PIEZOELECTRIC BASED ADAPTIVE WING FOR FLOW CONTROL

S. Sathyamoorthy*, S. Raja** and A. Joseph Stanley+

Abstract

An attempt is made to develop a piezoelectric based adaptive wing concept that can be used in Micro Air Vehicle (MAV) and Unmanned Air Vehicle (UAV) applications. Laminar boundary layer separation is considered to be a significant problem in low Reynolds number vehicles like MAV. Recently, periodic excitation has gained much interest in the control of flow separation through energizing the boundary layer. In the present study, a piezoelectric bimorph actuator has been used to develop a mechanism that will deflect or vibrate a segment of the wing to produce the required thickness variation and achieve flow control. A Finite Element model of the adaptive wing is developed in ANSYS® and numerical results are compared with experiments. A five percent increase in the camber has resulted in 4.39 percent additional lift at higher angles of attack.

Introduction

Micro Air Vehicles (MAV's) are tiny flying machines that have size around 15 cm, weighing approximately 100g. MAV's in general are expected to fly in the velocity range of 10 to 25 m/s for 30 minutes. Since these vehicles operate in a very low speed regime (low Reynolds number) viscous effect must be a critical issue between conventional aircraft and MAV. Generally an aircraft wing can be optimized for one particular type of flow condition. However, the aerodynamic efficiency depends on the shape of the wing in different flight regimes. Thus, the conventional wing is usually made efficient by introducing flaps, leading edge slots and other control surfaces. In contrast, an adaptive wing can be made flexible to change its shape during flight such that the aerodynamic efficiency is improved in all flight regimes.

Ever since its discovery by Prandal the boundary layer effect has been the main focus for scientists and engineers around the world. There has been a tremendous attempt made to achieve the control of the boundary layer. Since the laminar boundary layer cannot withstand even a small adverse pressure gradient, the flow usually tends to separate [7]. Traditionally the boundary layer is controlled by suction and blowing. However, these techniques are not suited for small scale flying vehicles where weight and energy are two major factors driving these systems.

There are several advantages an adaptive wing can offer.

- Improved aerodynamic efficiency in a variety of flight regimes.
- Better maneuverability
- Enhanced controllability

In the past, many adaptive wings were developed across the world; the classical example was the one employed by Wright brothers, where wing warping was effectively used in controlling the aircraft. Many of the earlier attempts were not successful mainly due to the following reasons.

- Mechanical actuators increased the weight of the aircraft, nullifying the efficiency gained in their use.
- Conventional aircraft wing was designed very stiff; deflecting such a stiff wing consumes energy.

However, smart materials widely available nowadays can be considered as distributed actuators to effectively bend the wings of the MAV's.

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* Research Student + Professor
Department of Aerospace Engineering, Madras Institute of Technology, Anna University, Chromepet, Chennai-600 044, India
** Scientist, Structures Division, National Aerospace Laboratories, Post Box No. 1779, Bangalore-560 017, India
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Problem Definition

Laminar boundary layer separation occurs in the vehicle at low Reynolds number. When the flow is laminar and the boundary layer at the onset of the pressure rise is still laminar. However it cannot withstand any significant adverse pressure gradients. Therefore, the performance of low Reynolds number airfoils is entirely dictated by the relatively poor separation resistance of the laminar boundary layer. When a laminar boundary layer separates, the separated layer very rapidly undergoes transition to become turbulent. However, turbulence may also give opportunity to the flow to get reattached. Therefore by giving a periodic excitation to the top surface of the airfoil, the flow can be agitated to turbulence even at low Reynolds number. Thus a turbulent boundary layer can attach the flow even in adverse pressure gradient avoiding laminar boundary layer separation.

Pinkerton and Moses [1] made a feasibility study on flow control using piezoelectric thunder actuator. By actuating the piezoelectric actuator electro statically the camber was increased 2° above the angle of attack to retain the region of attached flow. Jacob [2] presented details of development of adaptive airfoils, their origin and merits of using them. Seifert and Pack [3] had shown the advantage of periodic excitation over the suction process in flow control applications. It was experimentally demonstrated that using an *oscillatory* flow excitation, flow separation could be actively delayed. Even though the experiments were encouraging, active flow separation control is still a challenging task in theoretical and numerical analysis.

Oscillatory flow excitation has proved to be an effective and efficient tool in controlling the boundary layer separation over a wide range of chord Reynolds numbers. Wygnanski [4] reported that active flow control by means of excitation would be successful because it (gainfully) exploits the instabilities inherently present in the flow. Various experiments were conducted to prove the usefulness of periodic excitation in the flow control of medium to low Reynolds numbers.

Munday and Jacob [5] performed flow control experiments by moving the upper surface of the airfoil using a THUNDER actuator. THUNDER (Thin Layer Unimorph Ferroelectric Driver and Sensor) actuator is manufactured by binding a thin sheet of piezoelectric ceramic under hydrostatic pressure between metal substrate and aluminium electrode at 320°C. A change of lift was noticed and shifted to a higher angle of attack at stall. Also it was observed that the stall occurred at lower angle of attack if the airfoil less perturbed, whereas in case of most perturbed airfoils the lift was increased even above the unperturbed stall angle. It was concluded that if the geometric camber variation could be made around 3% at maximum thickness it would make a large influence on aerodynamic performance.

Literature review established the following facts:

- Periodic excitation helps to achieve an effective flow control at low Reynolds numbers.
- Also around 3% variation in thickness is adequate to establish the required aerodynamic performance.

Hence a research study has been conducted in this work to develop an adaptive surface to produce around 3% variation in the geometric camber through piezoelectric stripe actuator. Subsequently, the devised concept has been implemented to realise an adaptive wing for MAV with active flow control.

The flow can be altered either by static deformation or dynamic / periodic excitation or both. The THUNDER actuator used by Jacob [5] was quite heavy and required higher operational voltage (600 - 900V), hence not quite suitable for MAV applications. Therefore, in the present study an alternative flow control mechanism has been proposed using a lightweight piezoelectric bimorph actuator (Stripe Actuator). Raja et al. have extensively studied the use of bimorph actuators, both series and parallel types in structural control applications [8]. The stripe actuator is a flexible parallel type, 4 gram in mass and requiring a maximum operational voltage of 150V only. Further the developed mechanism is simple to construct.

Design and Construction of an Adaptive Wing

To build an adaptive wing configuration, Eppler 387 airfoil has been chosen. Literature clearly indicates that this airfoil is efficient at low Reynolds number. The aerodynamic coefficients like lift and drag are estimated for the designed airfoil configuration using XFOIL (MIT, USA). It has been verified that this software is sufficiently accurate in predicting the aerodynamic characteristics at low Reynolds number. The adaptive wing is constructed with spar-rib-skin assembly, where balsa is used for making the ribs, aluminum for spars, and rubber latex for skin. Polyurethane foam is also used in the wing construction.

The adaptive movable surface is however made by means of a thin balsa strip bonded to the rubber skin.

The designed wing geometry is given below:

- Span : 106 mm
- Root chord : 150 mm
- Planform area : 15900 mm^2
- Aspect Ratio : 0.70
- Taper Ratio : 1
- Maximum thickness : 13.6 mm

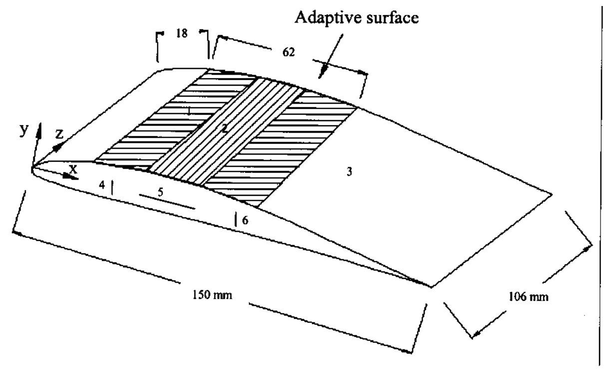
Adaptive surface details :

- Location : From 12% of chord to 53.3% of chord
- Width : 106 mm

A 3-D finite element model is built in ANSYS® to numerically test the flow control concept. Spars are idealized with shell 63 elements and Solid 45 has been used to model the balsa ribs and foam materials. The adaptive surface is made of rubber latex and balsa strip, which has been modeled with shell 63 elements. The full view of the geometry, FEM model, cut view and the fabricated adaptive wing has been shown in the Figs. 1, 2, 3 and 4.

Stripe Actuator Analysis and Testing

Piezoelectric bi-morph actuators are effective airfoil benders. The bending actuation mode can be efficiently employed to actively deflect a portion of the wing skin or



1. Rubber Latex
2. Balsa Stripe
3. Polyurethane foam
4. Front Spar (AL)
5. Stripe Actuator
6. Rear spar (AL)

Fig.1 Sketch of adaptive Eppler 387 wing

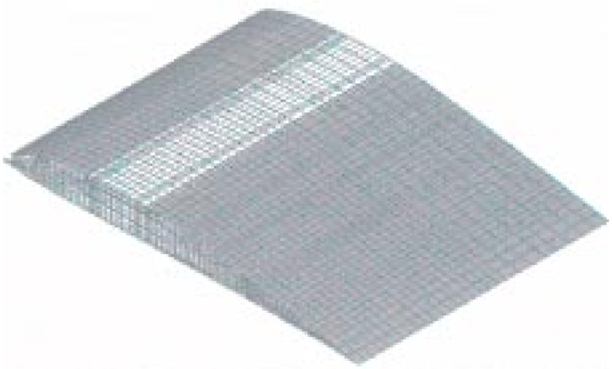


Fig.2 Finite element model

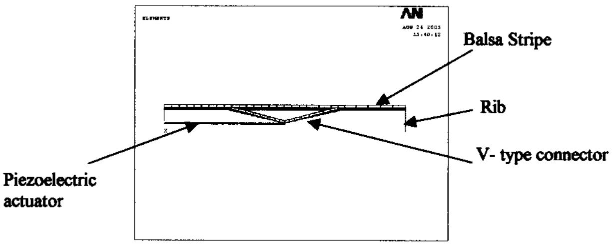
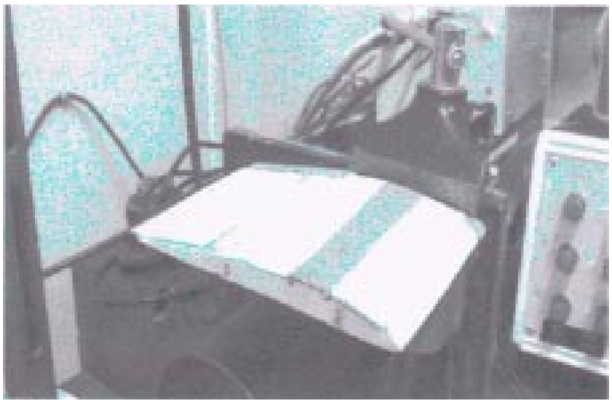
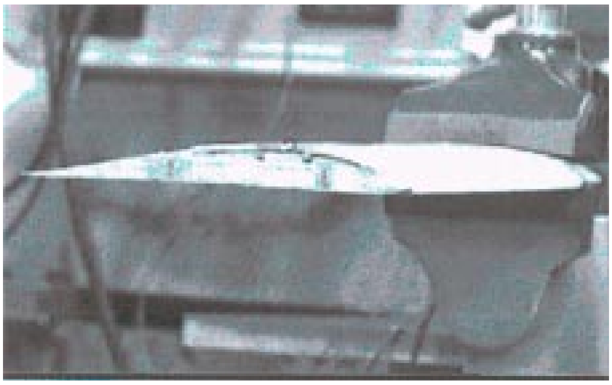


Fig.3 Cut view of the adaptive wing



(a) Top view



(b) Side view

Fig.4 Fabricated model

vibrate to produce a periodic excitation. Stripe actuator is a bender which works like a clamped- free beam (refer to Fig.5). The positive poling is identified by a thin white stripe, at the clamped end. The stripe actuator used is manufactured by APC®, USA. The dimension of the actuator is 60 X 20 X 0.6mm. It is capable of developing 0.25N block force and a free deflection of 2.5 mm at the free end. The adaptive wing concept for flow control study has been developed using this stripe actuator. Before the integration of the actuator into the wing, the actuator has been numerically characterized and experimentally verified for its performance. The numerical model is developed in ANSYS with solid 5 elements that capture the electro-mechanical coupling (see Figs.5 and 6). The actuator is actuated by applying voltage to shim and grounding the other two faces. Fig.7 shows the FEM and experimental deflections (tip) for various applied voltages. The experiments are performed on the actuator with a clamped-free condition, driving it by a voltage amplifier (APC®, USA). The piezoelectrically generated deflection is measured by a laser displacement sensor (sensitivity of 20 μm). It has been found that the actuator produces a maximum deflection when the shim is driven by voltage with other two electrodes are grounded. It can be seen from the experiments that the actuator exhibits a non-linear behaviour after certain amount of applied voltage. The piezoelectric constants are usually measured at lower electric field, however these values may change at higher electric field, which can bring non-linear actuation behaviour. The numerical results show a linear nature due to the limitation of linear piezoelectric theory assumption made in ANSYS.

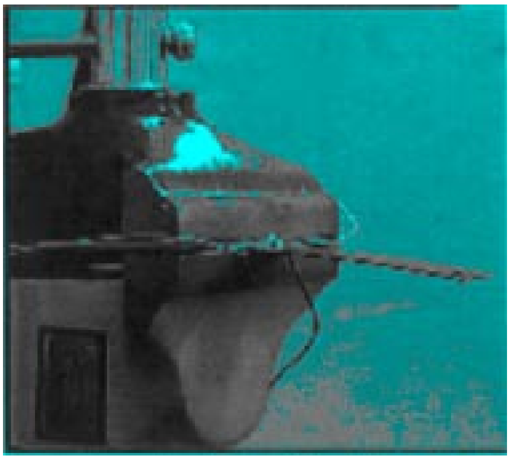


Fig.5 Clamped-free actuator under static electro-mechanical testing

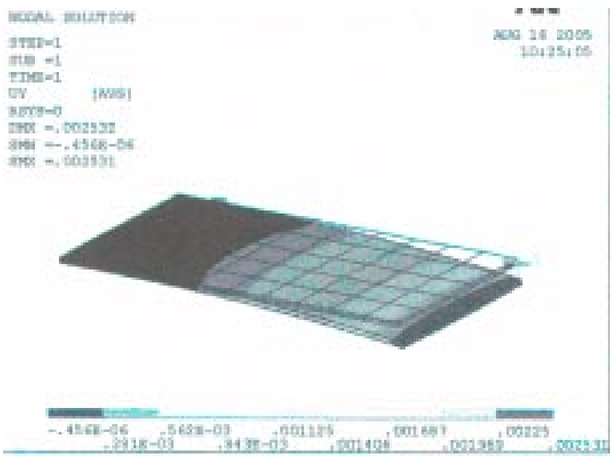


Fig.6 FE model of stripe actuator

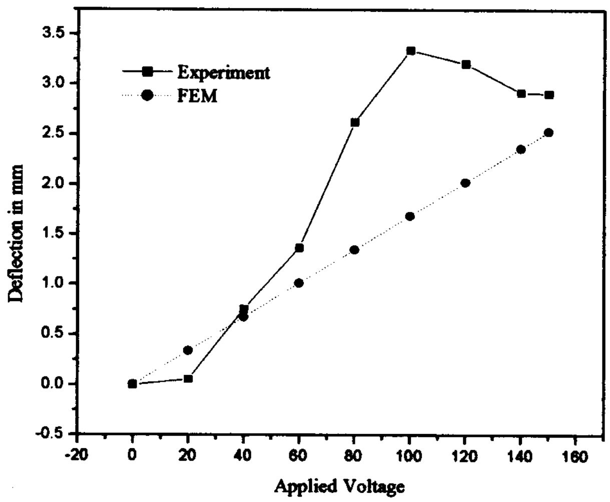


Fig.7 Actuator characterization

It is clearly seen that the actuator develops large deformation (~ 2.5 mm), even though the strain level is small. This demands a non-linear modeling technique, which involve inclusion of geometric non-linearity and non-linear electro-mechanical coupling.

Adaptive Wing Concept

A smart structure concept is proposed in the present work to achieve a flow control through variable thickness approach. The variable thickness is possible either by deflecting the top surface (skin) of the wing or by vibrating it periodically. In this concept a balsa strip is made to deflect or vibrate with the help of a cantilevered bender actuator to develop the necessary thickness variation actively during flight. Since the PZT bender can produce the maximum deflection at its tip, the C.G of the balsa strip is connected to the actuator tip to have the maximum benefit. In order to attain a smooth variation in the thickness on either side of the balsa strip, a rubber latex skin is provided. The relation between strain developed and applied field is given by

$$\in_{\alpha} = d_{31}\,(\phi/t)$$

$\in_{\alpha}$ - Strain developed

d_{31} - Coupling Coefficient (m/V)

ϕ - Applied voltage (V)

ϕ/t - Applied field (V/m)

t - Distance between the electrodes

Fabrication and Testing

The designed wing has been fabricated to verify the developed concept experimentally. Using aluminium, balsa wood, rubber latex, foam, along with hardwood as root rib, the composite wing is fabricated. Fig.8 shows the structural components employed in the construction of the wing. Two thin aluminium strips of 0.5 mm thickness are used as spars. The actuator is clamped at the root rib and its tip is attached through a V-shaped balsa piece to the moving balsa skin.

The experimental setup used in the measurement of deflection and vibration response is shown in Fig.9. It consists of signal generator, power amplifier (for actuator) and laser sensor. The actuator amplifier is capable of supplying both DC (150V) and AC (150V) signal to the actuator, using which the static piezoelectric coupling and dynamic response studies are conducted. The wing is tested with a support at the rood chord, subjecting to a sine sweep signal supplied to the actuator.

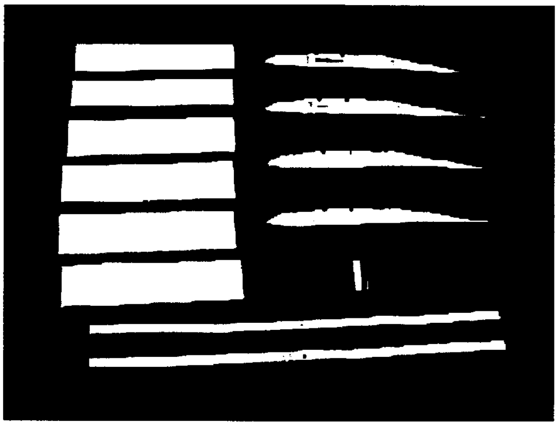


Fig.8 Individual structural components

Results and Discussions

The present study has focused on testing the adaptive wing concept with the static piezoelectric effect. However the adaptive surface is also vibrated with a wider frequency band to check for thickness change. The static deflection is measured at five locations in the span wise direction on the top surface in response to the applied actuator voltage (150 VDC). The force and deflection of an actuator is a function of applied voltage. Therefore, experiments are conducted for different applied voltages. However, the results corresponding to maximum operational voltage is presented. This is due to the reason that at this voltage the actuator is expected to develop a maximum force, upon constraining the deformation. Each of these 5 locations in span wise direction has 5 points along the chord wise location. The deflection contour of numerical simulation is shown in Fig.10, where as the locations or points on top surface are presented in Fig.11. The deflection pattern at different location is plotted in Fig.12. A small variation is observed among these deflection patterns, therefore for the calculation of aerodynamic coefficients on the electro-mechanically deformed surface, the average deflection pattern is obtained and is shown in Fig.13.

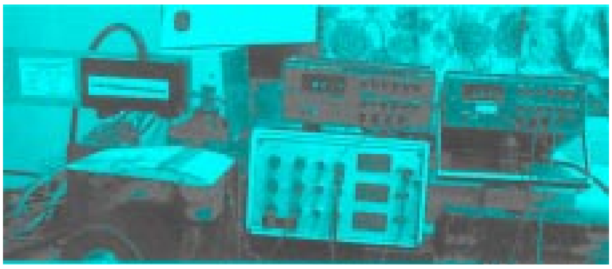


Fig.9 Experimental setup

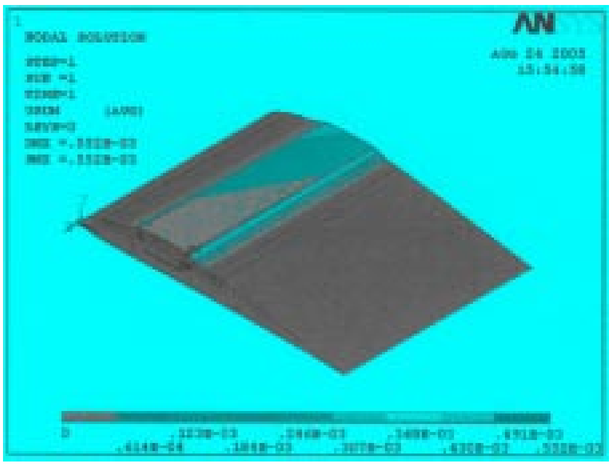
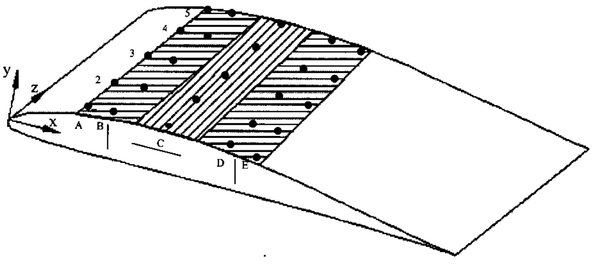


Fig.10 FEM deflection of wing



1 to 5 Span wise locations
A,B,C,D,E Chord wise locations

Fig.11 Locations where deformations are measured in both FEM and Expt.

Typically ~1 mm deflection is found and calculated at middle of the adaptive surface. The experimental deflections are measured at the same points where numerical values have been estimated and they are shown in Fig.14. All the experimental deflections are noted, an average effective deformation of the adaptive surface is presented in Fig.15. In this study, deformed shape is obtained with absence of aerodynamics and the effect of deformed shape on aerodynamic load is analysed separately. Even though the problem is coupled, it is studied in decoupled form. A comparative plot is shown in Fig.16 of numerically averaged deflection pattern of FEM against experiment. Experimental values appear to set an upper bound, as also seen in actuator behaviour comparison (refer to Fig. 6). It

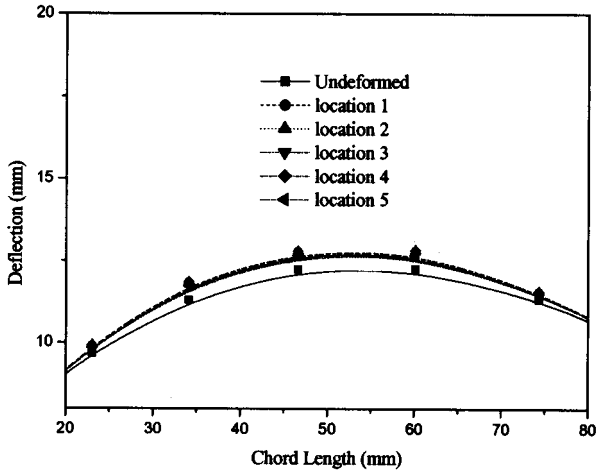


Fig.12 FEM deflection patterns

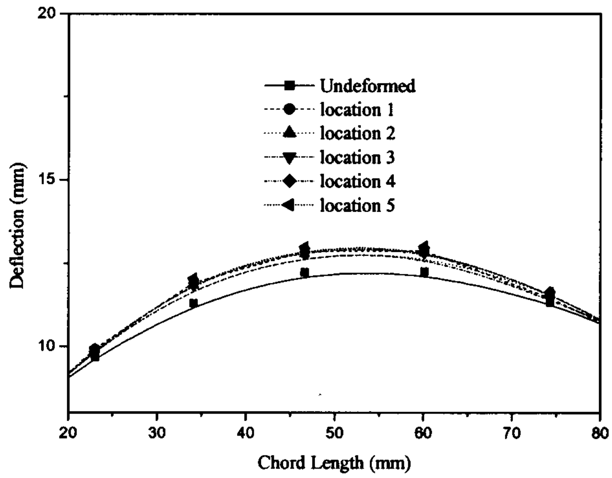


Fig.14 Expt. deflection pattern

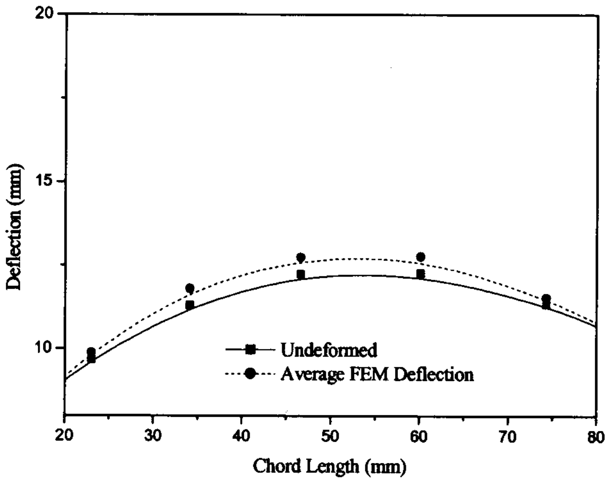


Fig.13 FEM average deflection

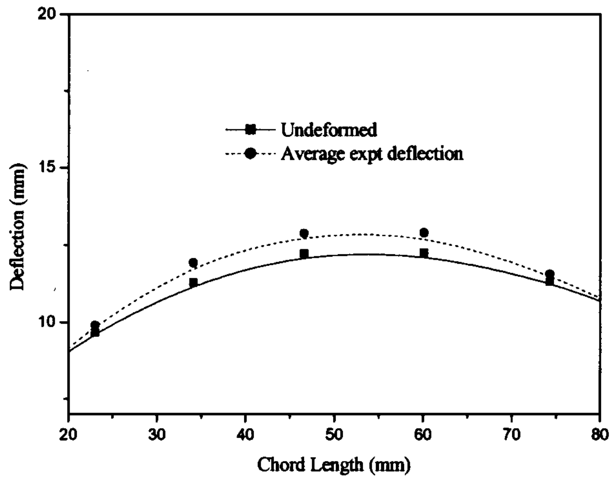


Fig.15 Expt. average deflection

is to be noted that a spline fit is carried out on the deflection data measured to obtain a smoother profile.

Further, the adaptive surface is vibrated using the stripe actuator with a periodic signal in the frequency band of 2 to 90 Hz (refer to Fig.17). This exercise is carried out to see the actuator effectiveness in producing the necessary amplitude level for flow separation control (adaptive flow control). The amplitude level is measured at the centroid of the vibrating adaptive surface by a laser sensor. The actuator voltage is limited to 33V, so that to operate it in a linear range. It is to be noted that at different angles of attack, it may be required to vibrate the adaptive surface in different frequency to attain better aerodynamic efficiency.

Since the focus of the present work is to show how a flow separation can be controlled through a piezoelectrically actuated adaptive surface, a mixed approach is followed by calculating aerodynamic coefficients using the experimentally measured deflection pattern. XFOIL program (a tool employed in CFD) is used for this purpose. XFOIL can be used for the design and analysis of subsonic isolated airfoils. It is a panel method, where the airfoil is discretised into number of panels and solved for the aerodynamic coefficients C_L and C_D. The formulation is applicable for both inviscid and viscous flow, where the undeformed and deformed surface of the wing is considered as a 2D aerofoil. The estimated results using average deflections of theoretical and experimental are plotted in Figs.18 - 21 for various cross sections along the span of the wing.

It is interesting to note that the variation in the thickness, achieved through deflecting the adaptive surface has increased the lift by 4.39%. This can be further improved

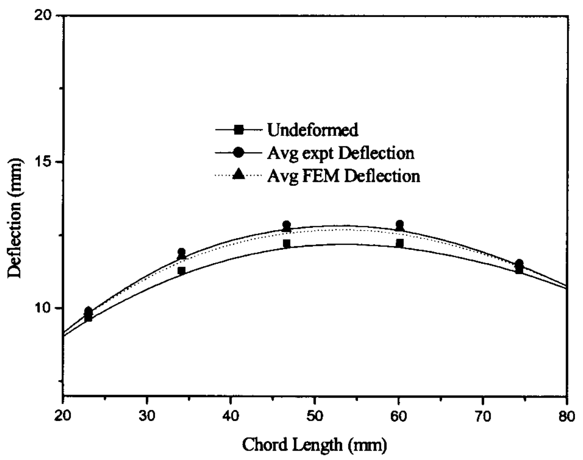


Fig.16 Average deflection pattern for experimental and FEM

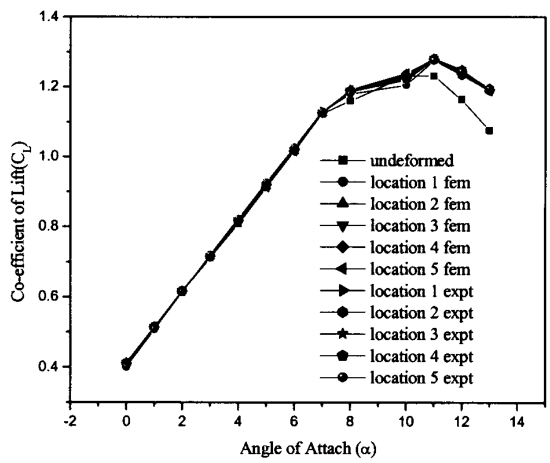


Fig.18 C_L Vs α (FEM and expt.)

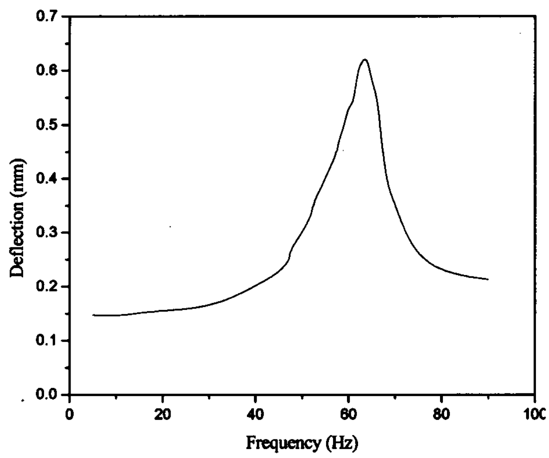


Fig.17 Frequency response of the adaptive surface Expt. applied voltage 33V)

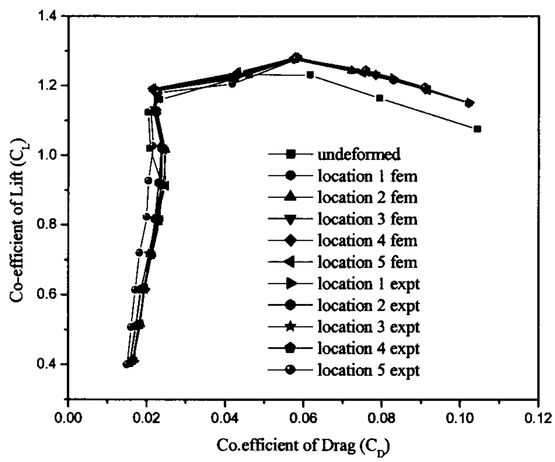


Fig.19 C_L Vs C_D (FEM and expt.)

by using a slightly thinner connecting rubber latex skin with the proposed adaptive surface (Presently 1.0 mm thickness is used). Also, by designing an effective transfer mechanism, the piezoelectric actuation can be further utilized to have more deflection on the adaptive surface. A wind tunnel testing is planned further to show experimentally the workability of the proposed concept.

Conclusions

A piezoelectrically actuated adaptive surface has been employed in the construction of a typical MAV wing to show the usefulness of smart structure concept in the flow separation control application. The PZT stripe actuator is used along with a suitable mechanism to actively deflect or vibrate an adaptive surface. Both numerical and experimental studies are conducted on the designed wing, which show a 5% maximum thickness variation using the developed concept. Further, the aerodynamic calculation on the actively deflected surface has developed approximately 4.39% increase in the lift. However, for real time applications, the present single adaptive surface concept may be extended with multiple actuators to construct segmented adaptive surfaces to achieve the required aerodynamic efficiency (L/D).

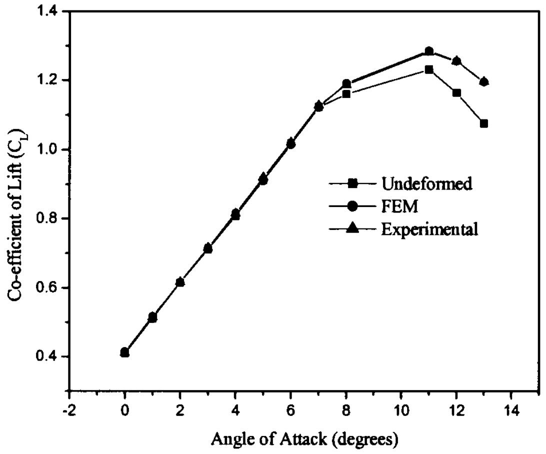


Fig.20 C_L Vs α (on a average deformed shape : FEM and Expt)

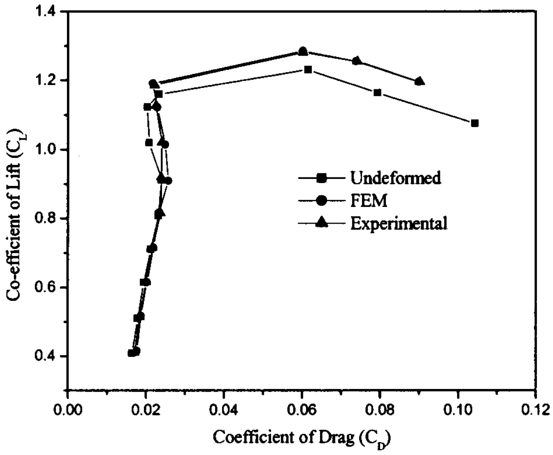


Fig.21 C_L Vs C_D (on a average deformed shape : FEM and Expt)

Acknowledgements

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