Universidad Carlos III de Madrid

Bachelor's Degree in Aerospace Engineering
Mechanics of Flight II
Academic Year 2021-2022

Lab 1: Longitudinal Static Stability Analysis of a Flying Wing

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Madrid, 2022

1. Introduction

In this first lab session, the goal is to study the longitudinal static stability of a flying wing. To do so, a total of four types of wings will be analyzed in order to check the effect of different design parameters of the wing on its longitudinal static stability. This study will be performed using the software XFLR5 to obtain the results while the software MATLAB will be used to display the obtained data form XFLR5.

The longitudinal static stability of a flying wing is found when its pitching moment is equal to zero, at the condition for which the slope of the pitch moment coefficient with respect to the zero lift line angle ($C_{m\alpha}$) is negative, and that the of the pitch moment coefficient (C_m) at zero lift ($C_L = 0$) is positive, that is $C_{m0} > 0$. Furthermore, it will be also studied that in case of finding a condition meeting the criteria just explained, it would be a realistic situation for the flying wing checking that indeed at that condition the lift is positive being able to sustain a straight flight. It is also important to mention that the values of α are considered and corrected from XFLR5 in order for this value to be measured from the zero lift angle of attack, being $\alpha = \alpha_w - \alpha_{zero\ lift}$, where α_w is the classical angle of attack with respect to the free stream flow used in XFLR5.

2. Positively Cambered Wing

In this first task a rectangular wing of 100mm of chord and 2000mm of wing span using NACA 1410 airfoils will be studied. In Figure 1, the evolution of C_L with α is presented, as expected this evolution is linear and it can be clearly seen that x_{CG} has no effect on this value as the center of gravity does not affect the behavior of a purely aerodynamic factor independent of its mass distribution.

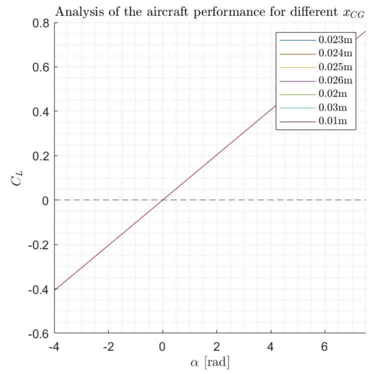

Figure 1: C_L vs α for the NACA 1410 case.

As it can bee seen in Figure 2, $C_{m\alpha}$ can be assumed to be 0 when the position of the center of gravity is placed at 0.025m, thus $C_{m\alpha}$ will be negative for all of the x_{CG} smaller than 0.025m which is the position of the neutral point, meeting one of the two conditions explained before in order to meet the longitudinal static stability condition. The second condition is only met for $x_{CG} = 0.01m$ for the analyzed conditions, as it is the only one having a $C_{m0} > 0$. This trend was expected as in a case with no tail $C_{m\alpha} = a_{wb}(\tilde{s}_{cg}$-$\tilde{s}_{ac})$, taking into account that $\tilde{s}_{ac}$ is fixed for a specific airfoil, moving x_{CG} upstream implies having a smaller $\tilde{s}_{cg}$ as this variable represents the distance between LE and center of gravity, and thus a more negative $C_{m\alpha}$. In addition, as the flying wing presents no tail, the position of the neutral point coincides with the aerodynamic center the static margin is defined as $\kappa \equiv \tilde{s}_{ac}$ - $\tilde{s}_{cg}$, therefore as x_{CG} is moved upstream the static margin is increased.

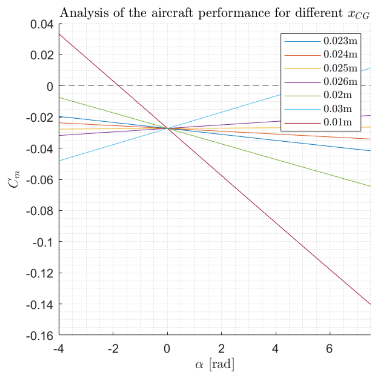

Figure 2: C_m vs α for the NACA 1410 case.

Now the focus is set in Figure 3 where C_m is displayed against C_L, this plot is interesting in order to see if for the stable C_m found C_L is indeed positive making the longitudinal static stability condition found reasonable for flight. For $x_{CG} = 0.01m$, when the value of C_m is equal to zero, C_L is negative, thus the only longitudinal static stability condition found for the wing used in this task is not valid.

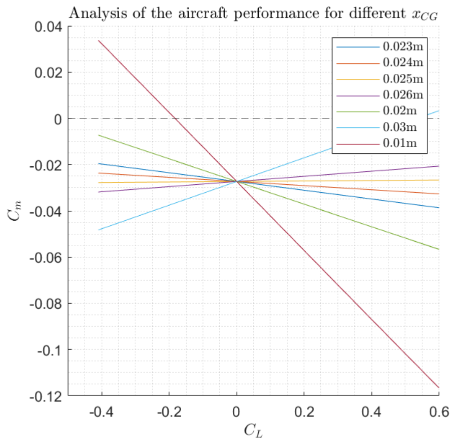

Figure 3: C_m vs C_L for the NACA 1410 case.

3. Flying Wing with Self-Stable Airfoil

In this section it is performed the same analysis as before, but making use of a self-stable airfoil (Eppler 186). A self-stable airfoil is, by definition, a kind of airfoil that provides a wing with longitudinal stability without any stabilizer required. The performance of the studied wing with this kind of airfoil is depicted in the three figures below:

In Figure 4, it is depicted the evolution of the C_L with α. As expected, such evolution is linear, where again x_{CG} has no effect on this value following the same reasoning as in the previous task.

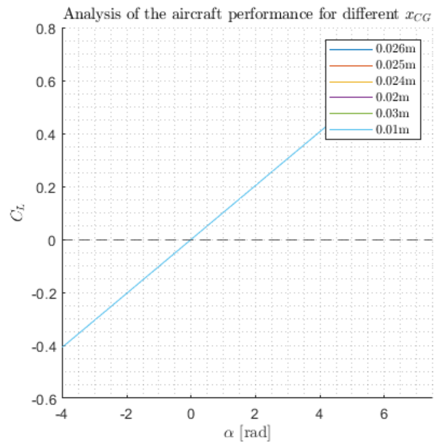

Figure 4: C_L vs α for the Epper 186 case.

In Figure 5, it is depicted the evolution of C_m vs α, which provides with an idea about the longitudinal static stability of the aircraft. It can be seen that for this airfoil configuration, the condition $C_{m,ac,w} > 0$ is always fulfilled (we need to bear in mind that this is a self-stable airfoil), so we need to focus on selecting a proper choice for the center of gravity location (CG) which allow us to ensure $C_{m,\alpha,w} < 0$, in order to achieve longitudinal static stability. In this case, it can seen that the choices for the location of the CG in order to obtain static stability are between 0.01m and 0.025m.

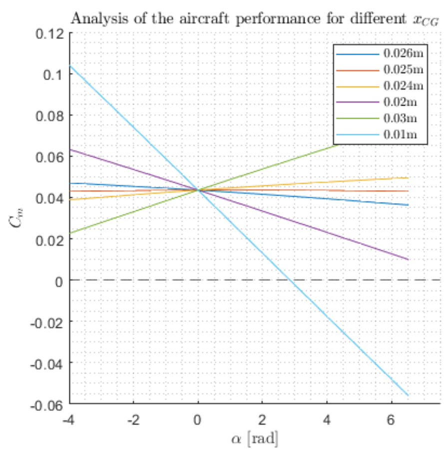

Figure 5: C_m vs α for the Epper 186 case.

If a similar analysis as in the previous section is performed, it is depicted in Figure 6 the plot of C_L vs C_m. In such figure it is clearly seen that the values of C_L which make the C_m equals zero are positive for values of x_{CG} greater than 0.025m, leading to longitudinal static stable configurations.

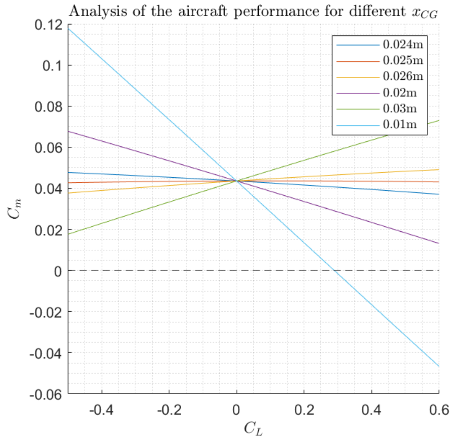

Figure 6: C_m vs C_L for the Epper 186 case.

4. Swept Wing with no Twist

For this task the positively cambered airfoil NACA 1410 is recovered, but in this case a sweep angle is added being the values of the chord at the root and at the tip 180mm and 120mm, respectively. In Figure 7, the relation between C_L and α is still linear as it was for the case of the rectangular wing. Regarding that plot, we may highlight that the variation in the sweep angle slightly affects the lift coefficient slope, being this slope decreased if the sweep angle becomes higher. In addition, $\alpha_{zero\ lift}$ is also affected by changing the sweep angle even though this changes are vanished in Figure 7 as all of the curves are corrected setting the reference for α with $\alpha_{zero\ lift}$, as discussed in the introduction. As it can be seen in Table 1, increasing the sweep angle reduces the value of $\alpha_{zero\ lift}$ even though this effect is almost negligible.

Offset [m]	0.15	0.2	0.3	0.5	1
$\alpha_{zero\ lift}$ [°]	-0.967	-0.967	-0.968	-0.968	-0.968

Table 1: Values of $\alpha_{zero\ lift}$ for different sweep angles (offset in XFLR5).

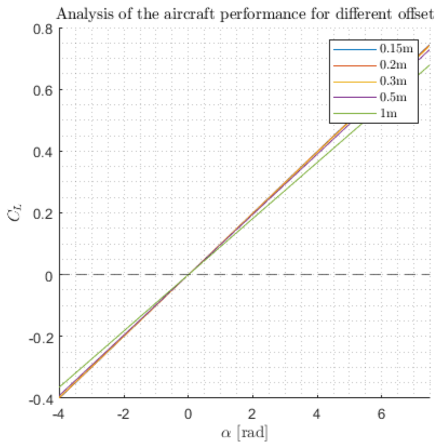

Figure 7: C_L vs α for no twist swept wing case.

In Figure 8, it can be seen that increasing the sweep angle (increasing the offset in XFLR5) has two direct effects on the relation between C_m and α being both of them inversely related, as increasing the sweep angle reduces both C_{m0} and $C_{m\alpha}$ as it can be clearly observed in the graph. It is also important to mention, that all of the conditions between 0.15m and 1m offset could present longitudinal static stability as they present a positive C_{m0} and a negative $C_{m\alpha}$. Again, in order to verify them Figure 9 is used. As it happened in the first task using the rectangular wing made of NACA 1410 airfoils for all of the potentially valid options, when $C_m = 0$ the value of the lift coefficient is negative, thus a condition yielding negative lift cannot be considered as statically stable.

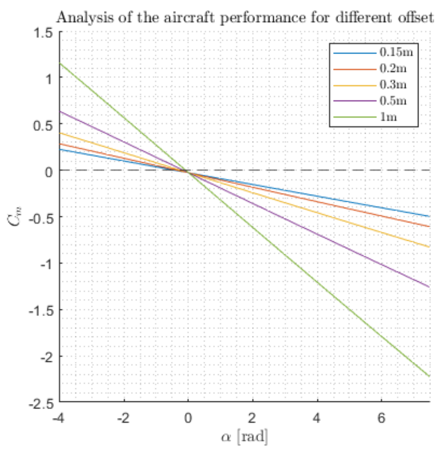

Figure 8: C_m vs α for no twist swept wing case.

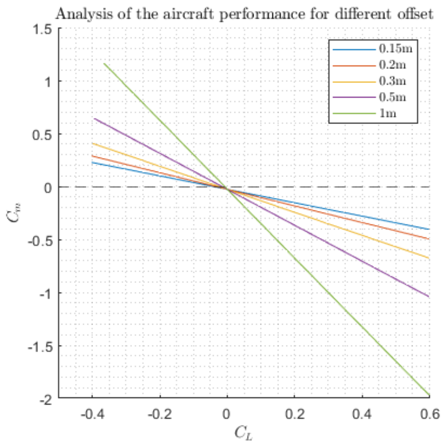

Figure 9: C_m vs C_L for no twist swept wing case.

5. Swept Wing with Twist

For this final task, a swept wing using positively cambered airfoil (NACA 1410) as it was the case in the previous task is considered, but now a twist at the tip is added being this effect the matter of interest for the analysis of this section. The effect of adding this twist at the tips of the flying wing is that it reduces or even changes the sign of the lift in these regions of the wing and reducing the total lift, being this the price to pay in order to obtain a specific positive value of C_{m0} that is being sought. Another interesting effect of twisting the tips of the flying wings is that when the net lift is zero, the forward part of the wing has positive lift, while in the rear one is negative.

Before beginning the discussion of this task, it is important to mention that Figure 10 has been done considering the angle of attack with respect to the free flow (α_w) as used by XFLR5. This exception among the other plots was decided as it is interesting to see how modifying the twist at the tips modifies the value of $\alpha_{zerolift}$ making the discussion easier and more visual. As it can be clearly seen, modifying the twist angle at the tips does not modify the slope of the lift coefficient with respect to α, but it is also obvious that as the twist angle becomes more positive the value of $C_L(\alpha = 0)$ becomes larger as well and thus displacing the $C_L - \alpha$ curves upwards.

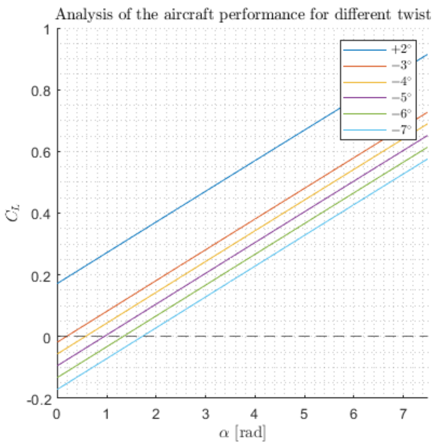

Figure 10: C_L vs α for swept wing with twist case.

Figure 11 shows the relation between the pitching moment coefficient and α. At first sight one can notice how all of the lines present the same slope, that is the same $C_{m\alpha}$, meaning that changing the twist at the tip does not have any influence on this important parameter for the longitudinal static stability. On the other hand, it can also be easily observed that as the twist angle at the tips is increased (meaning becoming more positive) the value of C_m at a certain α is decreased, meaning that the lines are displaced downwards. This has an effect on the value of C_{m0}, which becomes smaller as the twist angle is increased. It is also important the mention that C_{m0} is 0 really close to $-3°$, so it can be assumed that the limit between positive and negative values for C_{m0} is found at $-3°$. Therefore all of the flying wings with a more negative value for the twist angle at the tips than $-3°$ present potential conditions that yield longitudinal static stability. Once again, to check if these conditions are indeed longitudinal static stable, the relation between C_m and C_L is observed in Figure 12.

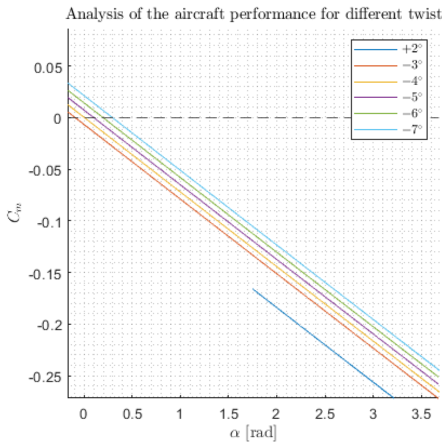

Figure 11: C_m vs α for twisted swept wing case.

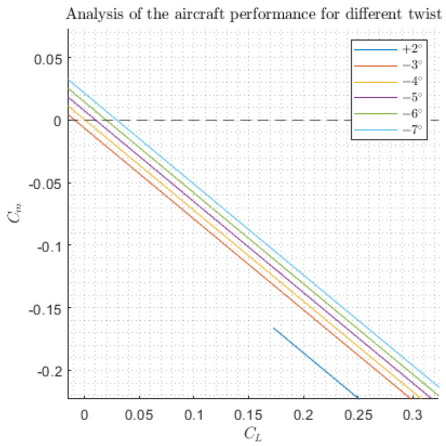

Figure 12: C_m vs C_L for swept wing with twist case.

Using the reasonings followed from the previous observations about the effect of the parameter of study in this task, only the lines corresponding to twist angles more negative than $-3°$ are worth of being studied. Anyways, a case of study with positive twist ($+2°$) has been carried out, but it was only possible to analyze it for values of α grater that $1.5°$ due to numerical unconvergences in XFLR5 software. For all them, when the value of C_m is equal to 0, C_L is positive. Even though these lift coefficient values for zero pitching moment are relatively small (implying that in order to sustain a stable flight a proper combination of air density, flight speed and wing surface should be used), finally longitudinal static stable conditions are found in the flying wing using NACA 1410 airfoils, after having included to the simple rectangular wing used initially a sweep angle and twist at the tips.

6. Conclusion

After all of the analyses performed in which the effect of different design parameters of a flying wing on its longitudinal static stability was studied, it was noticed how challenging it is to establish a condition in which the sought static stability is achieved, as many parameters change the behavior of the flying wing and not only the pitching one, but also its lift and relation between pitch and lift for example. In addition it also observed that in addition to including a sweep angle and twist at the tips to a NACA 1410 airfoil, there also other options of obtaining a flying wing capable of having a longitudinal static stable condition by going out of the box and looking, for example for new airfoils as the case of self-stable ones as the one used in this work, Eppler 186.

In addition, it is worth to mention that the followed approach was simplified as many more parameters can be studied and in a real design there should be a collaboration between departments, as a modification on the design of the flying wing (in one of its parameters such as the seep angle or the twist at the tips as just analyzed) may strongly affect its structural or aeroelastic properties for example.