FLUTTER CONTROL ANALYSIS OF AN AIRCRAFT WING USING CARBON NANOTUBES REINFORCED POLYMER

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Abstract - In this paper, an investigation of the use of carbon nanotubes (CNTs) reinforced polymer as an actuator for an active flutter suppression to counter the flutter phenomena is conducted. The goal of this analysis is to establish a link between the behavior of the control surface and the actuators to demonstrate the veracity of using such a suppression system for aeronautical field. A preliminary binary flutter model using simplified unsteady aerodynamics is developed to study the behavior of the wing while reaching the flutter speed and when the control system suppresses the flutter phenomena. The Timoshenko beam theory for bilayer materials is used to match the response of the control surface with the CNTs reinforced polymer (CNRP) actuators. According to Timoshenko theory, results show a good and realistic response for such a purpose. Even if the results are still preliminary, they show an evidence of a potential use of CNRP for control surface actuation for small-scale and lightweight system.

Keywords - Actuators, Aeroelastic, Aeroservoelasticity, Carbon Nanotubes, Flutter, Flutter Suppression.

I. INTRODUCTION

FLUTTER is the most important and most unpredictable aeroelastic phenomena encounter during the design of an aircraft. Flutter occurs when the interaction of the elastic, inertial and aerodynamics forces increase, causes the airfoil a bending and torsional movement [1]. Due to the very flexible structure of modern aircraft, its instability greatly limits performances in the flight envelope of aircrafts and can lead to its destruction [2]. The flutter problem is encounter while the called "critical velocity" is reached. To prevent it, an active flutter suppression system is the key to relax the aeroelastic constrains and enable the aircraft to fly beyond the critical speed. Current research to prevent the flutter always include a conventional control system using hydraulic and pneumatic systems, while smart materials have been more and more using for aeronautical purpose.

A studied was conducted by Jordi and al. [3] using large Electroactive Polymer (EAP) actuators on an 8m-long airship to deform the wing and propel the airship. Despite the benefits of such an actuator, the complex implementation, mechanisms and electrics requirements make this actuator limited and not suitable for production aircraft [3]-[4]. Another study developed by Michel et al. in 2007 [5] shows successful test using EAP materials as actuators on a 3.5m long lighter-than-air vehicle. CNRP have been widely researched to be used as an actuator generating bending displacement [6]. However, such researches have been conducting for actuators aimed for small-scale system requiring relatively weak force actuations [7]. CNRP such as CNTS reinforced Polyimide developed by C. Park et al. [8] would contribute to the design of intelligent components for aerospace purpose in the future.

II. AEROELASTIC MODEL

A simple rectangular wing model Hancock et al. 1985 [9] is used throughout the study, as shown in Fig. 1. Its span is b, chord is c and the position of the flexural axis is denoted xf. The control surface is situated at the trailing edge covering the full span. The distance between the flexural axis and the generated lift is denoted ec.

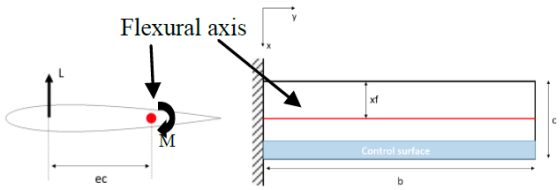


Fig. 1. Rectangular wing geometry

For this study a binary flutter model is developed, using the strip theory simplified unsteady aerodynamic. The system is considered as a rigid airfoil connected to two springs (one bending K_k and one torsional K_θ), as shown in Fig. 2, these two springs simulate the stiffness of the wing. The model will be considered with 2 degrees-of-freedom (pitch and plunge motion) to examine the behavior of the wing without a control surface.

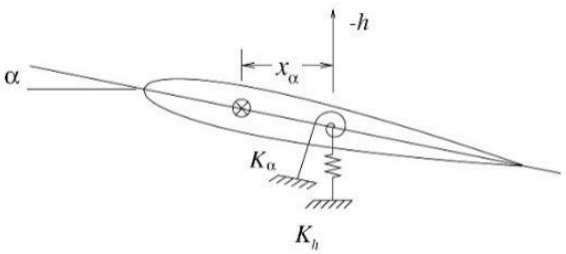


Fig. 2. Two DoF flutter model

The unsteady lift (acting at the quarter chord position) and pitching moment are the unsteady forces acting on the airfoil. Using Lagrange's equations [9]-[10], the following expressions are obtained:

$$L = I_k\ddot{k} + I_{k\theta}\ddot{\theta} + \rho V\left(\frac{cs^3a_w}{6}\dot{k} + \frac{-ec^2s^2a_w}{4}\dot{\theta}\right) + \rho V^2K_k k \quad (1)$$

$$M = I_{k\theta}\ddot{k} + I_\theta\ddot{\theta} + \rho V\left(\frac{-c^3sM_{\dot{\theta}}}{8}\dot{\theta}\right) + \rho V^2\left(\frac{cs^2a_w}{4}k + \left(\frac{-ec^2sa_w}{2} + K_\theta\right)\theta\right) \quad (2)$$

I_k, I_θ and $I_{k\theta}$ include an additional mass at the leading edge to position the center of mass (CG).
The simplified unsteady aerodynamic derivative term $M_{\dot{\theta}}$ is assumed to be a constant equal to -1.2, which is an important effect for the unsteady aerodynamic behavior. The governing equation for a 2-DoF aeroelastic system with general coordinates q can now be written as following:

$$A\ddot{q} + (\rho V\, B + D)\dot{q} + (\rho V^2 C + E)q = 0 \quad (3)$$

where A, B, C, D, E are respectively the structural inertia, aerodynamic damping, aerodynamic stiffness, structural damping and the structural stiffness matrices defined in (1)-(2). Where the structural damping is ignored for this study (D=0).

III. FLUTTER SUPPRESSION SYSTEM

Considering the aeroelastic model, the first order state-space model is employed for the control theory. Using the time domain control theory [9]-[11], the equations of motion for the dynamic system are,

$$\dot{x} = A_s x + B_s u + E_s w_g \quad (4)$$

$$y = C_s x + D_s u \quad (5)$$

where u={β} is the control surface demand angle and w_g is the gust disturbance. In that case, the matrices are different from the aeroelastic model. Where B_s and E_s are respectively the control surface vector and the gust vector. A_s is the matrix first order used to calculate the flutter behavior and D_s is assumed to be equal to zero as well as the flutter behavior.

To calculate the control surface demand angle, "u" is written in terms of the measured response. Which introduce a feedback effect to the active flutter suppression system as it is shown (6),

$$u = \{\beta\} = [K_v]\{\dot{z_{wing}}\} = K_s y \quad (6)$$

where K_s is the state space gain matrix. The feedback will alter the control system by closing the loop (initially an open loop for the flutter behavior) and therefore, the stability will be increased. A Linear-quadratic regulator (LQR) is used to calculate the feedback gains [12].

IV. CNTS REINFORCED POLYMER ACTUATOR

The CNTs reinforced polymer plays the role of the actuator for the wanted control surface angle. In this particular approach, the material is considered as a bilayer beam with one-layer rich of CNTs and the second layer rich of the polymer [8]-[14]-[20], as shown in Fig. 3,

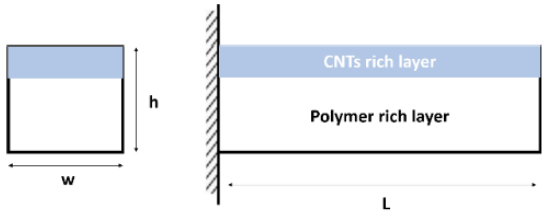


Fig. 3. Geometry of the bilayer beam

where L is the length, h is the thickness and w is the width of the beam. The actuator is set as a cantilever rectangular beam. The actuation performance relies upon the difference of the coefficients of thermal expansion (CTE) between the two layers. A heat-transfer analysis was performed to predict how the temperature is evolving as a function of the input power. The difference of the temperature is called the temperature gradient ΔT, which is obtained by the following equations,

$$\Delta T = T - T_0(\quad 7)$$

$$\Delta T = \frac{h\,P}{\lambda\, L\, w} \quad (8)$$

where λ is the thermal conductivity of the composite beam and P the power, h the thickness, w the width, L the length. T and T_0 are respectively the hot temperature and the initial temperature (considered as 20°C).

The Timoshenko beam theory for bilayer materials [13] was used to calculate the generated force F as the output result, giving satisfying preliminary results [14]. The equation of the force is then the following,

$$F = \frac{9\,\Delta\alpha\,\Delta T\,E\,I\,k}{h\,L} \quad (9)$$

where Δα is the CTE, E is the Young's modulus, I the moment of inertia, L is the length, h is the thickness, ΔT is the temperature gradient. k is given by the following equations,

$$k = \frac{(1+m)^2}{3(1+m)^2+(1+mn)(m^2+\frac{1}{mn})} \quad (10)$$

where n is the ratio of the young's modulus between the two layers and m is the thickness ratio between the two layers. Since no experimental study was

made regarding this research to compare the results, the mechanical properties and thermal properties of the CNRP were found by using the rule of mixture [15]. For this analysis the CNTs is taken as Single Wall Carbon Nanotubes (SWNT) configuration: SWNT (10,10). The reinforced polymer is set to be Polyimide, giving the composite good mechanical durability and thermal stability.

Observing the results of the actuator, the configuration studied uses the CNRP as the skin of the control surface as shown in Fig. 4.

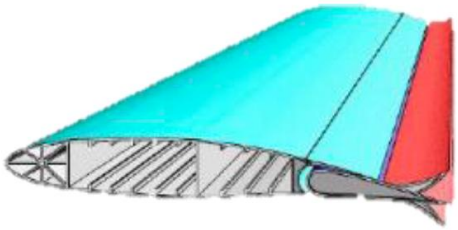


Fig. 4. Morphing flaps (red) configuration studied [16]. The actuator plays the role of the control surface in red

The exerted force is an important element for the configuration of the actuator. Since the aerodynamic forces acting on the control surface are taking into account, the actuator has to be able to withstand these external forces.

V. ANALYSIS

Both open loop and closed loop system have been developed under MATLAB and Simulink. The wing parameters, the aeroelastic system and the aeroservoelasticity were coded with MATLAB. While Simulink is using to run the two loops.

A. Open Loop Simulation Results

The wing was tested for flight conditions at sea level. Two studies were conducted, the first one is aimed to obtain the critical flutter velocity and the second one, to observe the behavior of the plunge and pitch motion of the wing. Triggering the wing was necessary for the open loop system to obtain the wing motion then a 1-cosine gust theory was used [17].K_k and K_θ are chosen to be small in order for the wing to reach the critical flutter velocity quickly.

Parameter	Value
s (semi span)	0.8 m
c (chord)	0.4 m
m (unit mass area)	150 kg/m²
xf (flexural axis position)	0.48*c m
K_h	1000 N/m
K_θ	600 N.m/rad
ρ (air stream density)	1.225 kg/m^3
α (angle of attack)	0 rad/deg

TABLE I - Parameters Of The Rectangular Wing

m=meter, kg=kilogram, m^3=cubic meter, N=newton, rad=radian, deg=degree.

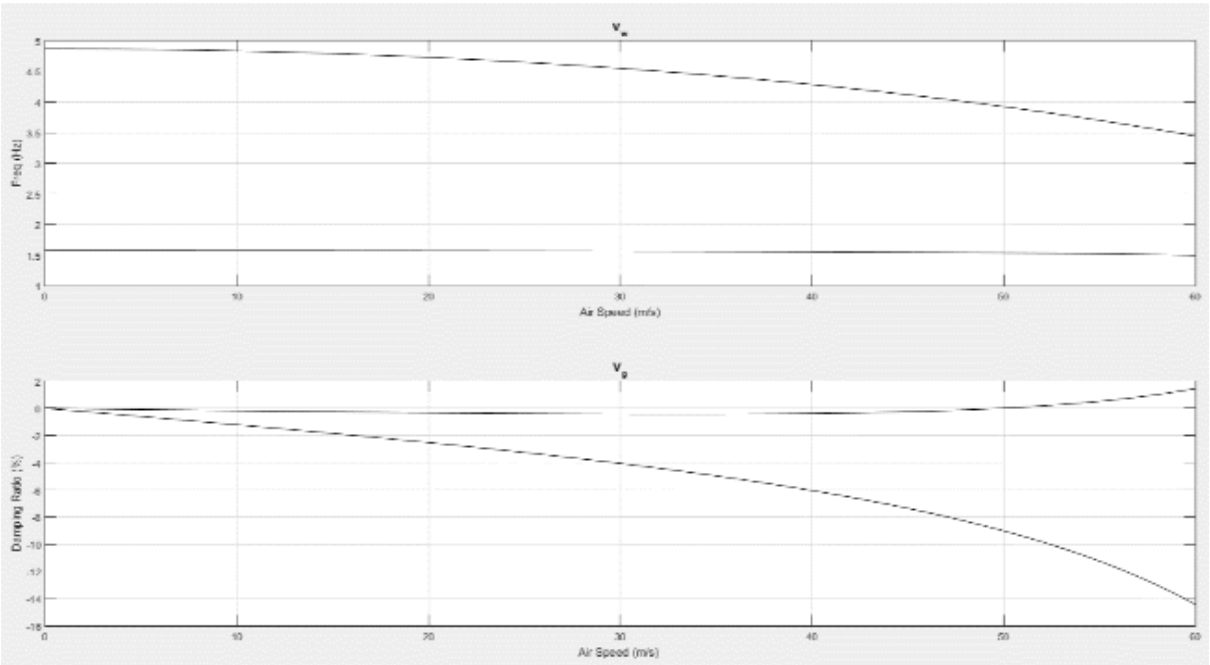


Fig. 5. Results of the aeroelastic binary model

The airstream velocity range of $0\mathrm{m/s} > \mathrm{V} > 60\mathrm{m/s}$ was chosen for the flutter evaluation. The binary model gives a critical velocity of approximately $\mathrm{V_f} = 49.85\mathrm{m/s}$ and the flutter frequency of $\omega_\mathrm{f} = 3.93$ Hz. The open loop system gives the results showing Fig. 6and7 agreed perfectly with the results obtained in Fig. 5.Indeed, the code developed with MATLAB allows to choose different speed to observe the behavior of the wing.

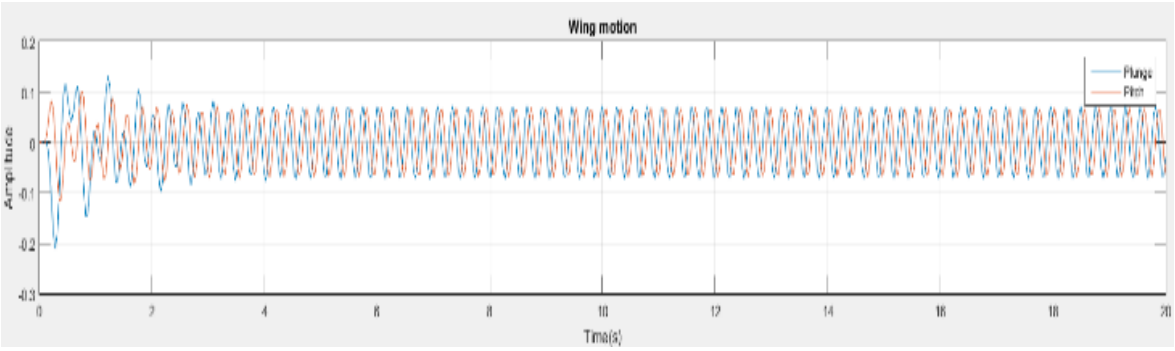


Fig. 6. Plunge pitch motion open loop simulation, $V = V_F$ for 20 seconds with a 1-cosine gust of 5m/s at 1 second

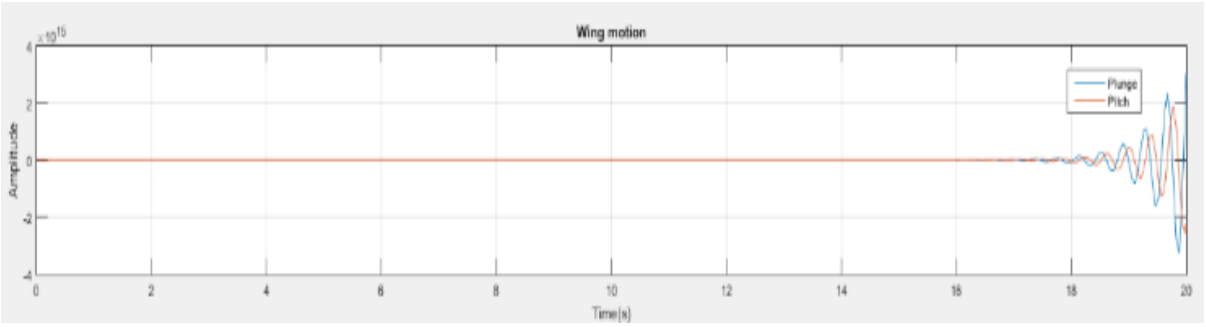


Fig. 7. Plunge pitch motion open loop simulation, $V > V_F$ for 20 seconds with a 1-cosine gust of 5m/s at 1 second

B. Closed Loop Simulation Results

The simulation using the LQR control shows a good behavior of the control surface to suppress the flutter. By using the open loop, the state space gain matrix is implemented in order to close the loop therefore, to have the system feedback.

Fig. 8 shows that the flutter controller is able suppress the flutter under 3 seconds with a maximum angle variation of $-3.49° < \beta < 3.07°$ when the critical velocity $V_f = 49.85\ m/s$ is reached. The best response of the control surface is given for the following dimensions: $80 * 800\ mm^2$ by tuning the LQR controller.

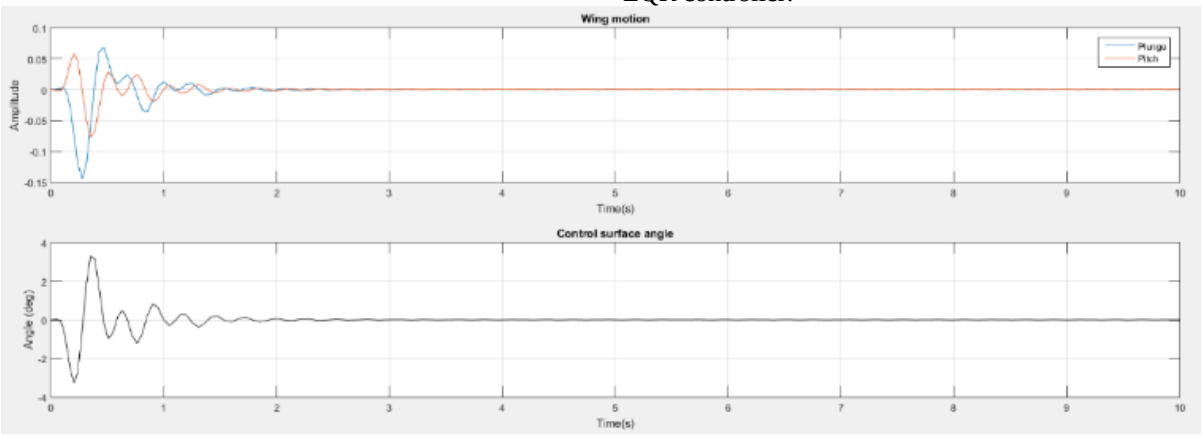


Fig. 8. Plunge pitch and control surface motion closed loop

simulation, $V = V_F$ for 10 seconds with a 1-cosine gust of 5m/s at 1 second

C. Actuators Results Theory

The previous paragraph shows the control surface response as a function of the time. Using the angle deflection of the control surface and the Timoshenko beam theory for the CNRP allow to match the behavior of the actuator. Not only the deflection angle (or displacement tip) is important but also the force that the actuator has to developed. In fact, dynamic pressure, due to the aerodynamic forces, is applied the control surface and the actuator has to be able to withstand them. The dimensions play an important role for the response of the actuator. Only the thickness of the actuator is studied since, the actuator plays the role of the control surface and is directly implemented as the skin.

To investigate if the forces exerted by the actuator are enough, I considered the following hypothesis: dimensions for the control surface $80 * 800\ mm^2$ with a maximum speed of $V_{max} = V_f = 49.85\ m/s$, with a dynamic pressure on the control surface of $97.4\ N$ $(1.52 * 10^{-3}\ N/mm^2)$. The actuator/control

surface has to withstand a force of 97.4 N and be able to generate an angle of $-3.49° < \beta < 3.07°$.
The Fig. 9. shows how the actuator behaves for 1% SWNT.
The actuator information is [6]-[18]-[19]:

Parameters	SWNT	Polyimide	CNRP
E Young modulus (GPa)	640	2.5	2.65
ρ Density (kg/m^3),	1330	1420	1419
α Coeff. Linear thermal expansion (K^{-1})	2.5E-6	4.5E-5	/
λ Thermal conductivity (W/m/K)	6000	0.35	0.39
Volume fraction (%)	1	99	/

TABLE II - Actuator Information Used For The Analysis Of The Flutter

GPa=Giga Pascal, kg=kilogram, m^3=cubic meter, K=kelvin, W=watt, m=meter, %=percentage

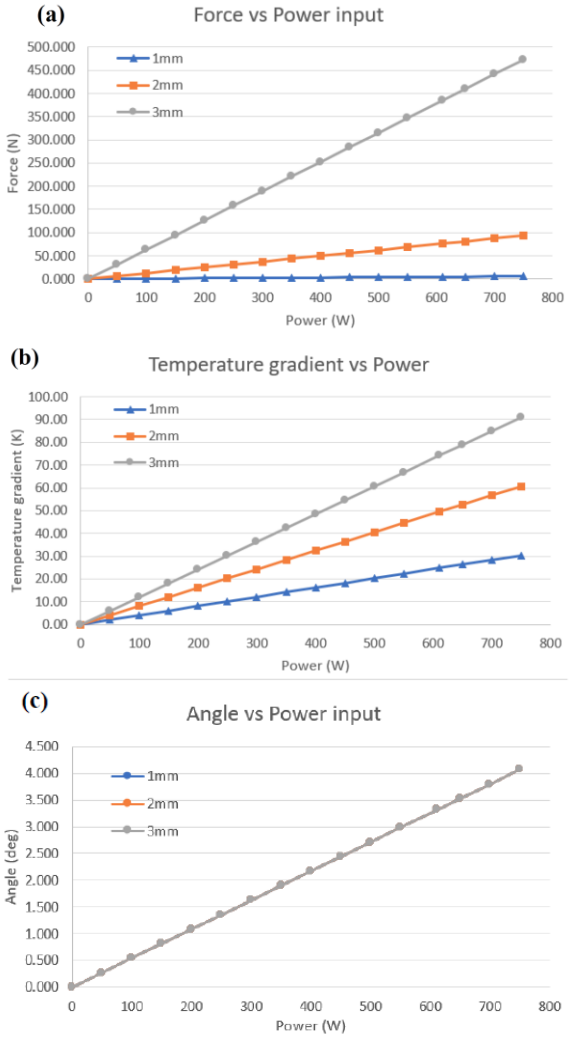


Fig. 9. Behavior of the actuator as a control surface for different thickness. (a) The force generated as a function of the applied power. (b) Temperature generated for different applied power. (c) The angle of the control surface generated by the actuator as a function of the input power.

Changing the thickness from 1mm to 3mm increase the exerted force by a factor of 81 for the wanted control surface deflection as shown figure 10.a. But the temperature gradient is affected too. A factor of 3 is observed between 1mm and 3mm. For a 1% SWNT, the necessary applied power is 611W to suppress the flutter as shown in Figure 8, which is relatively large for such a small deflection.

Such actuators show a good behavior between 0 and 5Hz [20]. Beyond 5Hz, the exerted force decreases for a same power. Thus, Timoshenko theory cannot predict the behavior of the actuator since the efficiency of the actuator considerably decreases after 5Hz. Moreover, Timoshenko has its limitation for the theorical part compare to the experimental part as discussed [14].

VI. CONCLUSION

The results obtained over the rectangular wing using an aeroelastic binary model show that the flutter can be successfully suppressed by using linear optimized controller. The suppression occurs under the 3 seconds which shows the effectiveness of this controller for this study. The theorical approach of the Timoshenko beam theory for bilayer materials shows a great overall and satisfying behavior regarding the results obtained with the closed loop simulation for the deflection angle of the control surface. The studies conducted regarding the EAP actuator shows that the dimensions and the volume fraction of SWNT of this one, are crucial for an optimal functionality when the controller surface operates to suppress the flutter.

However, due to the high thermal conductivity of the SWNT (6000 W/m/K), a high-volume fraction of CNTs cannot be used because of the significant increase of the applied power. Large dimensions of the actuator have to be avoided as well, which certainly increase the exerted force but considerably increase the temperature gradient which is not good when the maximum temperature is reached as well as the input power.

1% of SWNT give satisfying results for a system where small forces and large displacements occur. Using such an actuator for large scale aircraft will require enormous amount of energy. In that case, another EAP can be doubled with the CNTs reinforced polymer, giving better actuation behavior: such as Piezoelectric. Despite high applied power for large deflections and large dimensions, this novel actuator could be used for small-scale and lightweight aircrafts where large displacements and small forces occur.

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