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THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE FUSELAGE INFLUENCE ON THE WING AERODYNAMIC CENTER POSITION AT LOW SPEED CONDITIONS

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Abstract. *The wing aerodynamic center is the point where the pitching moment coefficient is constant, independent of the aircraft angle of attack. It is used as the reference point for longitudinal static stability and equilibrium calculations of the airplane. For subsonic flight and wing incidences up to 10 degrees, it is located between 23% and 25% of the mean aerodynamic chord behind the leading edge. The fuselage influence on the wing aerodynamic center position must be considered at the design phase. It moves the aerodynamic center position towards to the leading edge by some amount that could not be exactly calculated, but predicted by methods based on wind tunnel data and potential flow theory. This work presents a comparative analysis to indicate the most accurate between seven of these theoretical methods, using six configurations of wing-fuselage reduced scale models, with the dimensional proportions found in light aviation, at a low speed open circuit wind tunnel with a closed test section. The experimental aerodynamic center positions of the wing alone and of the wing-fuselage models have been found by using the distance of the balance trunnion to the wing leading edge, and the derivation of the pitching moment coefficient relative to the lift coefficient, for a range of angles of attack. The theoretical methods have been applied to all configurations of wing-fuselage models. The results show that most of the theoretical methods predict variations in aerodynamic center position in the same way as those obtained experimentally. The comparative analysis between theoretical and experimental results indicates the method from ESDU (Engineering Sciences Data Unit) as the most accurate.*

Keywords: *aircrafts, aerodynamic center, fuselage influence, aerodynamic interference.*

1. INTRODUCTION

At the design phases of an aircraft, an essential analysis to be carried out is over its stability and equilibrium states. An aircraft is at longitudinal static equilibrium state if the sum of the moments around its center of gravity is equal to zero, which means that its moment coefficient is null. This aircraft moment coefficient comprehends all separated contributions of wings, fuselage, horizontal stabilizer and propulsive systems. The wing contribution to the aircraft longitudinal static stability takes into account the forces and moments actuating on its aerodynamic center, which is the point located close to the mean aerodynamic chord line. At the aerodynamic center, the pitching moment coefficient is constant, independent of the aircraft angle of attack. Therefore, the aerodynamic center position is one of the most important parameters on aircraft stability analysis. Houghton and Carpenter (2003) enunciate that for subsonic flight and wing incidences up to 10 degrees, it is located between 23% and 25% of the mean aerodynamic chord behind the leading edge. As demonstrated by Phillips, *et al.*, 2008, changes in wing geometry could move the aerodynamic center position beyond this range. For wings with constant taper and quarter chord sweep angle, at subsonic flow, the wing aerodynamic center position will depend on its aspect ratio, taper ratio and quarter chord sweep angle, whilst camber, thickness and washout (or washin) have no significant effect over the wing aerodynamic center position.

According to Etkin and Reid (1996), the fuselage contribution to the aircraft longitudinal static stability is highly complex. As exposed by Perkins and Hage (1949), these contributions are almost always destabilizing. The aerodynamic interference effects due to fuselage influence could be summarized as a movement of the aerodynamic center position towards to the leading edge, an increment at the wing lift curve slope, and a decrease in the pitch moment coefficient at the wing aerodynamic center.

The wing aerodynamic center position shift due to the fuselage influence could not be exactly calculated, but only predicted by methods based on wind tunnel data and potential flow theory. A detailed research conducted in the present work has enumerated a list of seven relevant theoretical methods that were developed for obtaining it. These methods defer from each other by their wide range of geometrical and aerodynamic parameters used in order to obtain the final results. Furthermore, each method has its own sources of obtaining those parameters, such as historical data, wind tunnel test results, interactive graphs or analytical formulas. As a consequence of this, each method will provide a different result for the aerodynamic center position shift due to fuselage influence, leading design engineers to face a dilemma when choosing the most appropriated one, with almost any comparative analysis between them available.

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This work presents a comparative analysis to indicate the most accurate between these seven theoretical methods for predicting the aerodynamic center position shift due to fuselage influence at low speed conditions, helping engineers for addressing the appropriated choice. Six configurations of wing-fuselage reduced scale models were tested at a low speed open circuit wind tunnel for determining their aerodynamic center positions. Next, the theoretical methods were applied to these models, followed by a comparative analysis between experimental and theoretical results.

2. PROCEDURES AND MATERIALS

In this section, an overview of all the procedures applied and materials used is given, followed by an explanation about the methodology for analyzing the obtained results.

2.1 Wind Tunnel Tests

The wing scale model was built in solid wood, based on GA(W)-1 airfoil profile. As described by McGhee and Beasley (1973), it is a 17% thickness airfoil developed for low speed applications. The wing planform is rectangular, with a constant chord length of 0.148 m and span of 0.377 m (which in true is a semi-span, as the half-model concept was adopted). A balance trunnion of 0.012 m diameter is located vertically over the airfoil chord line, 0.042 m behind the leading edge, which gives 0.284 (or 28.4%) in chord fraction. The fuselage scale model was built using the half-model concept, being divided into three segments: forward, central and rear fuselage. The central fuselage segment has a semi-circular form, with a constant diameter of 0.075 m and 0.200 m length, made of polyvinyl chloride (PVC), with a notch for the accommodation of the wing at middle position. The PVC part was attached to a wood basis by using screws (the wood basis led to an increase of the wing semi-span from 0.377 m to 0.385 m). Forward and rear parts were modeled in expanded polystyrene by using a hot wire cutting process and sandpapers. Then, they were attached to a wood basis, which could be hooked to the central fuselage part by a notch.

Maximum and minimum fuselage scale model lengths were based on a research of the usual wing span per fuselage length ratios for light aviation, calculated using data provided by Jackson, *et al.*, 2004, as detailed on Tab. 1:

Table 1. Light aviation wing span and fuselage length typical values.

Aircraft	Seats	Wing Span (m)	Fuselage Length (m)	Ratio Wing Span / Fuselage Length
Beech A36 Bonanza	6	10.21	8.38	1.22
Cessna 172 Skyhawk	4	11.00	8.28	1.33
Piper PA-28R-201 Arrow	4	10.80	7.52	1.44
Cirrus SR22	4	11.73	7.92	1.48

Therefore, we adopted maximum and minimum fuselage lengths of 0.690 m and 0.490 m, resulting in wing span per fuselage length ratios from 1.12 to 1.57, covering the usual range showed in Tab. 1. For the forward fuselage, two symmetrical semi-cones were manufactured, one with 0.200 m and other with 0.100 m length. For the rear fuselage, besides two symmetrical semi-cones of 0.290 m and 0.190 m length, a third asymmetrical semi-cone of 0.290 m length was manufactured to evaluate the effects of the rear fuselage lateral shape by maintaining its top at the same level of the central fuselage top. So, six wing-fuselage configurations could be set up as shown in Fig. 1 to Fig. 6. Observe that their names (configuration 1, configuration 2…) will be used as a reference from this point of the text.

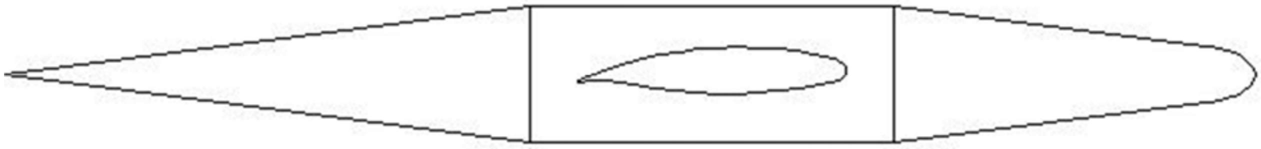

Figure 1. Configuration 1: extended forward and rear fuselage segments, total length of 0.690 m (scale 1:4).

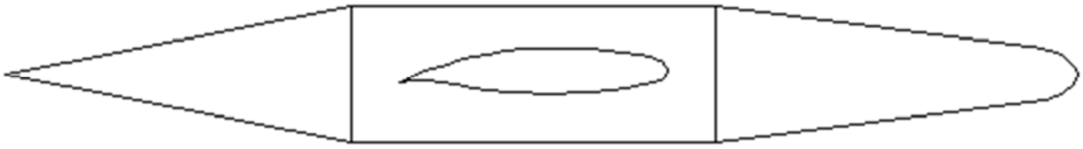

Figure 2. Configuration 2: extended forward and short rear fuselage segments, total length of 0.590 m (scale 1:4).

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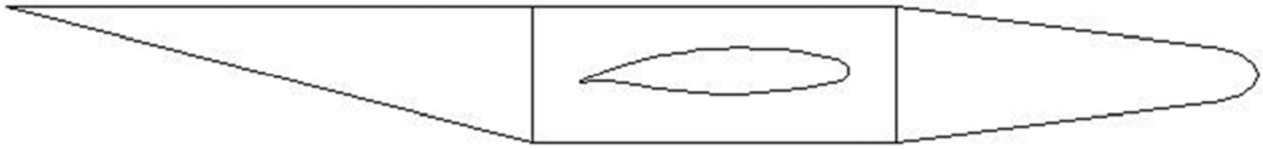

Figure 3. Configuration 3: extended forward and asymmetrical rear fuselage segments, total length of 0.690 m (scale 1:4).

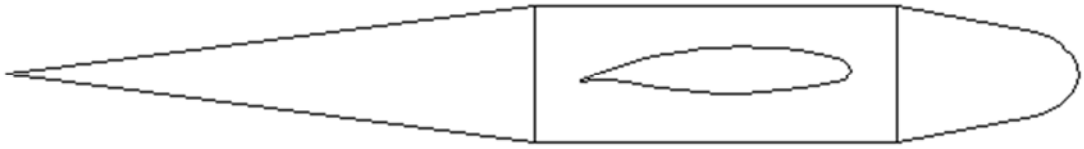

Figure 4. Configuration 4: short forward and extended rear fuselage segments, total length of 0.590 m (scale 1:4).

Figure 5. Configuration 5: short forward and rear fuselage segments, total length of 0.490 m (scale 1:4).

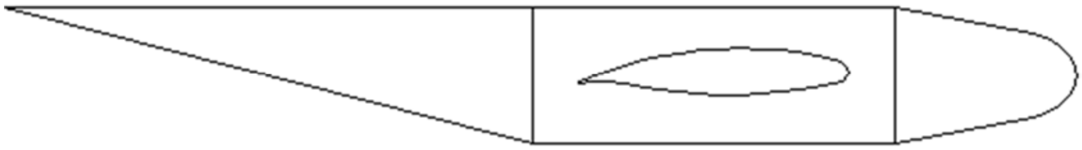

Figure 6. Configuration 6: short forward and asymmetrical rear fuselage segments, total length of 0.590 m (scale 1:4).

A low speed open circuit wind tunnel with a closed rectangular test section of 0.46 per 0.46 m was used for testing at the Aerodynamic Laboratory of the Aeronautical Engineering Department of USP (Universidade de São Paulo), located at São Carlos city.

Figure 7. Model at wind tunnel test section.

Experimental aerodynamic centers were obtained through a procedure described by Barlow, *et al.*, 1999, where their position in chord fraction (ac) is a function of the distance of the leading edge to the balance trunnion (tr, in this case, 0.284) and the derivative of the pitching moment coefficient at the balance trunnion (C_{Mtr}) relative to the lift coefficient at the aerodynamic center (C_L), as shown in Eq. (1) and Fig. 8.

$$ac = tr - \left(dC_{Mtr} / dC_L\right) \tag{1}$$

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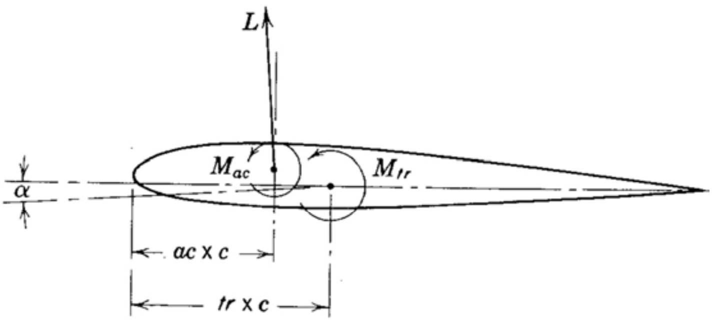

Figure 8. Geometry and parameters used for calculating the wing aerodynamic center position for a wind tunnel test (Barlow, *et al.*, 1999).

An aerodynamic balance assembled to the wing trunnion provided the aerodynamic forces values F_{fore} and F_{aft} (newtons, centesimal precision), while the dynamic pressure (P_{din}) was obtained from a digital manometer (pascals, decimal precision).

Figure 9. Aerodynamic balance and digital manometer.

The acquisition system mentioned above, plus the values of the moment arm between the measured forces (0.0635 m), wing chord (c) and wing planform area (A) provided all the data needed for calculating the lift and pitch moment coefficients by the following equations:

$$C_L = \frac{F_{fore} + F_{aft}}{P_{din}.A} \tag{2}$$

$$M = P_{din}.A.C_{Mtr}.c \rightarrow C_{Mtr} = \frac{0.0635.(F_{fore} - F_{aft})}{P_{din}.A.c} \tag{3}$$

So, the derivative in Eq. (1) was calculated by measuring C_{Mtr} and C_L for a wide range of angles of attack (-6 to 20 degrees for the wing alone; -3 to 17 degrees for configurations 1 to 6 of wing-fuselage models), and then extracting the slope from the linear portion (in this case, between -3 and 9 degrees) of the C_{Mtr} vs. C_L plots. Due to limitations imposed to the flow around the model by the wind tunnel walls and geometry, corrections for the dynamic pressure (three-dimensional solid blockage) and angle of attack (method of images), as detailed by Barlow, *et al.*, 1999, were applied for all test results.

2.2 Application of the Theoretical Methods

Here, a short description of the seven theoretical methods used for predicting the aerodynamic center shift due to the fuselage influence is given, reminding that all of them were applied to the reduced scale models. It is important to observe that the detailed description of how to obtain all mentioned variables for applying these methods could be found by consulting their respectively references at the end of this work.

Based on wing tunnel data provided by Jacobs and Ward (1935), Diehl (1942) developed an equation for obtaining the aerodynamic center position over the wing mean aerodynamic chord, $\Delta X_{a.c.}$, considering the fuselage influence:

$$\Delta X_{a.c.} = -0.080.\left(\frac{X}{L}\right).\left(\frac{A}{S}\right).\left(\frac{L}{c}\right) \tag{4}$$

Where X is the fuselage length ahead the wing quarter chord axis; L is the fuselage length; A is the fuselage planform area; S is the wing area and c the wing chord. It is useful to comment that this is the only method which gives as a result the aerodynamic center position of the wing-fuselage combination in chord fraction ahead of the quarter chord axis, whereas all other methods give the forward shift in chord fraction (which has to be subtracted from the original wing aerodynamic center position to find the wing-fuselage aerodynamic center position) as a result.

The Anscombe and Raney (1950) method is based on potential flow and low speed wind tunnel data. The aerodynamic center position shift in chord fraction due to the fuselage influence, ΔK_n, is given by:

$$\Delta K_n = -\Delta_{10}.\left(\frac{\Delta_A}{\Delta_{10}}\right).k.\frac{c.D^2}{a.S.\bar{c}} \tag{5}$$

Where c is the wing root chord; D is the fuselage width (or diameter) at the wing leading edge section; a is the wing lift curve slope; S is the wing area, and $\bar{c}$ is the wing mean chord; the factors Δ_{10}, $\left(\frac{\Delta_A}{\Delta_{10}}\right)$ and k are obtained by curves that are available at Anscombe and Raney (1950).

Torenbeek (1982) method could be synthesized by the following equation when applied to a rectangular wing:

$$\left(\frac{\Delta x_{ac}}{\bar{c}}\right) = -\frac{1.8}{(C_{L\alpha})_{wf}}.\frac{b_f.h_f.l_{fn}}{S.\bar{c}} \tag{6}$$

Where $\left(\frac{\Delta x_{ac}}{\bar{c}}\right)$ is the aerodynamic center position shift in chord fraction; $(C_{L\alpha})_{wf}$ is the wing-fuselage lift curve slope; b_f is the fuselage maximum width, and h_f its maximum height; l_{fn} is the fuselage length ahead the wing root chord; S is the wing area, and $\bar{c}$ is the wing mean chord.

The method presented by Roskam (1982) uses the derivation of the pitching moment relative to the angle of attack for asymmetrical bodies (in this case, the fuselage), $\frac{dM}{d\alpha}$, for obtaining the aerodynamic center position shift in chord fraction, $\Delta \bar{X}_{ac_B}$:

$$\Delta \bar{X}_{ac_B} = \frac{-\frac{dM}{d\alpha}(fuselage)}{\bar{q}.S.\bar{c}.C_{L\alpha w}(wing)} \tag{7}$$

The other terms of the equation above are defined as: $\bar{q}$, the dynamic pressure; S, the wing area; $\bar{c}$, the wing mean chord; and $C_{L\alpha w}$, the wing lift curve slope.

Stinton (1983) developed a simplified method where the aerodynamic center position shift in chord fraction Δh_0 is:

$$-\Delta h_0 = \frac{\{-0.75.[0.25.A_{nose} + 0.5.(A_{nose}/A)]\}}{\{[0.25.A_{nose} + 0.5.(A_{nose}/A)] + [S/S_{nose}]\}} \tag{8}$$

Where parameter A_{nose} is the ratio of the fuselage maximum width by its length ahead the quarter chord axis; A is the wing aspect ratio; S is the wing area and S_{nose} the fuselage planform area ahead the quarter chord axis.

Etkin and Reid (1996) describe a graphical method based on wing tunnel data for calculating the influence of the fuselage and nacelles on the airplane neutral point (which is the equivalent aerodynamic center of the whole airplane, including also the propulsive system and tail contributions), and so could be used for calculating the aerodynamic center position shift Δh_n (in chord fraction) for a wing-fuselage configuration by entering these parameters in the following curves: c, the wing root chord; $\bar{c}$ the wing mean chord; w, the fuselage maximum width; S, the wing area, l, the fuselage length, and l_N, the fuselage length ahead the quarter chord axis:

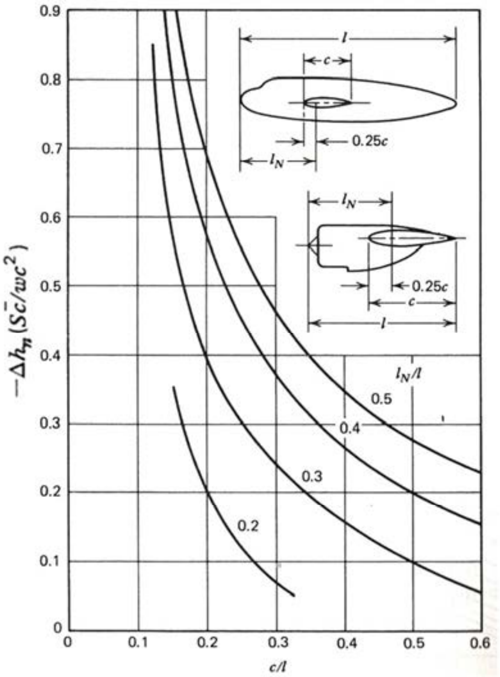

Figure 10. Fuselage and nacelle effects on neutral point position (Etkin and Reid, 1996).

Finally, ESDU (1996) provided a method for predicting the aerodynamic center position shift in fraction of the mean chord, $\frac{\Delta x_h}{\bar{\bar{c}}}$, by the use of Eq. (9):

$$\frac{\Delta x_h}{\bar{\bar{c}}} = \frac{c_r . d^2 . F . G}{\bar{\bar{c}} . a . S} . \left[1 + 0.15 . \left(\frac{h}{d} - 1 \right) \right] - \left(K_1 + \lambda . K_2 \right) \tag{9}$$

Where c_r is the root chord of equivalent wing planform; d is the width of fuselage at leading edge of root chord of equivalent wing planform; $\bar{\bar{c}}$ is the aerodynamic mean chord of equivalent wing planform; a is the lift curve slope of equivalent wing planform; S is the area of equivalent wing planform; h is the height of fuselage at leading edge of root chord of equivalent wing planform; λ is the taper ratio of equivalent wing planform; F, G, K_1 and K_2 are functions used in estimating effect of fuselage on aerodynamic center position, obtained from curves presented in ESDU (1996).

2.3 Methods of Results Analysis

After determining the experimental aerodynamic center positions for the wing alone and for six wing-fuselage scale models, the theoretical methods were applied for obtaining the aerodynamic center position shifts of the scale models due to the fuselage influence. Then, those calculated theoretical shifts were summed to the wing alone experimental aerodynamic center position for obtaining the theoretical aerodynamic center positions of wing-fuselage configurations. Next, an analysis took place by comparing the percentage differences from the theoretical results relative to the experimental aerodynamic center positions, considering the uncertainties induced by measure instruments and approximations assumed for obtaining curve slopes from experimental results. The main features analyzed for each theoretical method were: the influence of the forward fuselage length (comparing the pairs of configurations 1 and 4, 2 and 5, 3 and 6); the influence of the rear fuselage length (comparing the pairs of configurations 1 and 2, 4 and 5); and the influence of the rear fuselage lateral shape (comparing the pairs of configurations 1 and 3, 4 and 6).

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3. RESULTS

Figure 11 to Fig. 17 show the curves of the most relevant aerodynamic coefficients obtained in wind tunnel tests.

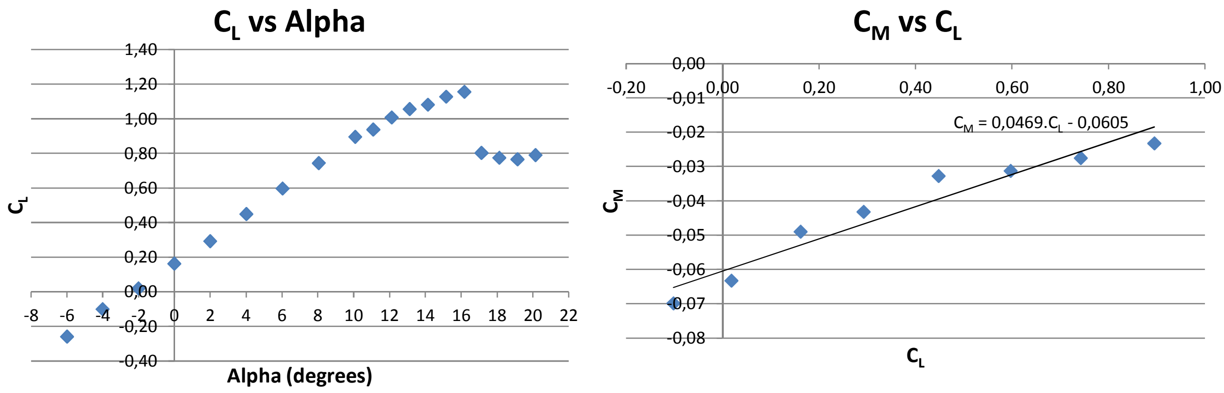

Figure 11. Wing alone - aerodynamic coefficients.

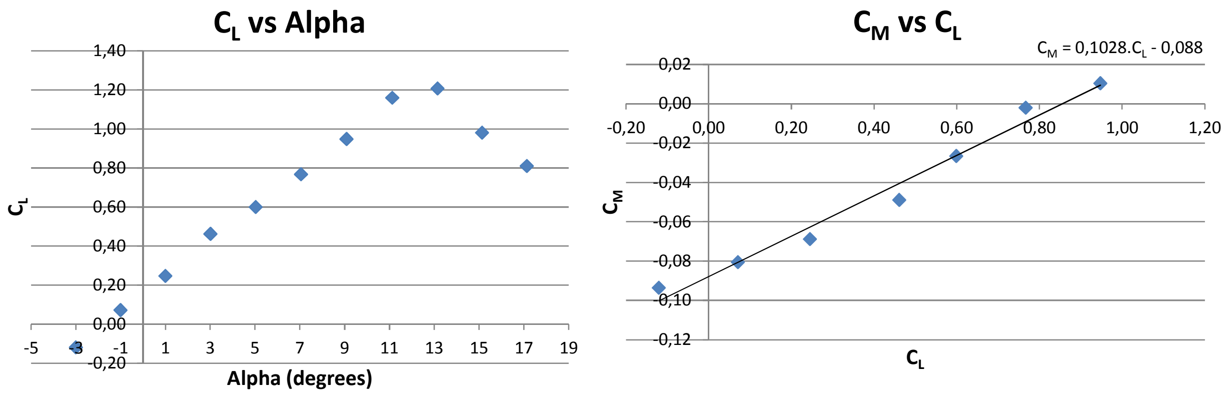

Figure 12. Configuration 1 - aerodynamic coefficients.

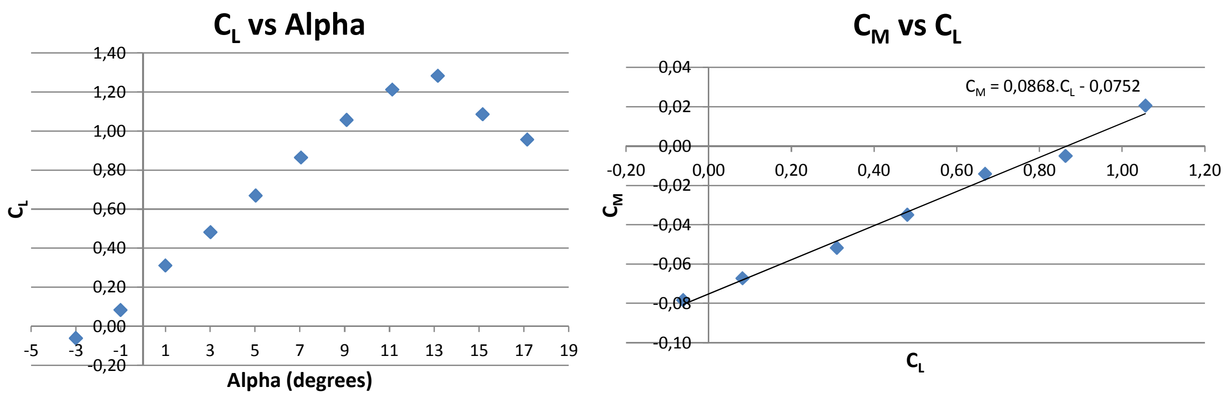

Figure 13. Configuration 2 - aerodynamic coefficients.

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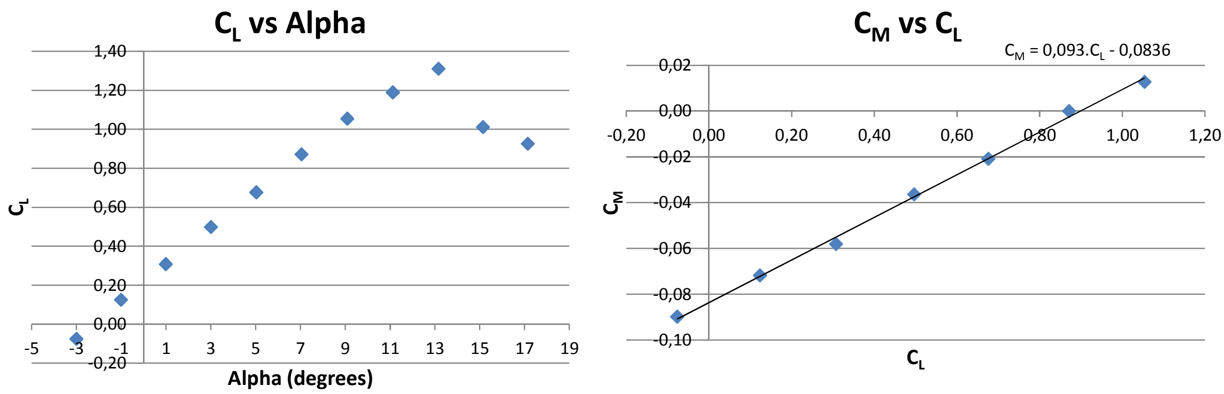

Figure 14. Configuration 3 - aerodynamic coefficients.

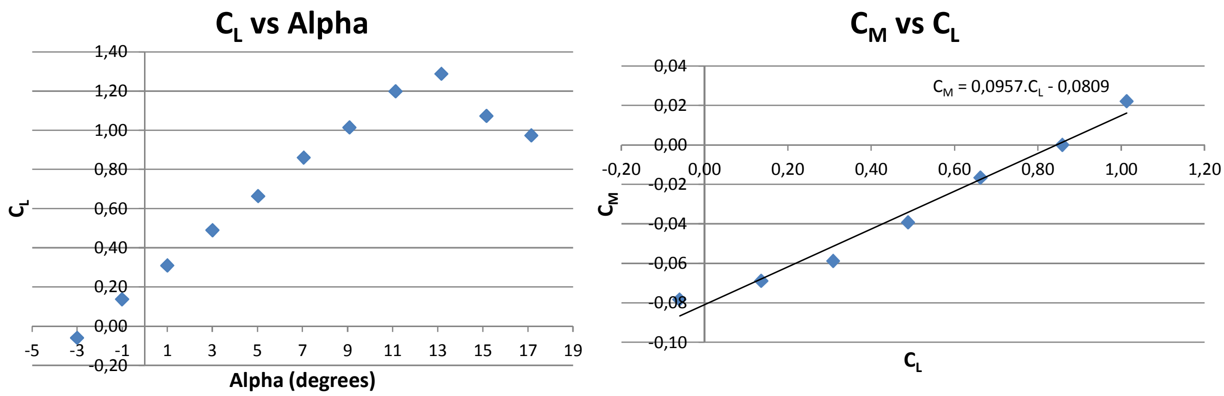

Figure 15. Configuration 4 - aerodynamic coefficients.

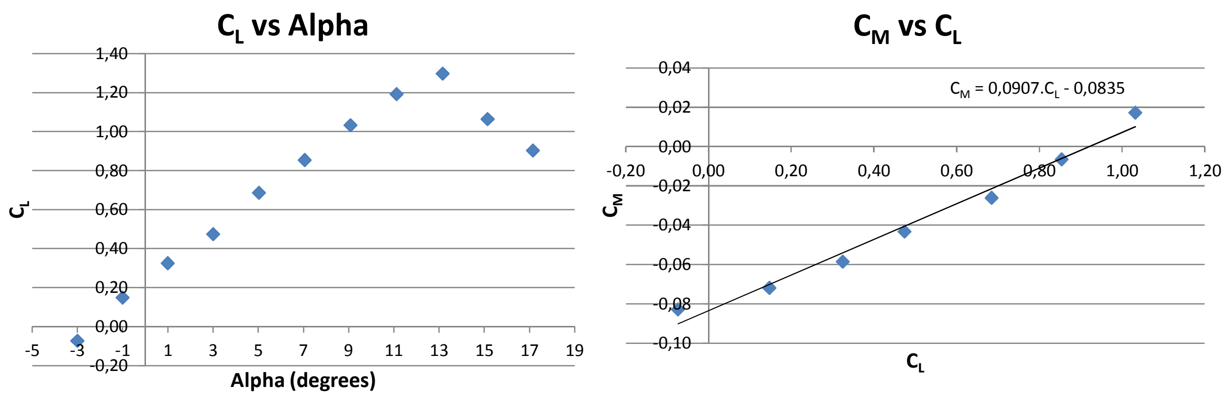

Figure 16. Configuration 5 - aerodynamic coefficients.

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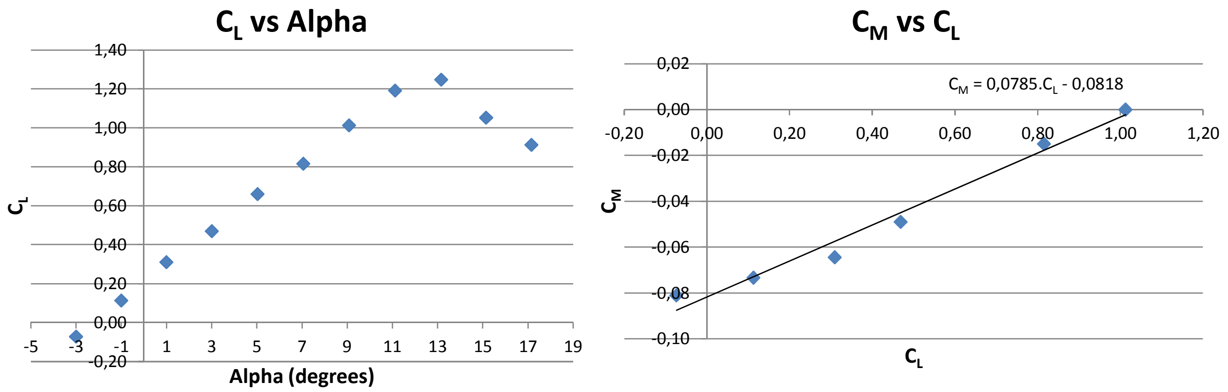

Figure 17. Configuration 6 - aerodynamic coefficients.

All acquired data were statistically analyzed and processed according to the guidelines suggested by Lapponi (2005). Experimental results for lift and pitching moment coefficients plotted above showed compliance with results found in aeronautical literature. Applying Eq. (1) to the data obtained in Fig. 11, the aerodynamic center position of the wing alone in chord fraction is calculated as 0.237 (or 23.7%), which also has an excellent compliance with the typical values between 23% and 25% found in the literature review for a low-speed wing. This same methodology was applied from Fig. 12 to Fig. 17 for calculating the experimental aerodynamic center positions of the six wing-fuselage scale models. Table 2 shows the aerodynamic center positions obtained from experimental tests and theoretical methods.

Table 2. Experimental and theoretical results for the wing-fuselage aerodynamic center positions in chord fraction.

Wing-fuselage configurations	Aerodynamic Center Positions of Wing-Fuselage Scale Models (chord fraction)							
	Experimental	Diehl	Anscombe and Raney	Torenbeek	Roskam	Stinton	Etkin and Reid	ESDU
1	0.181	0.206	0.197	0.210	0.208	0.228	0.188	0.191
2	0.197	0.210	0.200	0.212	0.208	0.228	0.189	0.194
3	0.191	0.206	0.200	0.211	0.208	0.228	0.188	0.191
4	0.188	0.226	0.211	0.222	0.213	0.227	0.212	0.208
5	0.193	0.229	0.214	0.222	0.213	0.227	0.210	0.211
6	0.205	0.226	0.214	0.222	0.213	0.227	0.212	0.208

On Tab. 3, the percentage differences from each theoretical method result relative to the experimental results are given. For a better comprehension, some averages (called "Av.") for relevant configuration combinations were included. Moreover, the best and worst result of each line (the lowest and highest absolute percentage difference) had their cells highlighted respectively in green and red.

Table 3. Percentage differences from the theoretical results relative to the experimental aerodynamic center positions.

Wing-fuselage configurations	Percentage Difference in Aerodynamic Center Positions						
	Diehl	Anscombe and Raney	Torenbeek	Roskam	Stinton	Etkin and Reid	ESDU
1	13.6%	8.9%	16.0%	14.9%	25.8%	3.8%	5.7%
2	6.8%	1.4%	7.4%	5.8%	15.6%	-4.0% (1)	-1.8%
3	7.8%	4.7%	10.8%	9.0%	19.3%	-1.5%	0.3%
4	20.1%	12.4%	18.1%	13.2%	20.4%	12.7%	10.7%
5	18.5%	10.9%	15.1%	10.5%	17.3%	8.6%	9.1%
6	10.0%	4.2%	8.2%	3.7%	10.3%	3.3%	1.4%
Av. conf. 1 to 6	12.8%	7.1%	12.6%	9.5%	18.1	5.7%	4.8%
Av. conf. 1 to 3	9.4%	5.0%	11.4%	9.9%	20.2	3.1%	2.6%
Av. conf. 4 to 6	16.2%	9.2%	13.8%	9.1%	16.0	8.2%	7.1%
Av. conf. 1 and 4	16.9%	10.6%	17.0%	14.0%	23.1	8.3%	8.2%
Av. conf. 2 and 5	12.6%	6.2%	11.3%	8.1%	16.4	6.3%	5.4%
Av. conf. 3 and 6	8.9%	4.4%	9.5%	6.3%	14.8	2.4%	0.9%

(1) negative percentage values means that the theoretical aerodynamic center is located ahead the experimental one.

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Table 4 and Tab. 5 were built considering the uncertainties over the experimental aerodynamic center positions.

Table 4. Results considering positive uncertainties over the experimental aerodynamic center positions.

Wing-fuselage configurations	Percentage Difference in Aerodynamic Center Positions						
	Diehl	Anscombe and Raney	Torenbeek	Roskam	Stinton	Etkin and Reid	ESDU
1	9.5%	5.0%	11.8%	10.7%	21.2%	0.0%	1.9%
2	4.8%	-0.5% (1)	5.4%	3.8%	13.4%	-5.8%	-3.6%
3	6.6%	3.6%	9.6%	7.8%	18.0%	-2.6%	-0.8%
4	16.1%	8.6%	14.1%	9.4%	16.4%	8.9%	7.0%
5	15.0%	7.7%	11.7%	7.2%	13.8%	5.4%	5.9%
6	7.0%	1.3%	5.1%	0.8%	7.3%	0.4%	-1.4%
Av. conf. 1 to 6	9.8%	4.4%	9.6%	6.6%	15.0%	3.9%	3.4%
Av. conf. 1 to 3	7.0%	3.0%	8.9%	7.4%	17.6%	2.8%	2.1%
Av. conf. 4 to 6	12.7%	5.9%	10.3%	5.8%	12.5%	4.9%	4.8%
Av. conf. 1 and 4	12.8%	6.8%	12.9%	10.0%	18.8%	4.5%	4.4%
Av. conf. 2 and 5	9.9%	4.1%	8.6%	5.5%	13.6%	5.6%	4.7%
Av. conf. 3 and 6	6.8%	2.4%	7.4%	4.3%	12.6%	1.5%	1.1%

(1) negative percentage values means that the theoretical aerodynamic center is located ahead the experimental one.

Table 5. Results considering negative uncertainties over the experimental aerodynamic center positions.

Wing-fuselage configurations	Percentage Difference in Aerodynamic Center Positions						
	Diehl	Anscombe and Raney	Torenbeek	Roskam	Stinton	Etkin and Reid	ESDU
1	18.1%	13.2%	20.5%	19.4%	30.7%	7.9%	9.9%
2	8.8%	3.4%	9.5%	7.8%	17.8%	-2.2% (1)	0.1%
3	9.0%	5.8%	12.1%	10.2%	20.6%	-0.5%	1.4%
4	24.4%	16.4%	22.3%	17.3%	24.8%	16.8%	14.7%
5	22.2%	14.4%	18.7%	14.0%	21.0%	12.0%	12.5%
6	13.3%	7.3%	11.4%	6.8%	13.6%	6.3%	4.4%
Av. conf. 1 to 6	16.0%	10.1%	15.7%	12.6%	21.4%	7.6%	7.2%
Av. conf. 1 to 3	11.9%	7.5%	14.0%	12.4%	23.0%	3.5%	3.8%
Av. conf. 4 to 6	20.0%	12.7%	17.5%	12.7%	19.8%	11.7%	10.5%
Av. conf. 1 and 4	21.2%	14.8%	21.4%	18.3%	27.7%	12.3%	12.3%
Av. conf. 2 and 5	15.5%	8.9%	14.1%	10.9%	19.4%	7.1%	6.3%
Av. conf. 3 and 6	11.1%	6.6%	11.7%	8.5%	17.1%	3.4%	2.9%

(1) negative percentage values means that the theoretical aerodynamic center is located ahead the experimental one.

4. ANALYSIS

The method from ESDU (1996) provided the best agreement relative to experimental results for three configurations (3, 4 and 6), as shown in Tab. 3. Results showed that it predicts a greater forward shift in aerodynamic center positions as both forward and rear fuselage lengths increase, but it does not take into account the effects of maintaining the top of the rear fuselage at the same level of the central fuselage top, which could be realized by comparing on Tab. 2 the results between the pairs of configurations 1 and 3, 4 and 6.

The method from Etkin and Reid (1996) provided the best agreement relative to experimental results for two configurations (1 and 5), as shown in Tab. 3. It is observed from Tab. 2 that it predicts a greater forward shift in aerodynamic center positions as the forward fuselage lengths increases; however, this behavior was not observed respectfully to the rear fuselage lengths. As ESDU (1996) method, it does not take into account the effects of maintaining the top of the rear fuselage at the same level of the central fuselage top, as seen in Tab. 2.

The method from Anscombe and Raney (1950) provided the lowest percentage difference when compared with the experimental results for configuration 2. Analyzing Tab. 2, the following behaviors could be inferred: as both forward and rear fuselage lengths increase, the aerodynamic center will move forward; the same was observed by using a rear fuselage with a straight top, at the same level of the central fuselage top.

The method from Roskam (1982) provided intermediate results in terms of percentage differences from the experimental results, not achieving the lowest or highest difference for any scale model configuration. On Tab. 2, it is clearly shown that it predicts a greater forward shift in aerodynamic center positions as the forward fuselage lengths increases, but the same could not be stated for the rear fuselage length by comparing the pairs of configurations 1 and 2, 4 and 5. As a matter of fact, the method also predicts a forward shift in aerodynamic center position when the rear fuselage length increases, but in a very slight way, so that we would need at least an extra decimal at the results, which is not the usual form of displaying aerodynamic center position in chord fraction. Besides, the effects of maintaining the top of the rear fuselage at the same level of the central fuselage top were not pronounced; it will happen only in case of a notable difference between the rear fuselages dynamic pressures.

The method from Torenbeek (1982) provided results close to each other for all configurations, and, as Roskam (1982) method, it does not achieved the lowest or highest percentage difference when compared with the experimental results for any configuration. From Tab. 2, we can deduce that it predicts a greater forward shift in aerodynamic center positions as the forward fuselage lengths increases; effects of increasing the rear fuselage length were also the same, but slighter. Keeping the rear fuselage top at the same level of the central fuselage top moved the aerodynamic center back.

The method from Diehl (1942) provided the highest percentage difference when compared with the experimental results for configuration 5 as noted on Tab. 3. Analyzing the available data at Tab. 2, we can notice that it predicts a greater forward shift in aerodynamic center positions as the forward fuselage lengths increases; the same behavior was observed when increasing the rear fuselage length. As this method do not take the rear fuselage lateral shape into account, no effect was noticed by keeping the rear fuselage top at the same level of the central fuselage top.

The method from Sinton (1983) provided the highest percentage difference when compared with the experimental results for all configurations, except configuration 5, as noted on Tab. 3. Analyzing Tab. 2, it is observed that this method deliveries results that show a forward shift in aerodynamic center position when reducing the forward fuselage length, which goes against the expected behavior mentioned in all literature reviews and results obtained from applying all other methods. Any kind of influence from the rear fuselage (length or lateral shape) is considered in this method.

Now, taking into account the experimental uncertainties that stem from measure instruments and approximations assumed for obtaining curve slopes from experimental results, some slight changes (only three) about which method provided the best or worst result in terms of percentage difference when compared with the experimental methods can be observed in Tab. 4 and Tab. 5. However, when looking at the whole range of obtained results in Tab. 3 (pure results), Tab. 4 (results plus calculated uncertainties) and Tab. 5 (results minus calculated uncertainties), the method from ESDU (1996) still has a remarkable performance over all other, providing the most accurate result in eight opportunities (between a total of eighteen opportunities), and assuming the second better result place in other nine opportunities. Furthermore, it had the lowest average percentage differences when compared with the experimental results for almost all configurations combinations, as noted on the bottom part of the cited tables above.

5. CONCLUSIONS

The aim of this work was to indicate the most accurate between seven theoretical methods for predicting the shift in wing aerodynamic center position due to the fuselage influence through a comparative analysis against wind-tunnel test data at low speed conditions. Based on the data available at section 3 and the analysis carried out at section 4, we came to the conclusion that the method described in ESDU (1996) is the most accurate one.

As suggestions for future works, other airplane configurations and flight conditions could be explored for verifying how the theoretical methods will behave when: the airplane (or model) is at high subsonic or supersonic flows; uses swept and/or tapered wings; uses winglets and/or high-lift devices; has a non-circular fuselage shape; the wing position is low or high, as only the theoretical method described by Etkin and Reid (1996) considers it. Besides, this work could be easily developed as a wind-tunnel class for engineering students, improving their knowledge and analysis sense.

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