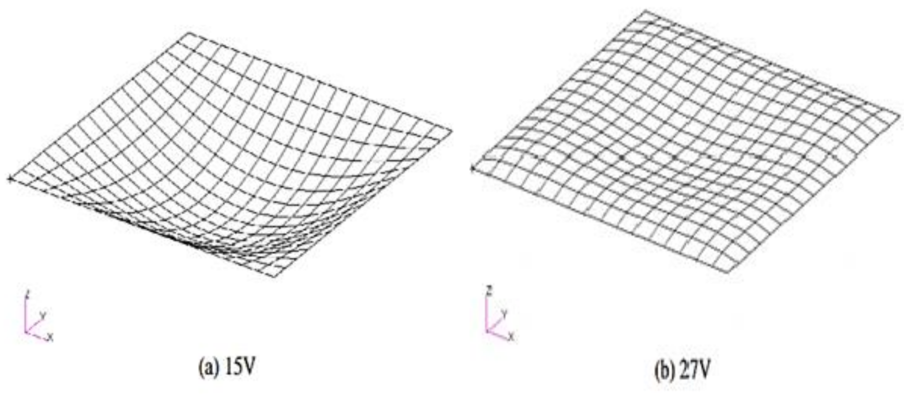


Fig. 2. Deformed shape of a composite plate.

In Fig. 3. 'Ritz solution' represents the result given in [21], where the displacement is calculated by using the shallow shell theory and the Ritz method. The numerical test above has confirmed that the thermal analogy works very well, especially when the coupling effect is relatively weak as it is found in thin PZT wafers.

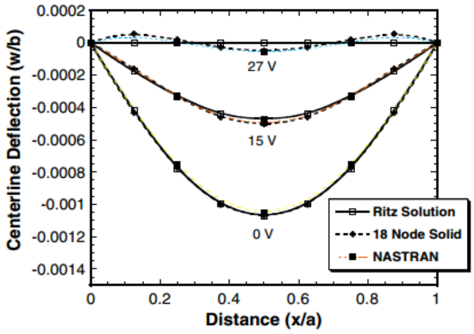


Fig. 3. Deflection of a simply supported composite plate along the centerline

6. Morphing wing using PZT

Deformation or shape change shown in Fig. 4. ofa piezoceramic actuator can be measured by using the linear elastic thermal analogy [20].

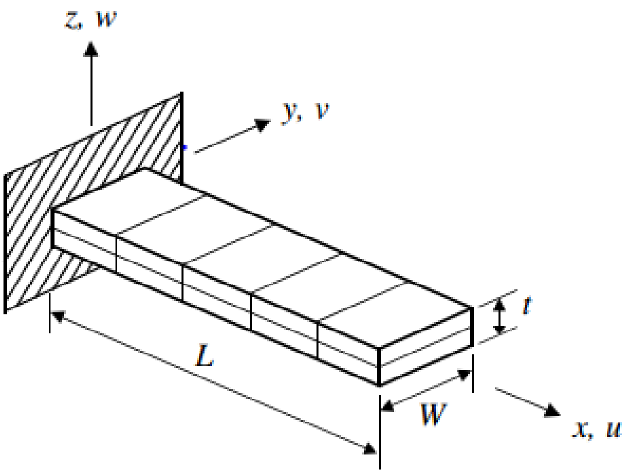


Fig. 4. Deformation principle of a PZT used Beam

Thermally induced strain upon the beam can be denoted by $\varepsilon = \alpha\ \Delta T$. Here, α is the (CTE) and ΔT is the temperature difference. The piezoelectric strain in the longitudinal in-plane direction (ε_1^p) which is induced by the given electric field along the thickness direction is given as in (1).

$$\varepsilon_1^p = d_{31}\frac{\Delta V}{t} \tag{1}$$

Where, d_{31} is the piezoelectric strain constant, ΔV is the electric potential, and t is the thickness of a piezo-electric layer. When this strain is equivalently merged by the piezoelectric strain.

7. Study of LIPCA material application for wing section

In this section, the design of wing sections with deformable trailing edges actuated by LIPCA-C2 actuators is explained. The deformed shapes of the biomimetic wing sections are numerically estimated by the thermal analogy explained in the previous section. For convenience of modeling and analysis, commercial finite element modeling/analysis software,NASTRAN [22], are used for modeling the structure and its finite element analysis, respectively.

8. Shape changing tailing boundaries

Since the deformation of the wing sections is produced by deflection of the trailing edges, only the rear parts of the wing sections are designed for numerical analysis [19]. Fig.5.shows the LIPCA-C2 actuator and the trailing edge with two LIPCAs (colored grey) at the upper and lower surfaces with a span of 150 mm, which has been named ‘KKU-1’.

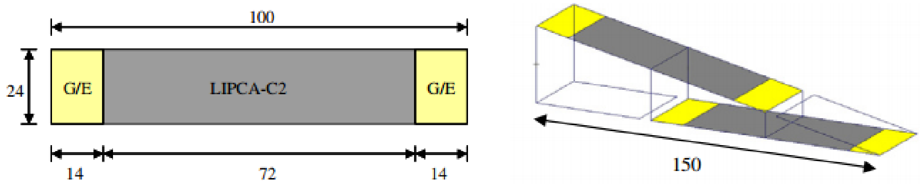


Fig. 5. LIPCA-C2 and a trailing edge of a wing

It is observed that the actuators are placed in parallel. Fig.6. shows LIPCA-C2s attached in series with a span of 245 mm to form the upper skin structure of the trailing edge of the wing. The serial LIPCA-C2 is co-cured in the autoclave during manufacturing of LIPCAs.

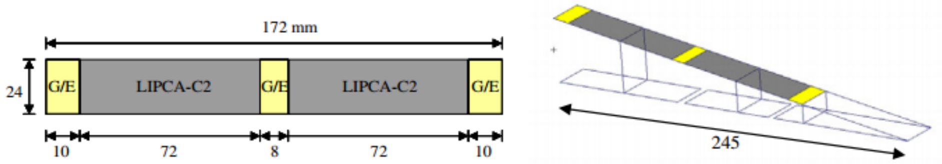
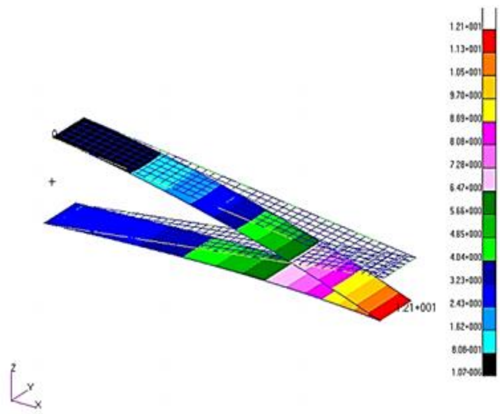


Fig. 6. LIPCA-C2 in series and trailing edge of the wing.

9. Estimation of actuation displacement

In all cases, the fixed boundary condition is applied for the finite element analysis at the far left top end and the sliding hinge condition at the far left bottom end. 'Effective Actuation' is the tip deflection over the length of the deformable portion of the wing section [23]. It has been observed that the actuation displacement of the wing for 170 V numerically analyzed quite close to that of the experimental. Due to the material nonlinearity of the PZT wafer in LIPCA actuators, we expected more actuation displacement than the estimated value for the same input voltage in the real actuation test as shown in Fig. 7.



(a) KKU-BW1

Fig. 7. Actuation Displacement of wing section

10. Conclusion

The following data has been observed from the experiments [19]. For LIPCA with actuators in parallel the effective actuation is 2.56/150 = 0.0171 when 100 V is applied and the effective actuation is 4.38/150 = 0.0292 when 170 V is applied. For LIPCA with actuators in series the effective actuation is 7.01/245 = 0.0286 when 100 V is applied and the effective actuation is 11.92/245 = 0.0487 when 170 V is applied. Here the effective actuation is implied by the ratio of tip displacement to the length of the deformable part. Using LIPCA the aerofoil shape can be changed. As a result the wing shape can also be changed. So different mission requirements can be fulfilled by the same wing which would be a great achievement. Our investigation of morphing was limited to the wing surface only. But morphing might also be implemented on fuselage as well as on the other parts of the aircraft, which needs further investigation.Besides, behavior of proposed smart materials in case of large scale aircraft is not yet been studied. However, all the theoretical aspects and experimental data suggests that PZT especially LIPCA can play a colossal role in the wing morphing technology.

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