Airfoil Selection for Fixed Wing of Small Unmanned Aerial Vehicles

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Contents

Airfoil Selection for Fixed Wing of Small Unmanned Aerial Vehicles

Ngo Khanh Hieu and Huynh Thien Loc

Abstract Vietnam has become a new market for small Unmanned Aerial Vehicles (SUAVs). In the case of SUAVs, the airfoil plays a crucial role in generating lift. This paper presents an approach using opensource/free software to evaluate and choose the airfoil for aircraft designs and suggests a set of criteria used to evaluate the airfoils. The method mentioned in this research can help designers of fixed wing of SUAVs in selecting the most appropriate airfoil from various sources. The obtained airfoil can be modified afterwards for the best performance.

Keywords XFRL5 · Airfoil for suavs · X-foil · Javafoil

1 Introduction

The market of UAVs in Vietnam as well as in other parts of the world is currently very competitive. The challenges that UAVs designers are facing are not only about how to make the aircrafts fly but also how to design an UAV for the best performance and possibly lowest cost.

Normally, in order to select an airfoil, the designers may either use tested data of airfoils or do their own test under the specific working condition of the airfoil. From the testing data acquired, they have to select the the most appropriate airfoil to the criteria needed. However, doing such a test could be time-consuming and costly. Moreover, the errors could be made because the working condition of the selected airfoils will not always be the same as the testing data as the result of the approximation in case of doing a test. In addition, there is no airfoil totally superior

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to others. Therefore, the method of selection and the criteria applied may cause problems to designers.

These difficulties lead to a need of a tool to select the proper airfoils in an effective and trustworthy way. These airfoils then can be selected from the database with the proposed method of selection and optimized afterwards by modifying the airfoil to adapt to the best performance of the SUAVs.

2 Airfoil Selection's Importance

To design an UAV, in general, the designer firstly has to gather all the requirements. After doing the initial sizing to have the operating Reynolds number and gathering the sizing baseline, the designer move to the configuration design where airfoil and aircraft configuration must be chosen, then does many stages of the multidisciplinary analysis and the optimization to give out the optimum configuration. A prototype will be made, based on the former configuration for the flight test. If the prototype meets the requirements, the UAV designed will be commercialized (see Fig. 1).

For UAVs, especially SUAVs, the airfoil is one of the most components to their performance which determine its likelihood of success. The airfoil is normally

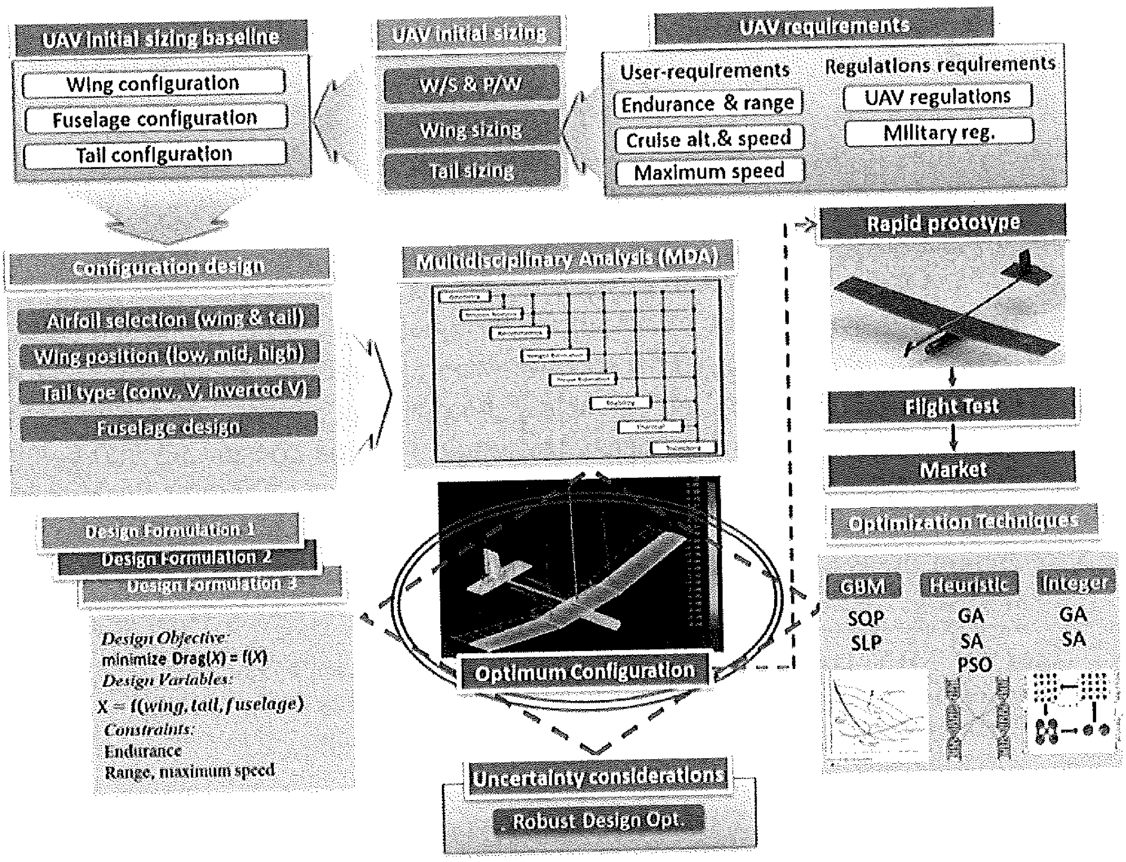

Fig. 1 UAV design flow chart [1]

selected from a database of airfoils operating in the same condition and will be optimized to best fit to the configuration of the SUAVs in the optimization phase.

3 Data Acquisition Method

3.1 Software Utilized

For SUAVs, the working condition is not as critical as other commercial aircrafts, in which many phenomenas may happen including the high flow separation at the trailing edge, the laminar separation bubbles and working beyond the stall angle.

The softwares presented are XFLR5 [2], whose airfoil analysis tool is based on X-Foil [3], and JAVAFOIL [4]. These softwares are medium-fidelity tools which use panel method to give the solution for vorticity and source distributions. From the solutions above, other parameters such as lift, drag and pitching moment coefficients can be computed.

For a shape discretization by N panels, the equation system consists of the matrix of influence coefficients, the unknown circulation strength at each panel corner point and the two vectors representing the conditions for 0° and 90° angle of attack. Each coefficient $C_{i,j}$ represents the effect the influence of the triangular vorticity distribution due to the vortex strength γi at each corner point on the center point of each panel j. The last row contains the tangential flow condition at the trailing edge which is needed to obtain a solution compatible (see Fig. 2).

3.2 Verifying Software Fidelity

Panel method used in the softwares mentioned above (XFLR5 and JAVAFOIL) has a limitation in predicting boundary layers, flow separation and rotational flows due to its calculation model. The calculation in transonic and supersonic flow and for

$$\begin{bmatrix} C_{1,1} & \cdots & C_{N+1,1} \\ \vdots & \ddots & \vdots \\ C_{1,N} & \cdots & C_{N+1,N} \\ 1 & \cdots 0 \cdots & 1 \end{bmatrix} \cdot \begin{bmatrix} \gamma_{1,0^\circ} & \gamma_{1,90^\circ} \\ \gamma_{2,0^\circ} & \gamma_{2,90^\circ} \\ \vdots & \vdots \\ \gamma_{N+1,0^\circ} & \gamma_{N+1,90^\circ} \end{bmatrix} = \begin{bmatrix} RHS_{1,0^\circ} & RHS_{1,90^\circ} \\ RHS_{2,0^\circ} & RHS_{2,90^\circ} \\ \vdots & \vdots \\ RHS_{N+1,0^\circ} & RHS_{N+1,90^\circ} \end{bmatrix}$$

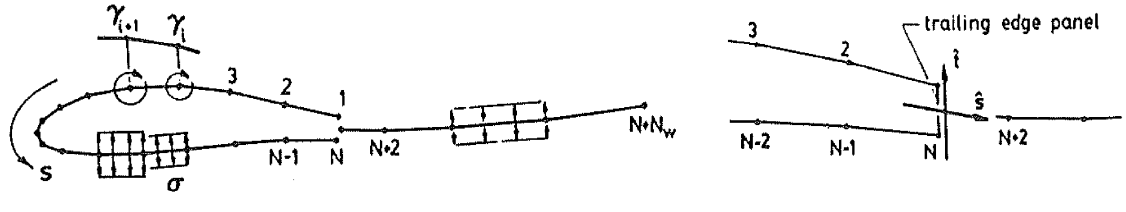

Fig. 2 Visualization of vorticity and source distributions in panel method [3]

airfoils with cusped trailing edges is also not reliable. However, as mentioned, these phenomenas and conditions are not applicable in case of the SUAVs.

To verify the fidelity of the software, the parameters obtained from the analysis of some well known airfoils of the softwares will be compared with the experimental data from University of Illinois Urbana-Champaign [5–7]. The representative airfoils are NACA 2412, NACA 24112 and S 9000 at Reynolds number of 2×10^5 and 5×10^5.

3.3 Airfoil Geometry Analysis

To analyze the reliability of the airfoil geometry, a study on the dependency of the number of points (panels) in the geometry of the airfoil must be conducted. The graph below presents the analysis of the lift and drag coefficients on the geometries having 50–300 points of NACA 2412 versus the data given.

There is a big difference between the parameters analyzed from a 50 point geometry and the others. The parameters received don't differ much from 150 points to 300 points geometries. Therefore, the analysis can be made with airfoil geometries having more than 150 points (panels) (see Fig. 3).

3.4 Fidelity of the Software

The parameters received from the softwares' analysis are compared with the experimental data from [7]. As the summary focus on airfoil in the same Reynolds

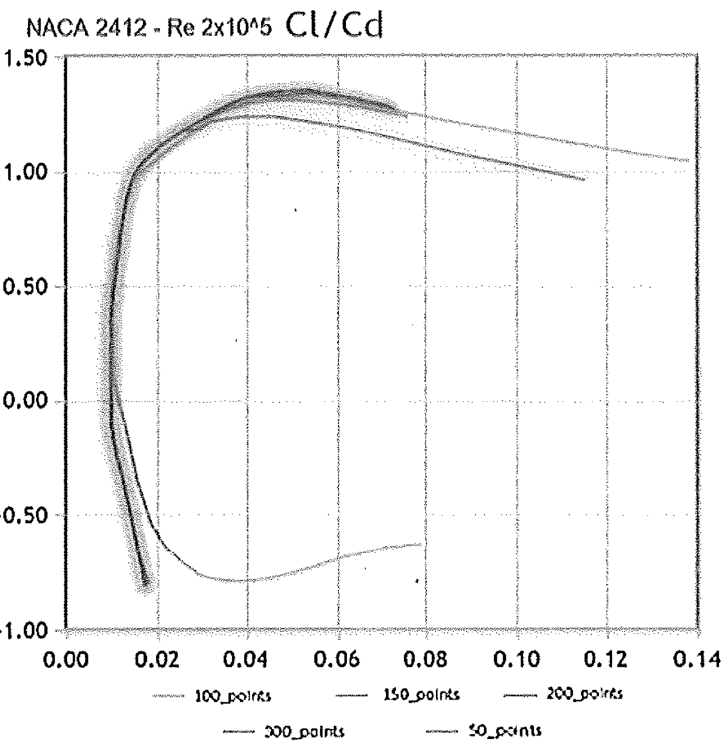

Fig. 3 Fidelity analysis from number of panels in the geometry of airfoils

number as the working condition of the fixed wing of SUAVs, it is for sure a precious reference for the fidelity analysis.

The airfoils tested are CAL 2263 and E 387 (selected randomly from the summary) to verify the fidelity of the software. The drag polars from the analysis versus the experimental data are plotted in the following figures.

As the drag polars plotted, the difference between the parameters acquired, especially XFLR5's calculation is quite precise (about 10 % error on high lift coefficient or below 0 lift coefficient). These error comes from the software unability to predict the high flow separation at trailing edge, laminar separation bubbles and the behavior of airfoil beyond stall angle. Even though XFLR5 gives more accuracy results, sometimes the solutions from XFLR5 can't be acquired due to the divergence of the iterations when Javafoil always manage to get the prediction of the parameters. That is why JavaFoil is also mentioned in this paper.

However, with SUAVs' working condition, these 'critical' cases are normally gone in seconds with an appropriate control reaction thus they won't affect their performance (Figs. 4, 5 and 6).

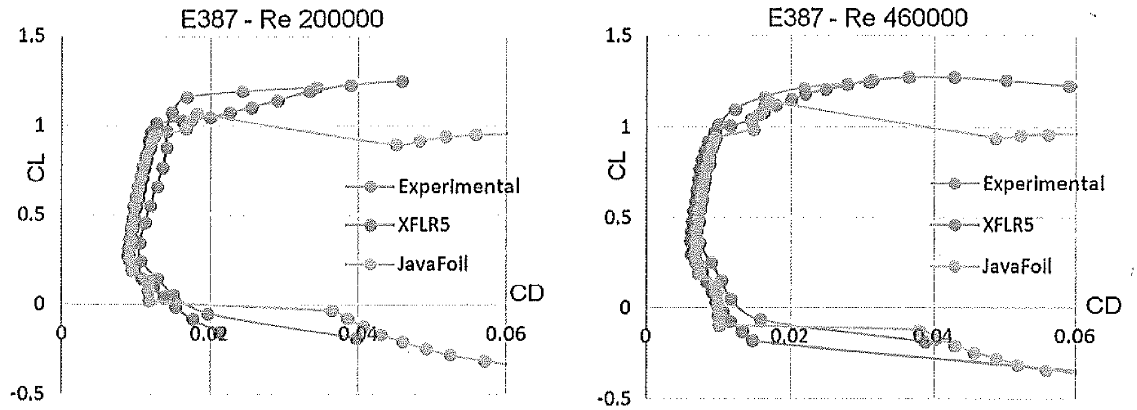

Fig. 4 Drag polars of E 387 airfoil at Reynolds number of 200 000 and 460 000

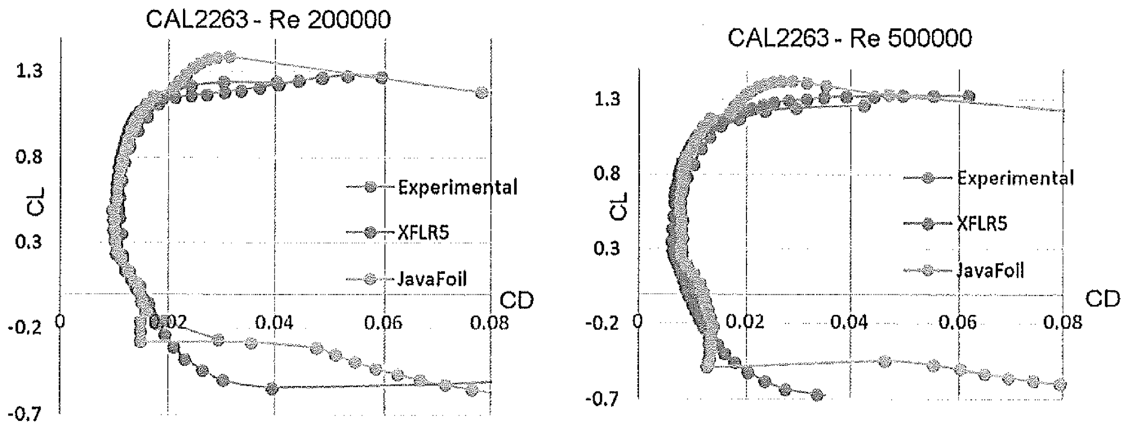

Fig. 5 Drag polars of CAL 2263 airfoil at Reynolds number of 200 000 and 500 000

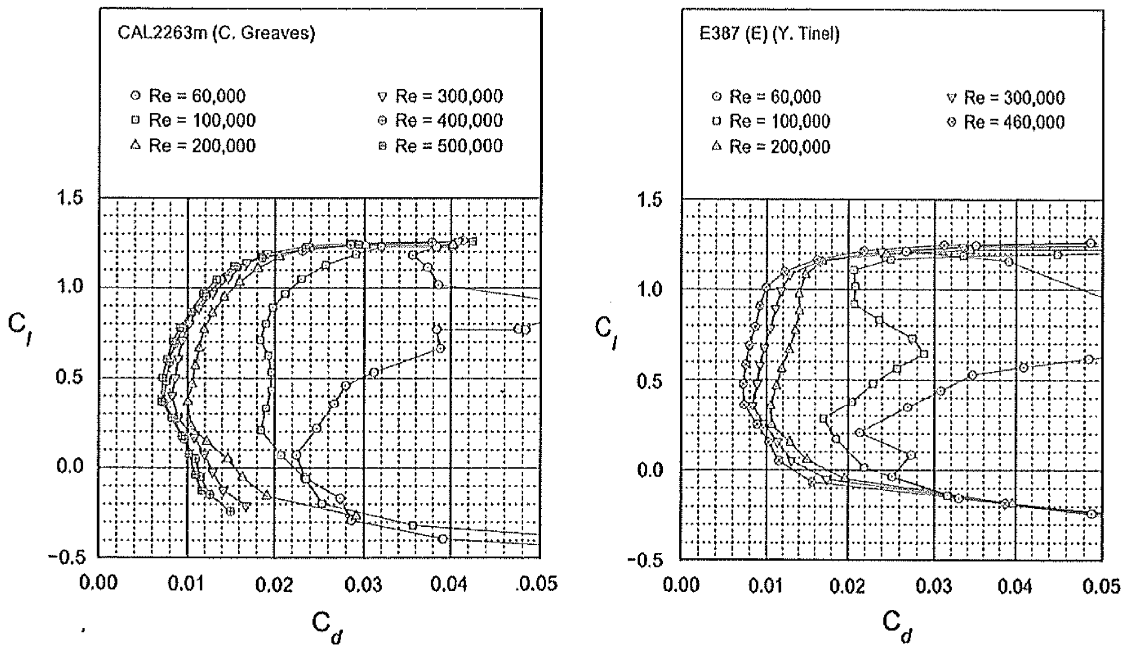

Fig. 6 Data published in summary of low-speed airfoil data, vol 5 about E 387 and CAL 2263

4 Airfoil Selection Method

4.1 Parameters Criteria

A set of criteria for the best performance of the SUAVs have to be set in order to select the best airfoil [8]. The criteria for each parameters is shown in the table below.

Note that there is no 'ultimate' airfoil that can respond to all the criteria as above. Therefore, a selection method is needed to optimize the airfoil selection. Weighted Scoring Method (WSM) is a selection method comparing multi criteria. It includes determining all the criterias related to the selection, giving each criteria a weighted score to reflect their relative importance and evaluation of each criteria.

With: C_{lo}: lift coefficient at angle of attack equal to 0°; C_{l_max}: maximum lift coefficient; α_{stall}: stall angle of attack; C_{d_min}: minimum drag coefficient; C_l/C_{d_max}: maximum of the range parameter; $C_l^{3/2}/C_{d\_max}$: maximum of the endurance parameter and $C_{m,c/4}$: pitching moment coefficient.

WSM consists of the following steps:

- Determining all the criteria.
- Distributing to each criteria a weighted score.
- Evaluating each criteria of an option.
- Multiplying the points evaluated by the weighted score.
- Making sum of all the products and selecting the airfoil with highest total points.

Table 1 Evaluation criteria of each parameter and the weighted scored for SUAVs

Parameter	Evaluation criteria	Weighted scored for fixed wing of SUAVs
C_{l0}	Close to Clcruise is the best	0.15
C_{l_max}	Highest is the best	0.15
α_{stall}	Highest is the best	0.15
C_{d_min}	Lowest is the best	0.15
C_l of C_min	Close to cruise is the best	
C_l/C_{d_max}	Highest is the best	0.15
C_l of C_l/C_{d_max}	Lowest is the best	
$C_l^{3/2}/C_{d\_max}$	Highest is the best	0.2
C_l of $C_l^{3/2}/C_{d\_max}$	Lowest is the best	
$C_{m,c/4}$	Low magnitude is best	0.05

4.2 *Proposal of a Set of Weighted Score for Fixed Wing of SUAVs*

For most of the fixed wing of SUAVs, the most important criterias are: High endurance/range, Easy to take-off, High performance, Easy to control.

These criterias can be interpreted as parameters as C_{lo}, C_{l_max}, α_{stall}, C_{d_min}, C_l/C_{d_max}, $C_l^{3/2}/C_{d\_max}$ and $C_{m,c/4}$. According to the demand of the customer which focus more on what he wants, a set of weighted score will be determined. Table 1 proposes a set of weighted score focusing more on the high endurance and less on the maneuverability since the design object is the fixed wing of SUAVs [9, 10].

5 Case Study

The recent design project of VSKYLINE Ltd. is for a SUAV having the following requirements: operating velocities from 60 to 100 km/h; take-off by hand-launch; operating altitude of 500 m; flight endurance of 60–90 min; maximum payload of 2 kg.

After the sizing steps (see Fig. 1), the aspect ratio (AR_w) of the SUAV's wing is 8 and the operating Reynolds number is 600 000.

5.1 *Airfoil Database*

The airfoil set utilized in the selection are the ones performing at the operating Reynolds number. They are gathered from [5–7] (see Table 2).

Table 2 Airfoil database for small UAVs

No.	Airfoil	Thickness (%)	Camber (%)	No.	Airfoil	Thickness (%)	Camber (%)
1	AG12	6.24	1.85	11	RG14	8.47	1.58
2	AG16	7.11	1.87	12	RG15	8.92	1.76
3	AG24	8.41	2.21	13	S7012	8.75	2.02
4	AG35R	8.72	2.38	14	S8064	12.33	1.18
5	CAL1215 J	11.72	2.28	15	S9000	9.01	2.37
6	CAL2263 M	11.72	3.52	16	SA7035	9.19	2.55
7	CAL4014L	10.00	1.84	17	SA7036	9.20	2.79
8	E231	12.33	2.46	18	SD7037	9.20	3.02
9	E374	10.91	2.25	19	SD7080	9.15	2.48
10	E387	9.07	3.80				

The AG airfoils which serve mainly for sailplanes were designed by Dr. Mark Drela from MIT. The CAL airfoils were designed by Christopher Lyon, the former member of the UIUC LSATs team (the University of Illinois at Urbana-Champaign Low-Speed Airfoil Tests team). The Eppler airfoils were designed by the code written by Prof. Richard Eppler, a pioneer of computational aerodynamics. The RG airfoils were designed by Rolf Girsberger based on Prof. Eppler code with some modifications for flexibility in modifying thickness and camber. The S airfoils were designed by Prof. Michael Selig from UIUC. The SD airfoils were designed by Prof. Michael Selig and John Donovan. The SA 7035 and SA 7036 airfoils were designed based on SD 7037 due to its popularity.

5.2 *Airfoil Analysis Results*

As discussed above, the airfoils are analyzed by XFLR5, the airfoil having the most preferable result in each criteria gets 04 points when the least preferable one gets 01 points. The points for other airfoils are calculated linearly.

The analysis result is shown in Fig. 7. As CAL 2263 M has the highest scoring points among the airfoils analyzed based on the criteria set, this airfoil is chosen for the SUAV. It can be seen that even though CAL 2263 M doesn't have the highest point in the criteria of maximum range and endurance parameter, it is still chosen as the most appropriate airfoil.

From this case study, the Weighted Scoring Method offers clearly a comprehensive way to select the most appropriate airfoil for the best performance of the aircraft.

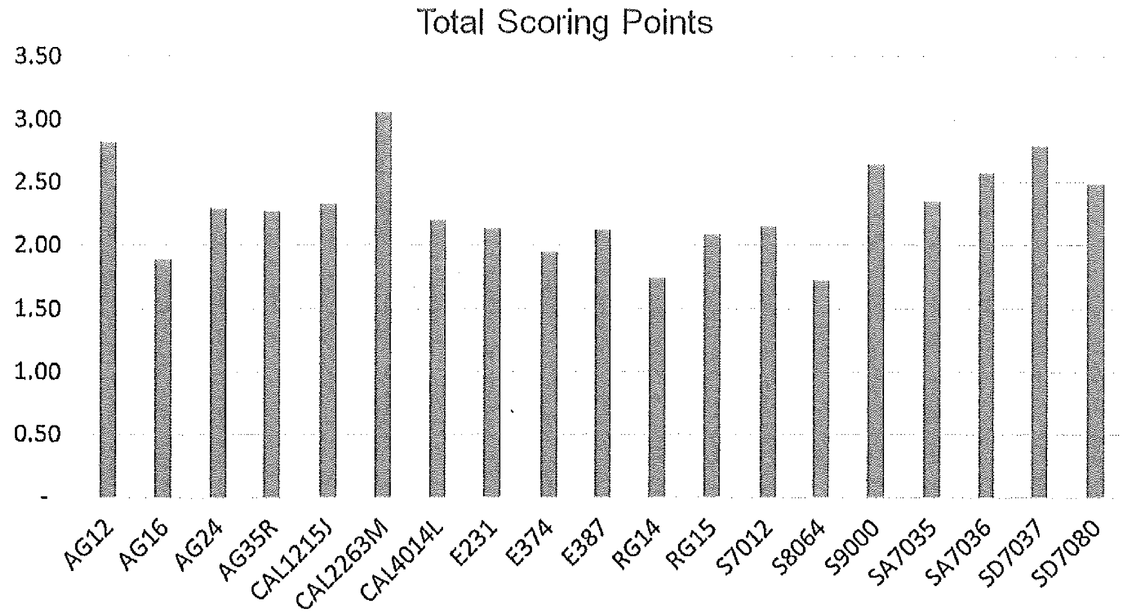

Fig. 7 Total scoring points of each airfoil tested

6 Conclusion

XFLR5 and JavaFoil with the Weighted Scoring Method offers a comprehensive and trustworthy approach for aircrafts designers to select the most appropriate airfoil to the requirements for SUAVs. Moreover, the airfoil selected can be then optimized by higher fidelity tools to ensure the best performance for SUAVs.

The airfoil selection is very important and necessary for designers to move to another steps such as multidisciplinary analysis and optimization.

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