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Morphology development of an airfoil by numerical analysis

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Abstract

As aerial application is not quite feasible for small croplands with current aircrafts in the market, because their higher operational speed. An adequate solution is to generate morphology in the airfoil of the wing of an aircraft, that would allow to decrease the operational speed of the aircraft by increasing the lift that the wing can generate at lower speed without the issue of reach the stall speed. Different airfoils were evaluated in order to compare their characteristics of high-lift and low Reynolds number with those of the NACA 4415, which is the current airfoil of the chosen agricultural aircraft. Such evaluation was carried out by numerical analysis in two dimensions, using Computational Fluid Dynamics software (CFD) at the same air conditions. It is observed that some airfoils obtain much better lift, compare with the base airfoil, but the geometry became very complex. The GOE 449 airfoil was selected due to the minimum geometric changes to do in order to perform the morphology from the original airfoil obtaining 26% more lift. In order to obtain the minimum geometric changes as possible in the morphology from the NACA 4415 airfoil to seek the GOE 449 lift performance a new airfoil was obtained. The aerodynamics properties of this airfoil, called FUSION, are close to the GOE 449 airfoil, obtaining a 7% less lift. It is expected to substitute the use of any auxiliary mechanism like flaps, slats or airbrakes, using smart materials in order to increase the operational capacities of the aircraft and replace the weight of this by payload.

1. Introduction

The morphology applied to an aircraft is not a new subject in aeronautics, but in recent times it has been retaken by the development of new materials, sensors, microelectronics and support systems[1].

The first design that attempt to emulate the flight of the bird was made by Leonardo Da Vinci, by a rigorous analysis of the mechanics of bird flight [2]. Nowadays whit the development of modern aviation and in particular in World War II, aircrafts whit some type of mechanical morphology appear like the F4U “Corsair” that can fold their wings for easy storage on the aircraft carries[3], other designs were made by the Luffwafe with the Me 1102/5 that was a concept of a jet bomber capable of change the sweep angle of the wing in flight, a similar morphology was used in the Me P.1101 prototype capable of change the sweep angle of the wing from 35 to 45 degrees on ground[4].

A the end of the war the American Army took possession of the Me P.1102/5 and whith the aid of NASA and Bell aircraft corporation, the X-5 was developed and became the first aircraft capable of change the sweep angle in flight. From these programs the F-111 “Aardvark” and the F-14 “Tomcat” were born[5].

In the late 80’s and the early 90’s, NASA developed 2 coordinate programs that were aimed to research new technologies that involucrate different areas, “The NASA aircraft morphing program”[6] and “The mission adaptive wing program”[7]. In these programs were used for the first time smart materials.

In 2002 the DARPA launched a program aimed to develop an aircraft whit morphing structures the "Morphing aircraft Structures (MAS)" was born. The main objective of the program was to investigate the capability of an aircraft to change the shape of its wing in order to increase its aerodynamic efficiency[1]. In this program only 2 prototypes were able to change the geometry of the entire wing one from Lockheed-Martin[8] and other from NextGen[9].

The aircraft morphology can be classified depending in what is the target of the change Fig.1.[10].

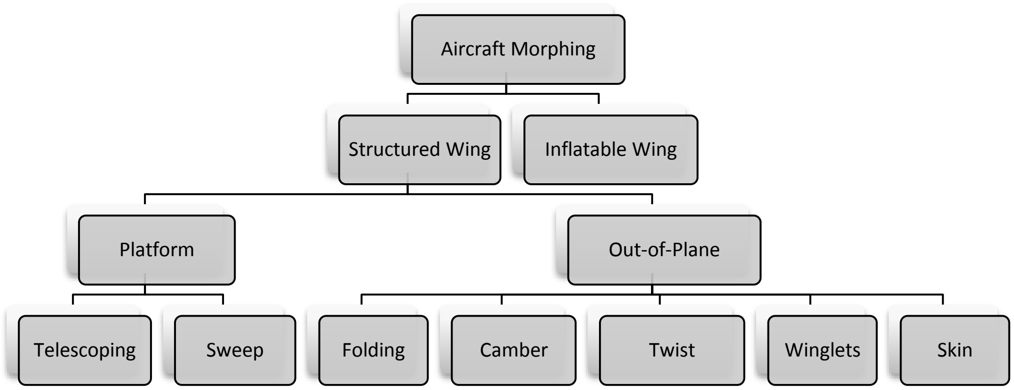

Figure 1. Categories of morphing wing in aircraft.

In this research work, the aim is focus on making the morphology in the upper camber of the airfoil, and in this particular area most of the research have been made changing the leading edge of the airfoil using smart materials, using Macro-Fiber Composite (MFC)[11], Electric Active Polymer (EAP)[12], Post-Buckled Pre-compressed Piezoelectric (PBP)[13], Lightweight Piezo-composite Curved Actuator (LIPCA)[14] and shape memory alloys[15, 16].

The objective to make a morphology on an aircraft, more precisely in the upper camber of an agricultural aircraft, is because the work speed to perform an aerial application is too high, leaving farmers whith less that 10 Ha out of this service[17]. A solution to this issue is to make the change from the original airfoil, that the aircraft have, to another airfoil whith specific characteristics like high lift and low flight speeds[18], by doing this the lift required can be obtained at lowers speeds, being able to access small farming areas.

2. Aerial application analysis parameters

According to Food and Agriculture Organization of the United Nations (FAO), some general parameters in aerial application need to be taken into consideration [19]. For this research work the standard atmosphere is considered at Monterrey Sea Level, and the working conditions used in this work are showing in table 1.

Table 1 Operational Conditions for Aerial Application based on standard atmosphere, considered in the numerical analysis

Parameters	Value	Units
Altitude	600	m
Density	1.155978	Kg/m^3
Atmospheric Pressure	94323.87	N/m^2
Viscosity	1.77049 e-5	N*s/m^2
Airfoil Cord	2.07	m
Working Speed	66.59318	m/s
Reynolds Number	9 e 6	
Mach Number	0.197	

2.1 Numerical analysis results versus the experimental analysis results

In order to validate the numerical analysis results obtained from CFD software is necessary to compare with experimental results obtained from wind tunnel test published in literature as Ira H. Abbot [20]. The airfoil to be analyzed, which is used by the aerial application aircraft, is the NACA 4415. Table 2 shows the parameters selected to carry out the numerical analysis considering the standard atmosphere.

Table 2 Wind Tunnel Parameters considered in the numerical analysis of the NACA 4415

Parameters	Value	Units
Altitude	0	M
Density	1.225	Kg/m^3
Atmospheric Pressure	101327.3	N/m^2
Viscosity	1.78372 e-5	N*s/m^2
Airfoil Cord	1	M
Working Speed	51.05	m/s
Reynolds Number	3.49 e 6	
Mach Number	0.15	

As many CFD computational programs are used to acquire data in scientific papers, it was decided to perform the analysis results in three of them ANSYS FLUENT, Design Foil (Demo Version), and XFL 5 (Free Software), in order to obtain the best approximation to the experimental data, each one of these use the same input parameters and good results have been obtained as shown in Fig.2.

All of the software shows a good approximation to the experimental data within the linear zone of the graph Lift Coefficient (C_L) versus Angle of Attack (AOA). Making a comparison among these software, in the linear zone is observed that the data obtained from ANSYS FLUENT has the minimum percentage of error to the experimental data, the percentage of error for each program is shown in Table 3.

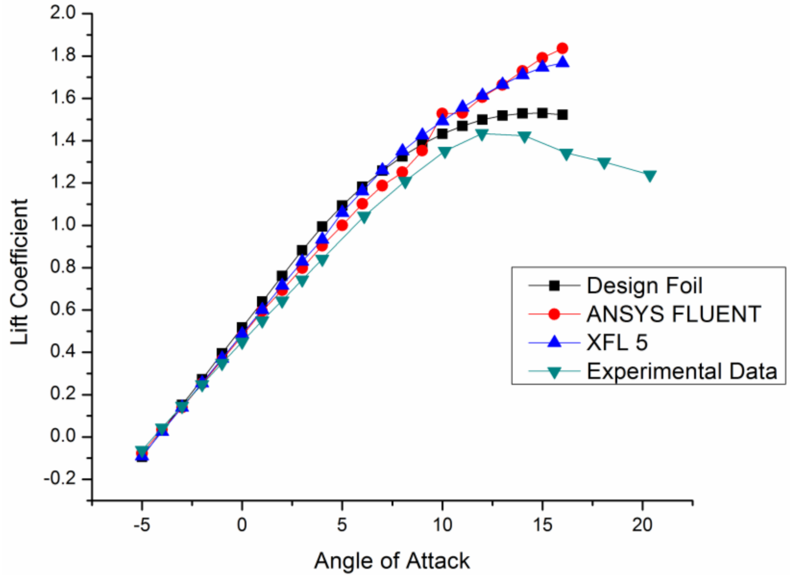

Figure 2. C_L vs AOA graph, comparison among experimental data and numerical analysis for the NACA 4415 airfoil.

Table 3 Percentage of error among experimental data and numerical analysis data from different software programs for the NACA 4415 airfoil

Experimental Data Average Error Linear Zone	**Design Foil**	**ANSYS FLUENT**	**XFL 5**
	5.97%	2.32 %	3.18%

3. Airfoil Selection process for morphology

In order to achieve the change in geometry of the NACA 4415 to improve the aerodynamics properties an airfoil selection must be carry out to match the necessities set by the operation of the aircraft. The selected airfoil must fit the important aspects seek to improve the NACA 4415, such as lowers working speeds and a greater lift force, these airfoils are within the group of low Reynolds number.

A group of 81 airfoils, classified airfoils of low Reynolds number, were selected using the UIUC Airfoil Data Base [21] from the University of Illinois. These airfoils are showed in Table 4.

Table 4 Airfoils of low Reynolds number selected from [21]

A18	E171	E423	FX76-120	GOE 289	GOE 449	K3311	S1223 RTL	USA 35B
Apex 16	E174	Falcon	FX76-140	GOE 386	GOE 418A	MB253515	S2048	
Aquila	E176	FX05-188	FX76-160	GOE 390	GOE 498	MH113	S2050	
Avistar	E178	FX60-100	FX83-108	GOE 398	GOE 508	Miley	S2091	
CH10 S	E180	FX60-100S	FX83-160	GOE 404	GOE 523	N-24	S4020	
DF102	E182	FX60-126	Gemini S	GOE 413	GOE 527	NACA 2414	S4233	
DH4009S	E184	FX63-137	GOE 225	GOE 420	GOE 533	NACA 2415	S8036	
DU86-084	E201	FX69-281	GOE 234	GOE 433	GOE 534	RG-15	SA7035	
E168	E210	FX73-152	GOE 241	GOE 441	GOE 612	S1210	SD6080	
E169	E220	FX74-140	GOE 288	GOE 446	GOE 798	S1223	USA 34	

The procedure to select the airfoil required for this work is achieving as follows:

- C_L selection.
- Geometric selection.
- C_D selection.

The software used to obtain numerical information from each airfoil is "Design Foil" due to the short period of time required to obtain results.

3.1 C_L selection

In order to improve the Lift force given by the NACA 4415 the new suggested airfoil must give the same Lift force with a lower operational speed, meeting the following statement in the linear zone of the $C_L\ vs\ AOA$ chart:

$$L = \frac{1}{2}\rho V^2 S C_L \qquad 1$$

Where L is the Lift force, ρ is the density, V the velocity, and S the Surface.
If

$$L_{Base} = L_{Candidate}$$
$$\rho = constant$$
$$S = constant$$

Where L_{Base} is the Lift force of the NACA 4415 airfoil and the $L_{Candidate}$ is the Lift force of the suggested airfoil: Then

$$V = \sqrt{\frac{2L_{Base}}{\rho S C_{L_{Candidate}}}} \qquad 2$$

Where V is the velocity, so the following statement is:

$$V_{candidate} < V_{Base} \therefore C_{L_{Candidate}} > C_{L_{Base}}$$

Where the selected airfoil must give higher C_L at lower velocities, compared to the NACA 4415.

After the C_L selection, only 29 airfoils met the stated condition. Three groups were formed from the selected airfoils according to the magnitude of the C_L compared to the NACA 4415. Fig. 3.

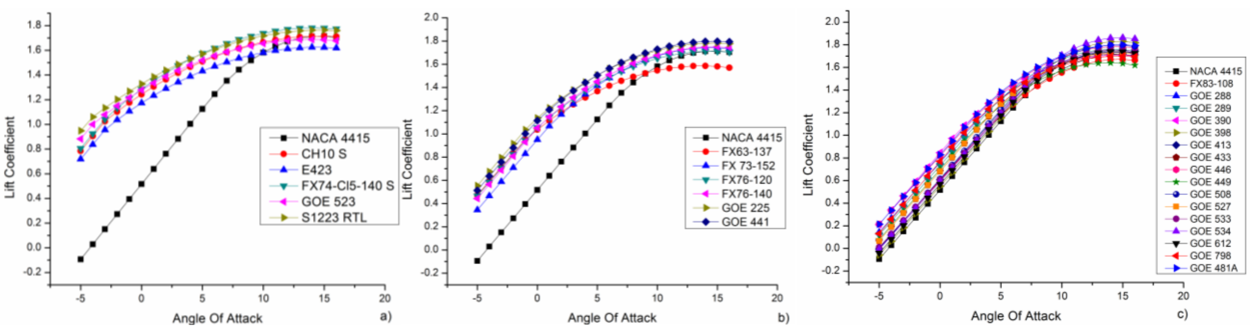

Figure 3. Group of selected airfoils showing a better lift coefficient in comparison to the base airfoil (NACA 4415); a) Group of selected airfoils with the highest CL., b) Group of selected airfoils with a moderated CL., c) Group of selected airfoils with slightly higher CL.

3.2 Geometric comparison

From the 29 airfoils selected by C_L magnitude, considering the most approaching geometry to the NACA 4415 the geometric selection is carried out. The changes are considering achieving the morphology from the original airfoil to the selected one. The aim in this section is to avoid the complicated shapes of the selected airfoil that can originate a sophisticated and too complex morphology design in the airfoil as seen in Fig. 4a, and select the airfoils with shapes similar to the NACA 4415 airfoil as seen in Fig. 4b.

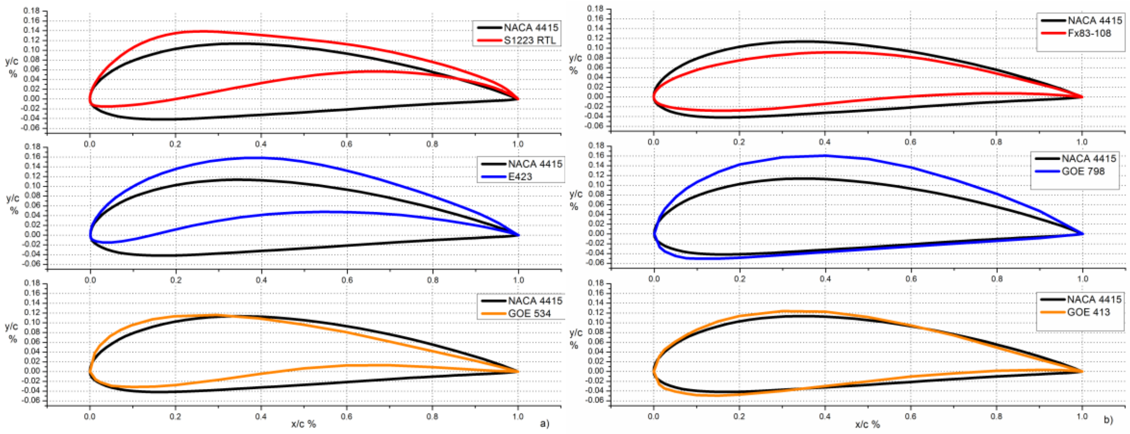

Figure 4. a). Airfoils with a complex geometry to achieve, b). Airfoils with geometry not too complex to achieve.

At this stage, 12 airfoils were chosen; most of them are from the third group of the C_L selection. Table 5 shows the airfoils selected, which fits with the purpose of this stage.

Table 5 List of candidate's airfoil's whit adequate geometric change

Fx83-108	GOE 288	GOE 289	GOE 390
GOE 398	GOE 413	GOE 446	GOE 449
GOE 508	GOE 527	GOE 612	GOE 798

3.3 Drag coefficient selection

The C_D selection is done similar to the C_L selection. It is seek the less possible amount of the drag force obtained from the suggested airfoil compared to the NACA 4415 airfoil. From the drag equation:

$$D = \frac{1}{2}\rho V^2 S C_D \qquad 3$$

Where D is the Drag force.
If

$$D_{Candidate} \leq D_{Base}$$
$$\rho = constant$$
$$S = constant$$

Where $D_{Candidate}$ is the Drag force of the suggested airfoil, and D_{Base} is the Drag force of the NACA 4415 airfoil, the next equation is obtained:

$$V = \sqrt{\frac{2D_{Candidate}}{\rho S C_{D_{Candidate}}}} \qquad 4$$

So

$$V_{candidate} < V_{Base} \therefore \; C_{D_{Candidate}} < C_{D_{Base}}$$

Where $C_{D\ Candidate}$ is the Drag coefficient of the suggested airfoil, and the $C_{D\ Base}$ is the Drag coefficient of the NACA 4415 airfoil.

12 airfoils are within this stage to be selected, there is not much difference of their C_D compared to the NACA 4415 airfoil. In order to select the airfoils the condition is that the C_D should be similar or equal to the base airfoil, reducing the group into 6 selected airfoils as observed in Fig. 5.

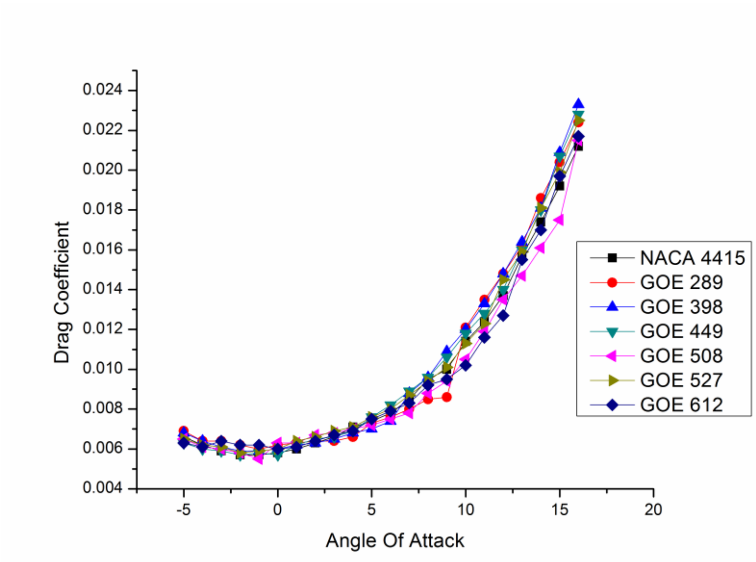

Figure 5. Comparison of the CD between the base airfoils and the selected airfoils that have a similar drag coefficient.

3.4 The final choice

From these six selected airfoils one of them must be selected to achieve the morphology. Repeating the geometric selection the airfoil GOE 449 was selected because the biggest geometric change take place in the upper camber and just an smaller geometric change take place in the lower camber close to the leading edge as observed in Fig. 6a.

In order to make easier the morphology it is take into account the geometry change in the upper camber giving a new airfoil called FUSION. The FUSION airfoil is made with the upper camber of the GOE 449 airfoil and the lower camber of the NACA 4415 airfoil as observed in Fig. 6b.

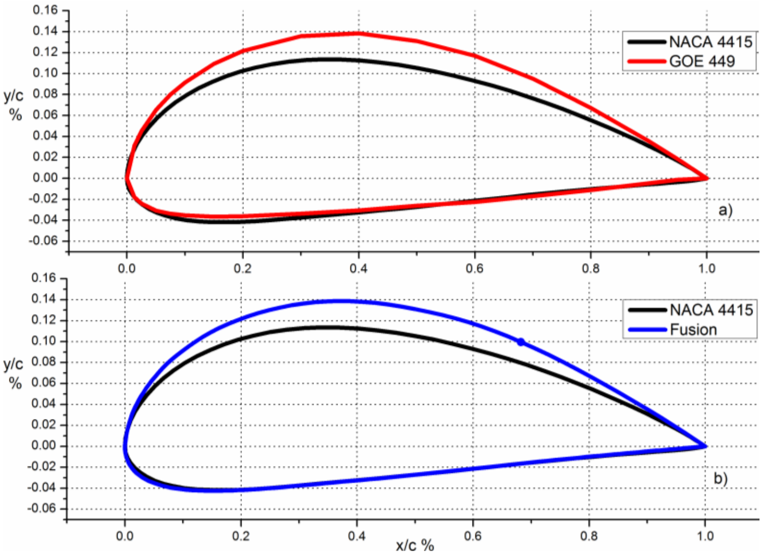

Figure 6. Geometric comparison between a). The NACA 4415 airfoil and the GOE 449 airfoil, and b). The NACA 4415 airfoil and the FUSION airfoil.

4. Numerical simulation of the selected airfoils

Whit the airfoil selected and the new ones, these were simulated at the operational conditions the aircraft during an aerial application Table 2, the simulation take place using ANSYS Fluent, because of the major capabilities against the other simulation software's.

The intention of putting to simulate the three airfoils is to have a visual comparison between the wing with and without the morphology. In Fig. 9 we can see that GOE 449 presented an increment of 29.5 % of lift coefficient in relation to the NACA 4415, but the different between the GOE 449 and the Fusion is only of 4.75% average in the liner zone.

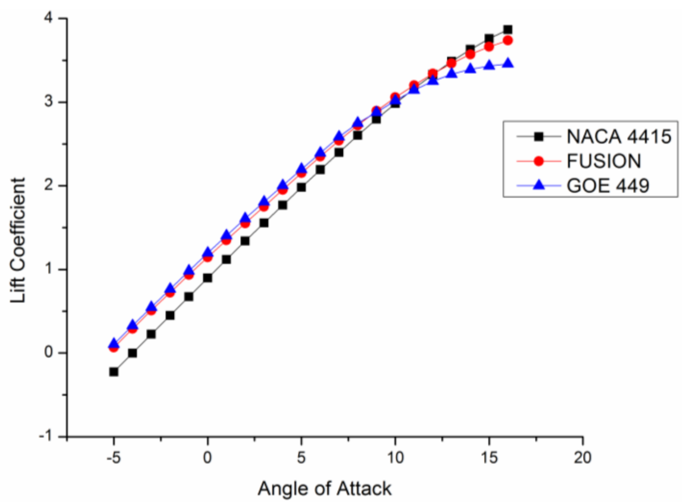

Figure 9. Lift coefficient comparison between GOE 449, Fusion and NACA 4415 airfoils

Another think that we saw is at high AOA the GOE 449 drop faster unlike the FUSION that almost maintain equal to the NACA 4415.

In terms of the operational speed, the lift force generated by the NACA 4415 in the simulation level fly is of $127.9107x10^3\ N$, applying the lift force equation and the but the lift coefficients of the GOE 449 and FUSION instead of the NACA 4415, it can be calculate the new operational speed of the aircraft has shown in Table 6.

Table 6 Speed require for operational conditions for each airfoil

Airfoil	Lift Force (N)	Lift Coefficient	Operational Speed (m/s)
NACA 4415	127.9107x(10)^3	1.339	66.593
GOE 449	127.9107x(10)^3	1.552	60.766
FUSION	127.9107x(10)^3	1.608	61.863

So it is possible to reduce the speed of the operation, by making a morphology, in this particular case the reduction is only of 8.75% for the GOE 449 and of 7.10 % for FUSION meaning only a difference of 2%. For this reason and that only the upper surface have to change, the FUSION airfoil is the one to make the morphology aircraft wing.

5. Conclusions

Throughout this work an evaluation of airfoils to improve the aerodynamics of the actual airfoil has been done selecting one, which is similar to the actual airfoil in order to have the improvements without complicated geometric changes. It is observed that:

- Making a change from a base airfoil in the wing by a morphology valid way to change the mission speed of a particular aircraft
- At this moment by lack of manufacture we have to choose an airfoil that we gain little speed.

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