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# SMA Based Adaptive Concept on Wings of Large Civil Aircraft

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## ABSTRACT

**Shape memory alloys (SMA) are being increasingly tried out to achieve large shape changes such as Leading Edge (LE) droop of wings. LE droop of wings of large civil aircraft have to overcome two major forces in order to realize the droop. These are, structural load required for flexing the structure and the aerodynamic load that acts against the drooping force. Conventional actuators like pneumatic, hydraulic or electromechanical actuators have serious problems like concentrated actuator mass, stress concentration and also jamming. In the case of a power failure, the conventional actuators get jammed in that particular position and it is very difficult to revert them back to the neutral position. It becomes difficult for the pilot to control an aircraft with a jammed control surface. The proposed SMA based actuators overcome the limitations of the conventional actuators stated above. SMAs have distributed actuator mass and hence do not produce stress concentration, and also improve the dynamic characteristics of the structural components. Since they are active elements, in the event of a power failure, they revert back to the neutral position. For capturing large deformations due to the LE drooping non-linear analysis has been carried out by considering the geometric non linearity of the structure. In order to obtain the large deformations in the LE advanced structural concepts have thus been used.**

## 1. INTRODUCTION

It was found from aerodynamic study that Leading Edge (LE) droop in wings of large civil aircraft significantly increases the lift without reducing the overall efficiency. Presently the LE droop in civil aircraft is obtained by means of pneumatic actuators as explained in [1]. NAL has been working in the area of Shape Memory Alloy (SMA) actuation for quite some time. The SMA based smart structures technology have matured well enough to be incorporated in actual wing like structures with the aim of realizing morphing/ adaptive features.

From the Computational Thermal Fluid Dynamics (CTFD) analysis the target shape has been obtained and it was deduced that a LE droop of 20$^{o}$ will give a substantial aerodynamic benefit. The aerodynamic benefits will among other things enable to reduce the takeoff and landing distances. Drooping of LE (i.e. flexing the structure without any gap or discontinuity between the drooped part and the main wing) is inevitable to maintain the stream line flow past the wing surface while at the same time enhancing the aerodynamic efficiency. This paper examines the different structural configurations of the LE which will enable the LE droop by application of distributed forces along the span at appropriate locations. The distributed forces are applied by means of smart SMA actuators. The force developed by the SMA actuators should overcome the force required for flexing the LE as well as the externally applied aerodynamic load. These actuators are energized by electrical heating. In order to electrically heat the actuators, the required current is drawn from the available aircraft battery source through the miniaturized DC-DC converters. Also, to deploy and maintain the LE at a given position a closed loop control system will be implemented. The analysis and design effort that is involved in arriving at light structural configurations in order to effect the drooping using SMA actuating elements is presented. The current status of SMA actuation technologies in relation to the LE droop is also discussed.

## 2. FLEXING OF THE LEADING EDGE

From the aerodynamic point of view one can easily say that flexing of LE within the limits can increase the lift and thus can bring about additional benefits with existing features.

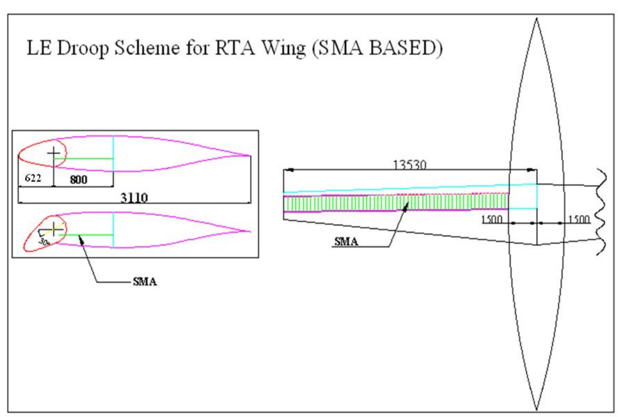


**Figure 1 SMA based LE droop scheme**

When compared to the LE slats or rotation of the LE, drooping the LE as stated earlier minimizes the loss in aerodynamic efficiency due to flow separation from the aerodynamic surface. Drooping thus enhances aerodynamic efficiency of wing without increasing much of the drag. Since the contour of the wing is having a gradual change the loss of aerodynamic efficiency is minimized. This flexing of LE is done only during takeoff and landing as shown in figure 1.

## 3. DEVELOPMENT OF MINIATURISED POWERING DEVICES

Main aim of this project is to use SMA actuators to effect the drooping of LE of wing by using miniaturized power electronics for powering the SMA actuator bank. Here SMA wires are used as actuators compared to the conventional actuator like pneumatic or hydraulic actuator. SMA actuator has distributed actuator mass leading to improved dynamic characteristics of the aircraft. Another very important area of work is the development of miniaturized power electronics for the actuation of SMA wires.

For using SMAôs as actuators they can be actuated by heating using external heaters or by resistive heating. For better control, high efficiency, compactness and silent operation resistive heating is preferred. The resistive heating can be done using constant voltage or constant current type power supplies. The force generated by all SMA wires of the same bank should peak at the same time. In order to achieve this constant current mode is preferred. In both modes of resistive heating if any SMA wire loses its property or gets cut and falls on any other SMA wire or SMA bank, the performance of other SMA wires will get affected. Individual miniaturized, electrically isolated power supplies have been developed. These power supplies are called DC-DC convertors which converts the 28 V DC available in the aircraft to the necessary level that is required. This voltage and current level depends on the length and diameter of the SMA wires chosen as the actuators. Earlier transformer based linear power supplies were developed to power the SMA element. These powering devices were heavy and voluminous. In the recent past the powering technologies have undergone rapid changes from transformer based linear powering to transformer less switched mode power supplies. This resulted in having discrete miniaturized powering devices for the SMA actuator. The miniaturized powering devices developed were programmable with respect to their heating profiles. This permitted ready interfacing with the computer and electronic synchronized actuation of the SMA elements. This also permitted an electronic switch over from one bank of SMA to another bank if required. Such schemes have been tested for different control surfaces of aircraft like the rudder model and the Mousche (additional aerodynamic surface below the cockpit of pilot) of a typical military aircraft which is deployed only during landing and remains retracted at all other times. The evolution of the powering devices from the transformer based technology to switched mode in the last decade is shown in figure 2.

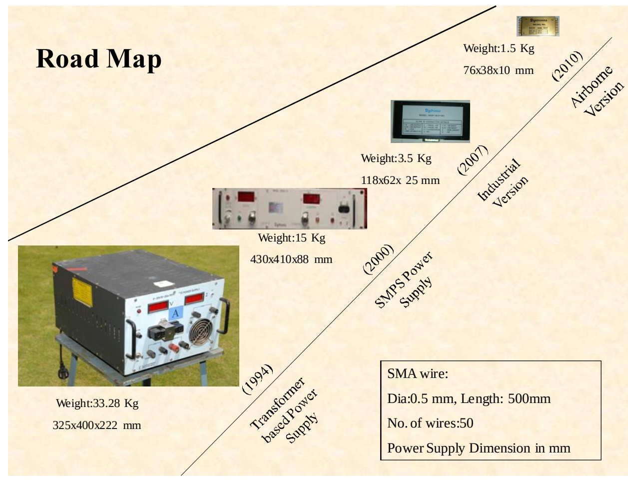


**Figure 2 Evolution of powering devices**

The comparison of weights of the powering devices to power an identical number of SMA elements is shown in table 1. In the next few years the weight and volume of the powering devices is expected to further come down due to improved designs and packaging technologies. The reduced weight and volume of the powering device is certainly a very encouraging development in order to examine the feasibility of using the SMA technologies in aircraft morphing

| Sl. no. | Design and Technology | Voltage (Volts) | Current (Amps) | Power (Watts) | Dimension (mm) | Weight (Kg) | No. of SMA wires | Weight of power supply per unit SMA element (Kg) |
|---|---|---|---|---|---|---|---|---|
| 1 | Linear Mode Power supply (Transformer based) | 20 | 25 | 500 | 325x400x222 | 34 | 50 | 0.68 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 | Switched Mode Power Supply | 5 | 50 | 500 | 430x410x88 | 15 | 50 | 0.3 |
| 3 | Industrial DC-DC Converter | 8.5 | 6 | 850 | 118x62x25 | 3.5 | 50 | 0.07 |
| 4 | Airborne DC-DC Converter | 7 | 7 | 690 | 76x38x10 | 1.5 | 50 | 0.03 |

**Table 1.Comparison of the powering devices**

## 4. INTEGRATING SMA ACTUATORS WITH THE STRUCTURE

SMAs capability of undergoing reversible phase transformation by application of heat is a very well known fact. During the phase transformation, the shape of SMA changes (here length) due to which they generate recovery forces which can be used for performing useful work. This property of SMA was exploited and used in various cases before. Some of those are ñDeployment of mousche using shape memory alloysò, ñPreliminary design and fabrication of SMA embedded GFRP beamsò and ñSMA based smart trimming surface system development of typical civil aircraft applications.ò

In the case of deployment of mousche using SMA, an SMA bank consisting of 138 wires of 1.2 mm diameter and 650 mm length was designed. This, when actuated, was capable of generating over 2 tonnes of force while undergoing 2 % strain.

In the case of SMA embedded GFRP beams, thermal SMA elements (1.2mm diameter) were embedded off the neutral axis in pre strained condition (nearly 2.5 % strain).This produced a curvature which was counter balanced by placing super elastic SMA wires of 1.2mm diameter on the opposite side of the beam. When the thermal SMA wires were actuated the beam gave large deflections at the center (ref [3], [4] & [5]).

Another area where the SMA wires are being used is in the trim tab deployment mechanism of HANSA aircraft. Here the servo motor that is conventionally used for trim tab deployment is being replaced by two antagonistically acting SMA wires (1.2mm diameter) and these wires when actuated produce upward and downward rotation of the trim tab about its hinge axis.

## 5. LEADING EDGE DROOP

The work presented here is the FEA of one feet segment of LE of the aircraft wing. Only FEA has been done assuming the lay-up sequence for skin and stiffener of the LE as explained in further sub sections. LE model considered was a double skin construction since single skin construction will not be stiff enough to take droop load while undergoing large rotations yet preventing local deformations at the point of application of the loads. Since the drooping should not change the external contour of the LE, it was decided to stiffen up the LE of the wing by making it a double skin construction. Loads were applied at 2 places on the inner skin one at the top surface and other at bottom surface. The load applied at the top surface of inner skin was dissipated on to the structure by means of a T-stiffener connecting the inner skin and outer skin. Similarly the load applied at the bottom surface of the inner skin was dissipated on to the structure by means of a trapezoidal stiffener as shown in figure 3.Different configurations of LE were tried to obtain the required droop angle within allowable strain limit. These are discussed below. Here the sections shown are at the root of the wing.

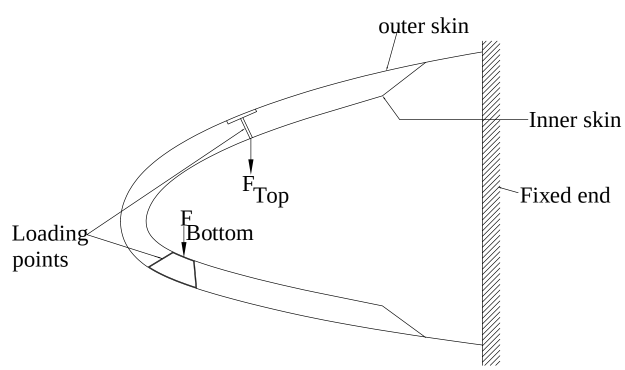


**Figure 3 Loading points of LE**

### 5.1. LE with 30mm offset:

Here the material used is glass fiber reinforced plastic (GFRP) BD (bi-directional) and lay-ups are of ±45°orientation.The skin thickness selected were 1.92 mm $[(\pm45^{o})_{16}]$ for inner skin and 1.44 mm $[(\pm45^{o})_{12}]$ for outer skin and the distance between them is 30 mm and the two skins were joined at 120 mm from fixed end as shown in figure 4.

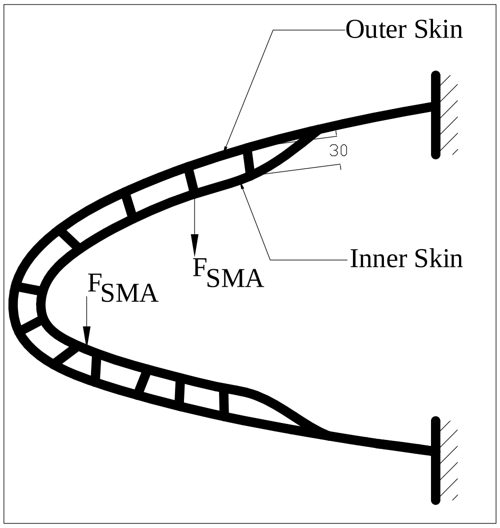


**Figure 4 Section of LEof the wing (30mm offset)**

After loading it was observed that the deflection was more of local deformations at the point of application of load. It was also observed that the LE was stretching out at the top position near to the fixed end and compressing at the bottom position. The maximum strains were observed at these positions but the rotation was not sufficient to meet the required angle of 20° inspite of application of very large forces of the order of 500Kg at both top surface and bottom surface. Instead of drooping, warping of the selected section was observed. The strains and stresses were also higher near the point of application of the load. This gave an idea that the loads were not properly diffused into the structure instead they were concentrated near the point of loading. Hence it was concluded that the model was stiff .Thus it required to lower the stiffness to achieve the aim of getting very large deformation without unrealistically high actuating forces.

### 5.2. LE with 15mm offset:

In this case the offset distance between the skins was reduced to 15 mm and the skin thicknesses were also reduced and web elements were provided for transferring the load from inner layer to outer layer at different places to make the model diffuse the flexing load from inner skin to outer skin without local deformations. The model was analyzed and found that the deflection and rotation were not sufficient. This section of LE is shown in figure 5.

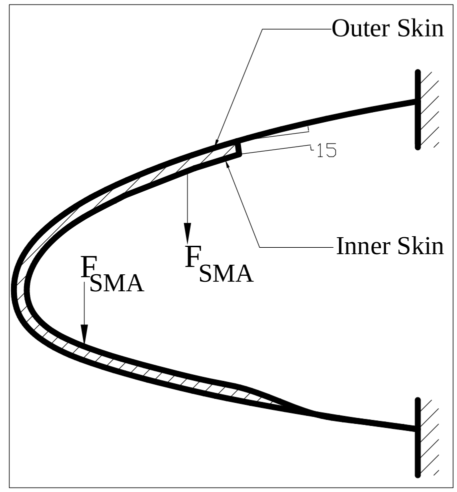


**Figure 5 Section of LE of the wing (15mm offset)**

### 5.3. LE with gazettes:

Further gazettes were provided at different locations inside the LE model and thickness was varied to obtain required angle of rotation as shown in figure 6. But all these configurations failed to give required angle of rotation and instead warping/twisting was observed.

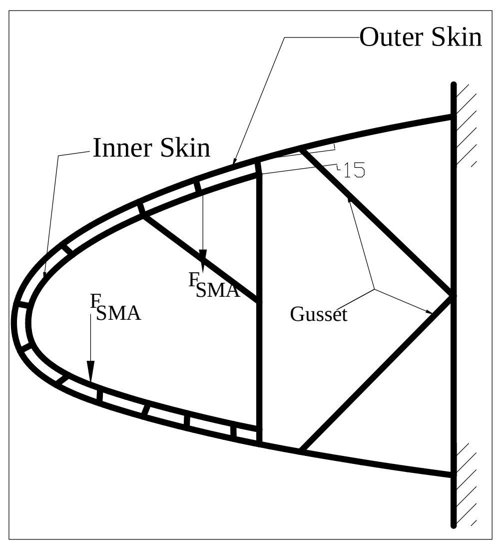


**Figure 6 Section of LE of the wing (with gussets)**

### 5.4. LE with grooves:

After all these trails grooves were introduced near the fixed ends of the LE model as shown in figure 7.

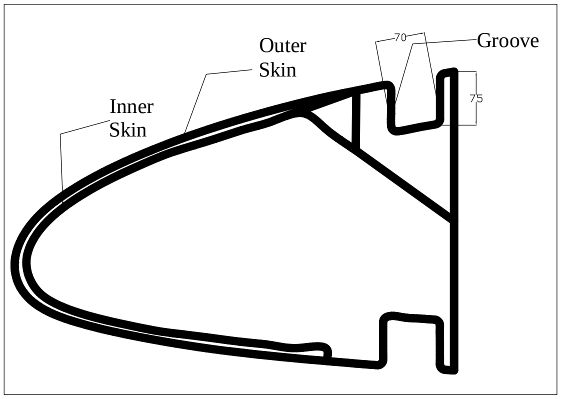


**Figure 7 Section of LE of the wing (with grooves)**

The first spar was designed to be at 20 % of the chord length. This model with groove produced deformation more than that compared to model without groove. The angle of rotation obtained was significantly increased. The problem of local deformation was eliminated and loads for flexing the LE was brought down. Warping was also eliminated. By providing a number of I-stiffeners between outer skin and inner skin it was possible to diffuse the load from inner skin to outer skin without local deformation of the structure. Modifications were done in depth and width of the grooves and results obtained for deflected position of LE was comparable to the required droop position as shown in figure 8.

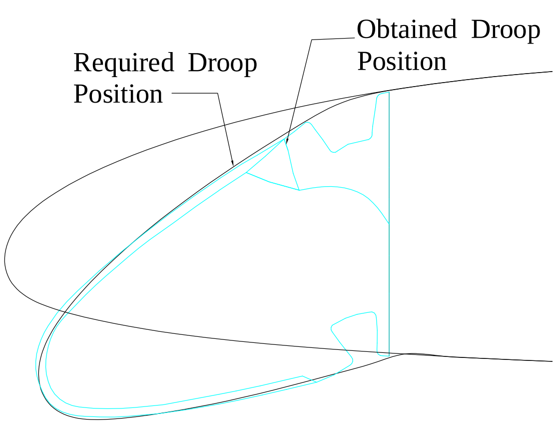


**Figure 8 Comparison of FEM analysis with required droop**

## 6. ANALYSIS OF LEADING EDGE

Initially the LE was analyzed by assuming it as a linear problem to begin with. This approach was correct since the deflections, rotations and strains were initially very less. Hence linear analysis was a fairly good approximation to the problem. When the grooves were introduced to the LE, the deflections, rotations and strains became large and hence the problem was no longer a linear one. Further non-linear analysis was done. The difference in the tip deflection of LE for different values of load is shown in figure 9. From figure 9 it was found that there is indeed a difference in deflection for linear and non-linear case when the deflection increases from low values to high values. Henceforth only non-linear analysis was carried out in the LE.

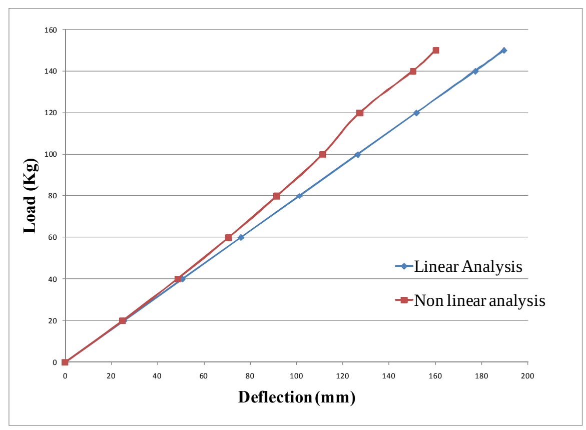


**Figure 9 Comparison of linear and non-linear analysis**

Non-linear analysis takes in to account the geometric non-linearities involved like large strains, large deformations, large rotations, membrane stretching etc. When the LE was analyzed using linear analysis it was found that the vertical deflection was high and the horizontal deflection was varying from 7mm at the tip of LE to 40mm near the bottom groove of the LE. The angle of rotation was approximately 18~19 degrees. Here the LE was getting squeezed out because of the vertical deflection of about 177mm and perfect flexing was not observed.

In the case of non-linear analysis, the tip deflection in the horizontal direction was 30mm near the tip of the LE and 40mm near the bottom groove of the LE. The vertical deflection was 150mm and the angle of rotation was 18~19 degrees. Here the LE was not getting squeezed out as in the case of linear analysis and the rotation was also near to the target value of 20 degrees. The flexing force required was of the order of 70Kg for both top side and bottom side of the inner surface of the LE.

## 7. POWER CALCULATION FOR SMA ACTUATOR FOR FLEXING LEADING EDGE

From previous experience, it is known that for a wire of 1.2 mm diameter and 650 mm length, the current 5is 6 A and voltage is 4 V. Here load required for flexing1 feet segment of LE is 70kg for both top and bottom and hence no. of wires required = 6no.s. Deflection required =180 mm.

If we use movement amplification mechanism, the contraction required by SMA is only 180/3 =60 mm. For a span of 330mm, deflection = 60mm. Length of wire required = 60/.02 = 3000mm = 3.00m

$\therefore$ No. of wires = 6x3=18 nos.

Span of the aircraft wing that is to be drooped is 10 m, which is approximately 30 times the span of the 330mm segment under consideration

We have no. of wires = 18 x 30 =480 no.s.

For 2 wings, we have total no of wires =480 x 2 =960 no.s

Voltage for 3.0 m of wire = $\frac{4}{0.65}$ x 3.0 = 18.46 V.

Power, P=18.46 x 6 =110.8 watts.

Considering only one side, for 480 wires, we have power =110.8 x 480 =53170Watts= 553.17KW.

Considering both sides, for 720 wires, we have power P =110.8 x960 =106340 Watts=106.34 KW.

Though the power requirement is high efforts are being made to reduce the weight and volume of power supplies as explained in the road map of section 3.

## 8. CONCLUSION:

The scheme of using SMA as actuators for effecting the LE droop has been brought out .The advantages of using SMA wires compared to pneumatic or hydraulic actuators have been brought out. The requirement for development of necessary miniaturized power electronics for actuation of SMA has been brought out. From the analysis it was established that the proposed LE droop scheme can be flexed by 20$^{o}$.This calls for large deformation and strains in the LE, which it was capable of undergoing, as verified from analysis.

### Acknowledgment

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