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THE AERODYNAMIC STUDY ON THE MUTUAL AERODYNAMIC IMPACT OF THE WINGS IN THE TANDEM WING CONFIGURATION

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Abstract

The paper presents the aerodynamic study on the mutual impact of both wings in a tandem wing configuration. Analysis is focused on a numerical model similar to the model to be built for aerodynamic tests in a wind tunnel. The model comprises the fuselage and the front and rear wing. The main goal of the paper is to check the correctness of two numerical models, especially the aerodynamic coupling between two wings. Aerodynamic analysis was made by two software: Ansys Fluent and MGAERO. The emphasis was placed on phenomena at angles of attack from 10 to 25° as they are unsteady in Fluent but not in MGAERO. Results show that the impact the front wing has on a rear wing is modelled similarly between the numerical models, but bigger discrepancies regarding the opposite effect appear. Thus, further verification by wind tunnel tests is required.

Keywords: tandem wing configuration, aerodynamic coupling, CFD

1. Introduction

Aerospace engineering, like any field of technology, is subject to constant development, which involves the search for new solutions. The case of aviation is special in that the first airplanes were not constructed according to what we now call a conventional configuration, which assumes that the airplane has a fuselage, wing and empennage located close to the rear end of the fuselage [1]. For example, the well-known Wright brothers' first aircraft was constructed in a canard configuration [2, 3, 10], i.e. the horizontal tail was placed in front of the main wing. This shows that in aviation, the search for innovative solutions may be based on ideas invented a long time ago but pushed aside, e.g. because of the lack of tools appropriate for analysing aircrafts with a strong aerodynamic coupling.

A similar story is related to another unconventional aircraft configuration - a tandem wing. One of the first structures of this type – unmanned Langley Aerodrome - was built at the end of the 19th century. The first manned tandem wing to successfully fly was Blériot VI in 1907 [4]. Figure 1 shows other examples classified as tandem wings. Although this configuration initially developed parallelly with airplanes in other arrangements, it is problematic to find one universally accepted definition.

Figure 1 - Tandem wings. Left column: SolarXOne [5], Rutan Quickie [6]; middle column: Scaled Composites Proteus [8], M39B Libellula [9]; right column: Arsenal-Delanne 10 [7], Pou de Ciel [8].

According to one definition, tandem wing is an aircraft that uses two independent wings to generate lift, thereby eliminating the need for a tail stabilizer. Additionally, both wings have comparable aspect ratio and are usually placed on two different planes [4]. One could argue whether the definition should mention comparable span rather than aspect ratio. Additionally, some claim that tandem wings should not be a separate category, since conventional aircrafts are also tandems as they have two surfaces behind one another [11, 12]. But a main attribute differing tandem wings from conventional airplanes is strong aerodynamic coupling [13] which makes it impossible to use superposition - e.g. lift coefficient is not the same for each wing and the lift curve for the rear wing is fully nonlinear.

What rises the computational cost for tandem wings even more is that at near-stall angles of attack (AoA), the flow is highly unsteady. This phenomenon has been observed in the experimental conditions [23-24], but thus far no attempt has been made to explain physical groundings behind it.

Despite problems with calculations, tandem wings have many advantages in comparison with a conventional aircraft, like reduced wings span. That makes it more compact and reduces the bending moment, allowing for lighter structure. Another advantage is stall delay [4], which can be obtained thanks to the downwash, i.e. the negative AoA induced behind a front wing on a rear wing (Figure 2) [20]. This phenomenon, together with upwash, i.e. positive angle induced in front of a rear wing on a front wing [21], shows how wings mutually influence each other in a tandem wing.

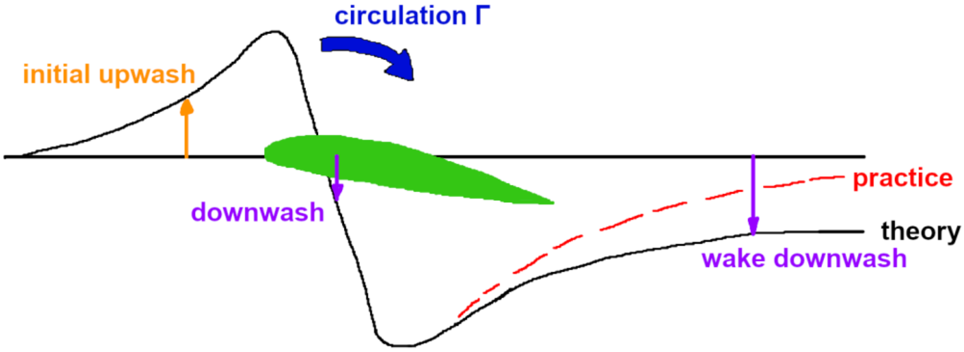


Figure 2 - Upwash and downwash [13].

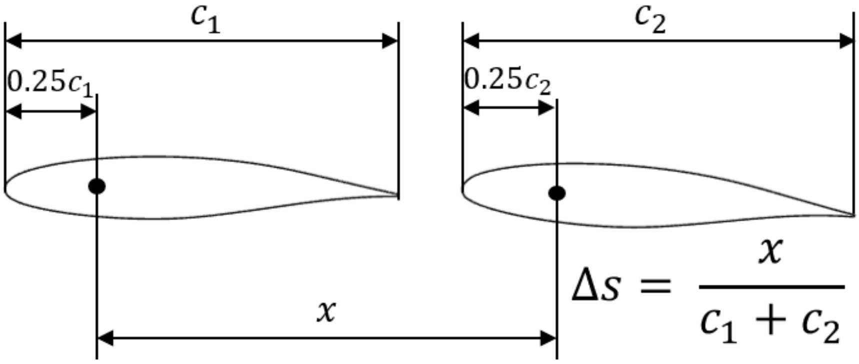


Figure 3 - Definition of stagger (Δs).

Another advantage of a tandem wing is reduced induced drag [1, 4, 13-19]. Depending on the details of the design, total drag may not be reduced [17]. This confirms the need for the research regarding tandem wings. Especially since the strong interference between the wings makes it impossible to use the same calculation methods as for conventional aircrafts. Even for more advanced approaches (e.g. Computational Fluid Dynamics – CFD), it cannot be stated that the results obtained from one method are reliable without verifying them, e.g. by comparing with another method. As such, the need for developing a reliable tool for analysing tandem wings arises. The main goal of this research is to check the correctness of two numerical models in the field of the aerodynamic coupling between both wings in a tandem wing configuration. The analysis is focused on a numerical model similar to the model planned to be built for aerodynamic tests in a wind tunnel for further verification. The variable parameters in the calculations are AoA and nondimensionalised streamwise distance between the wings called stagger (Δs, see Figure 3). The results in the form of aerodynamic coefficients were compared between two software. What is more, the position of the centre of gravity (CoG) for which a given safe static stability margin is achieved was determined.

2. Methodology

2.1. Geometry

The geometry of the model was first created in a CAD software (Figure 4) as follows:

- the span $b = 1.5\ m$, mean aerodynamic chord and airfoil are the same for both wings,
- the reference length for the moment coefficient (C_M) is the sum of chords ($2c = 0.556\ m$),
- the reference surface for the lift (C_L), drag (C_D) and moment coefficients is the combined surface of both wings, hence $S = 0.835\ m^2$,
- the front wing is set at $\tau_1 = 0°$ and the rear wing at $\tau_2 = 3°$.

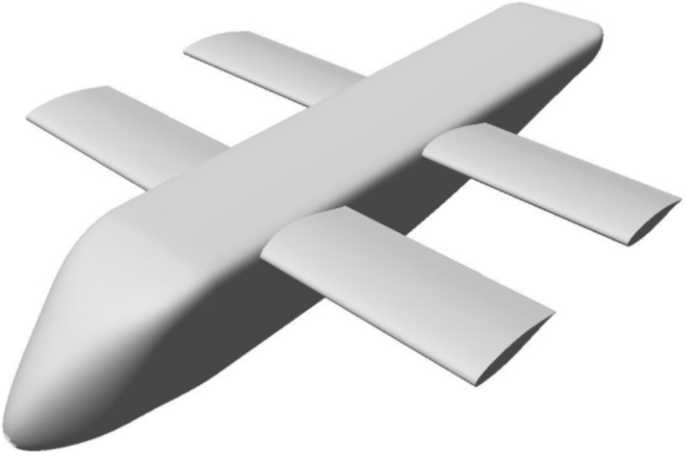


Figure 4 – Geometry of the analysed aircraft.

2.2. Numerical models

The subject of the analysis were the aerodynamic characteristics in the range of AoA from $-4°$ to $25°$. Such a choice of the range was dictated by the fact that both practical and near-stall AoA were considered. The airplane is in a clean configuration (without controls). Calculations were conducted for two software – MGAERO and Ansys Fluent. Chapter 5 explains convention for naming coefficients. Stagger (Δs) was changed by moving the rear wing, with extreme positions shown in Figure 5.

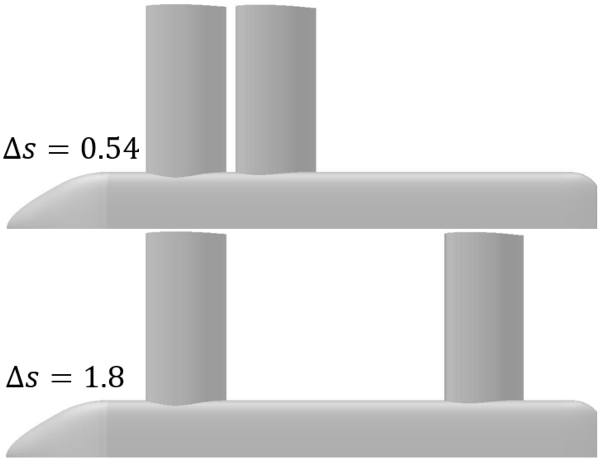


Figure 5 - Extreme positions of the rear wing.

2.2.1. MGAERO

MGAERO is a software used for preliminary aerodynamic analysis. It uses Euler's equations and multigrid scheme to compute the flow field around the aircraft [26]. In comparison with Ansys Fluent, MGAERO is a simpler software, generally giving less accurate results, but the computational cost is incomparably lower. That is why for this software, more cases of Δs were considered than for Fluent. Figure 6 shows grid used for calculations. The model consists of Multigrid blocks: 7 levels and surface mesh. They comprise around 35 000 on-body panels and 4 500 000 off-body panels. Thanks to the blocking approach, the mesh stays consistent between different cases of Δs and that makes the calculations more reliable [27].

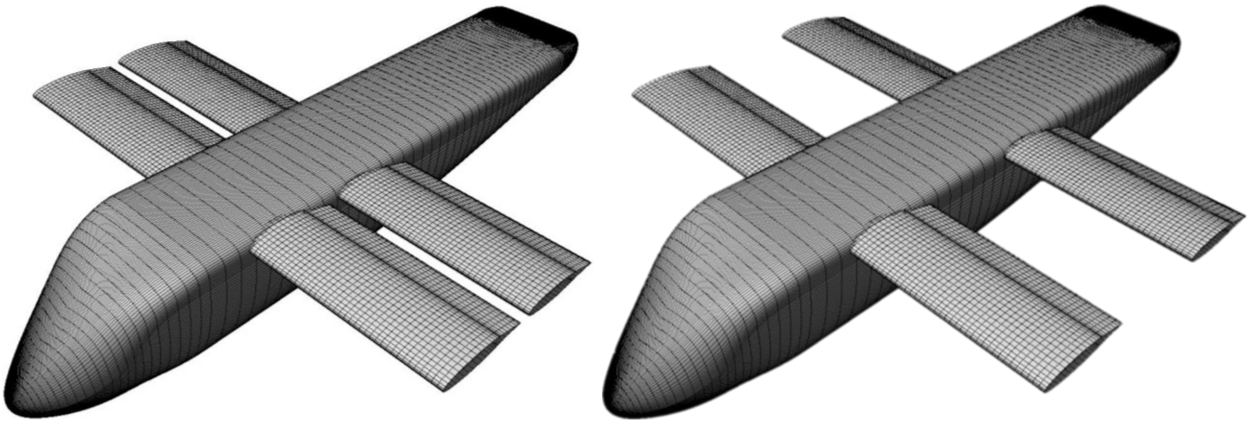


Figure 6 – Mesh used for calculations in MGAERO.

2.2.2. Ansys Fluent

Ansys Fluent is a more advanced software for simulating the fluid flow using Reynolds-Averaged Navier-Stokes (RANS) equations. The strong aerodynamic coupling causes unsteadiness in the flow at $AoA > 10°$, thus the calculations in Ansys Fluent are transient. Consequently, the computational cost is extremely high and a limited number of values of Δs is considered: 0.54, 1 and 1.8 (see Figure 5). Furthermore, the aerodynamic characteristics consist of two curves: one corresponding to the maximum value of a given coefficient reached for a given AoA and the other - to the minimum.

The flow is viscous. A two-equation Generalize k-ω (GEKO) turbulence model with the Curvature Correction option was used. For this analysis, the parameters of the model were set at values giving results similar to the SST k-ω model [22]. As an additional verification for calculations in Fluent, some computations were performed also for one-equation Spalart-Allmaras (S-A) model. In general, the results from both turbulence models are similar within acceptable tolerance. For unsteady AoA, the amplitude of the oscillations is bigger in the case of the S-A model.

Figure 7 shows mesh used for calculations in Ansys Fluent (around 13 million elements). Thanks to imposing AoA by rotating part of the mesh, changing Δs requires generating anew only this fragment.

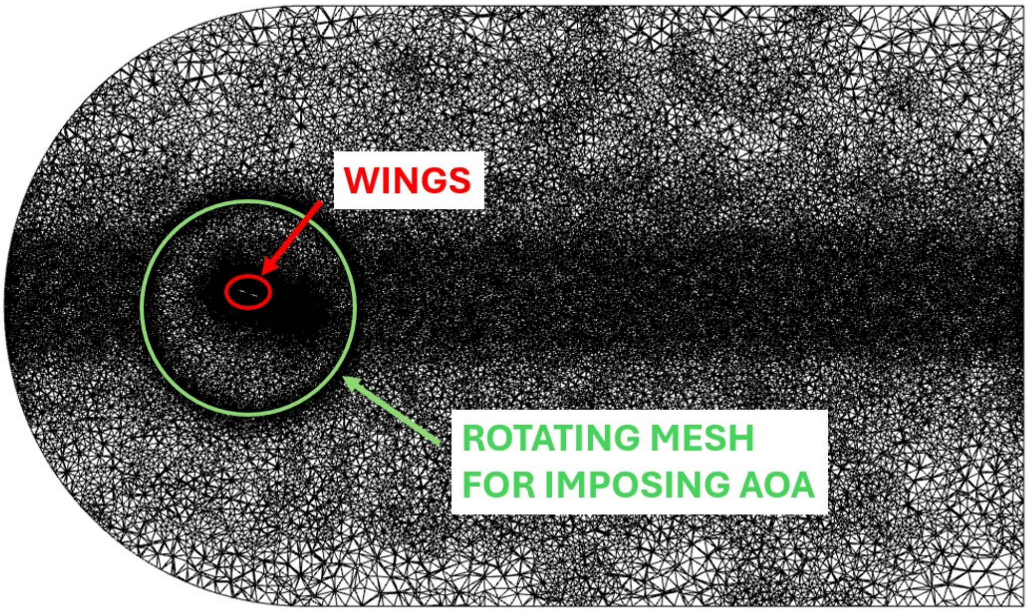


Figure 7 – Mesh used for calculations in Ansys Fluent.

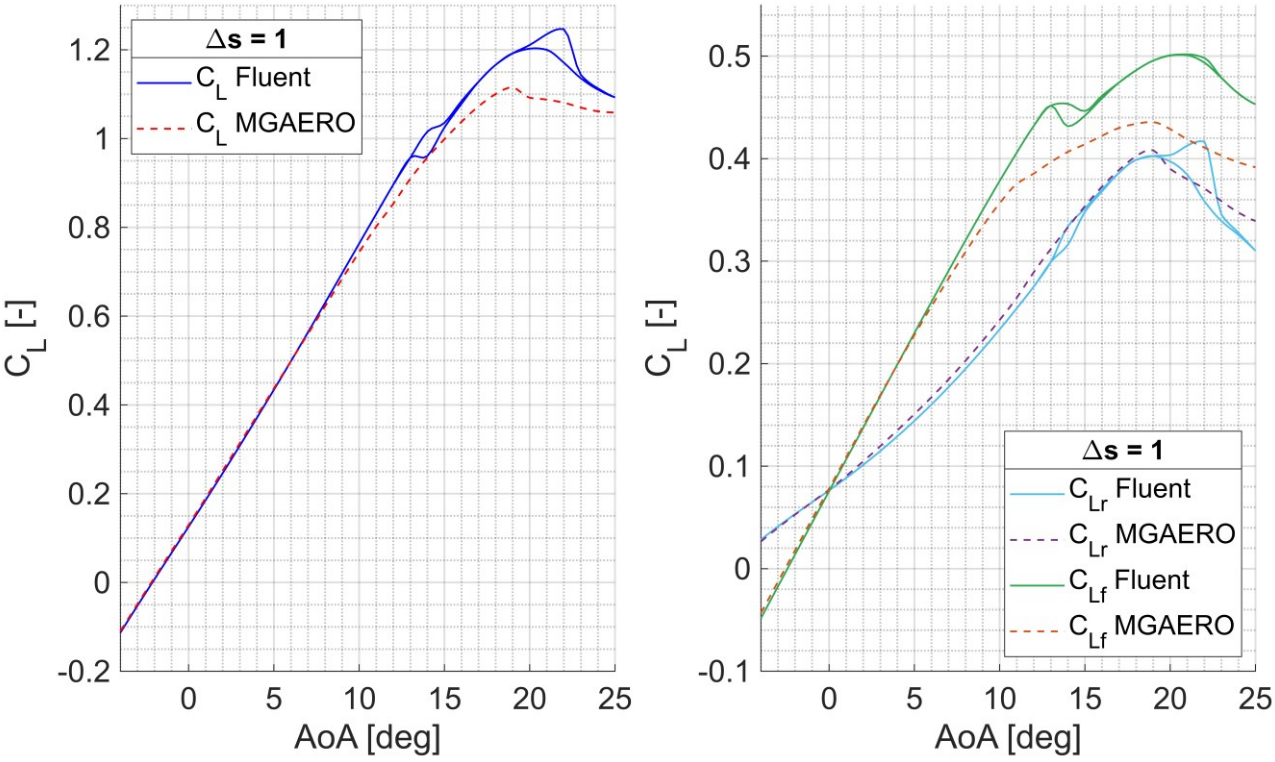
Apart from the calculations for the geometry above, some consideration was also given to the 2D case of two symmetrical airfoils in tandem. From there, it is concluded that increasing the velocity of the undisturbed flow dampens the oscillations significantly, but never disposes of them entirely. The calculations in Fluent for a 3D case were conducted with a freestream velocity of $20\frac{m}{s}$.

The frequencies of oscillations vary between different Δs and AoA. They are in most cases well above 1 Hz. That begs the question whether the changes of aerodynamic coefficients with time would affect the actual flight. Thus, it would be desirable to conduct aerodynamic analysis for a tandem wing without resorting to computationally costly transient calculations. That is why the search for a simpler yet reliable software is vital. For this paper, the software chosen for comparing with Fluent is MGAERO, as introduced before.

3. Results

Firstly, the results from both software are compared as for lift and drag coefficients. The fuselage is accounted for in the total coefficients, but it is not considered in separate analysis. Figure 8 and Figure 10 show the comparison for exemplary $\Delta s = 1$ and Figure 9 – the percentage difference between the results, where positive values indicate that MGAERO is giving a higher result. Like said before, the characteristics for Fluent consist of two curves. The percentage difference is calculated for average.

For small AoA (below $10°$), C_L from both models is similar, with maximum difference of 2.5%. For higher AoA, the difference reaches 10%. A likely cause of the increasing discrepancy is the fact that above $10°$ transient calculations in Fluent become necessary. Analysing lift coefficients seperately for each wing, the difference stems mostly from the front wing. In the literature, the impact of the front wing on the rear wing is often considered vital and focused on while the opposite effect is neglected. But from Figure 8, it seems that simpler software does not struggle with predicting correct results for the rear wing. Instead, it significantly underestimates the positive impact the rear wing has on the C_{Lf}.

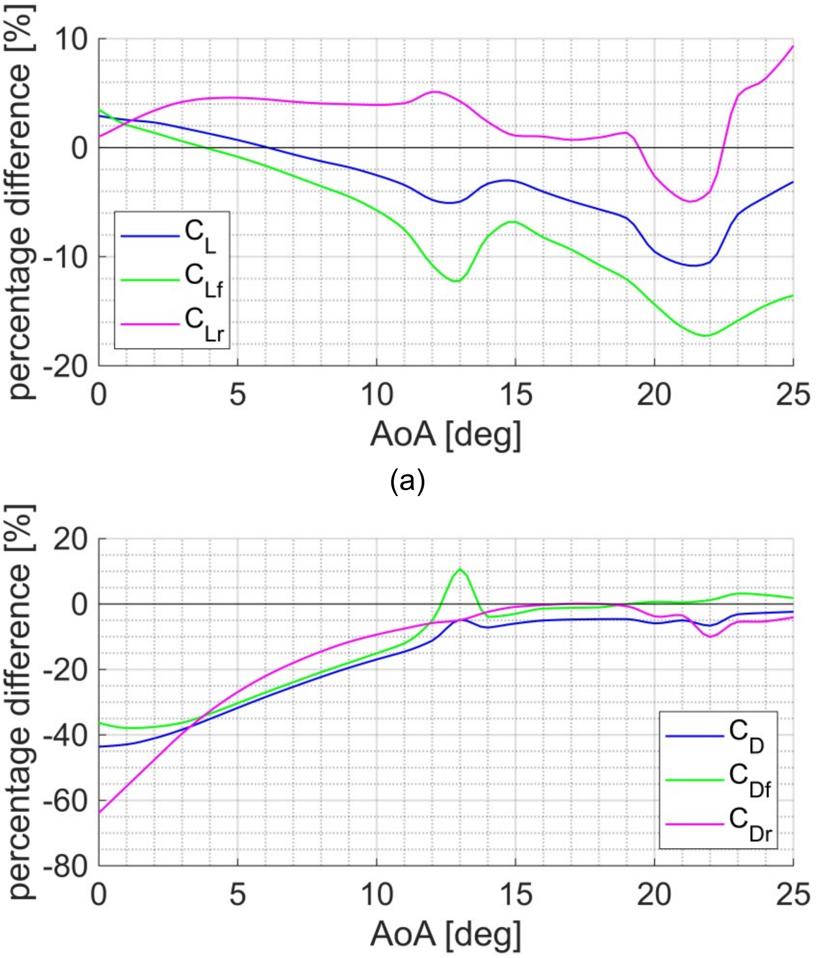


(a) (b)

Figure 8 – Lift coefficient comparison for $\Delta s = 1$: (a) total, (b) components.

There are two unsteady ranges of AoA for calculations in Fluent. For C_{Lf}, the first unsteady range coincides with a phenomenon resembling stalling, but further C_{Lf} keeps on increasing and the second unsteady range coincides with actual stall. Such behaviour for a tandem wing has already been observed in the literature and it is called *secondary stall* [25]. Both software predict high critical AoA: $21°$ for Fluent and $19°$ for MGAERO. That confirms that stall delay is achieved.

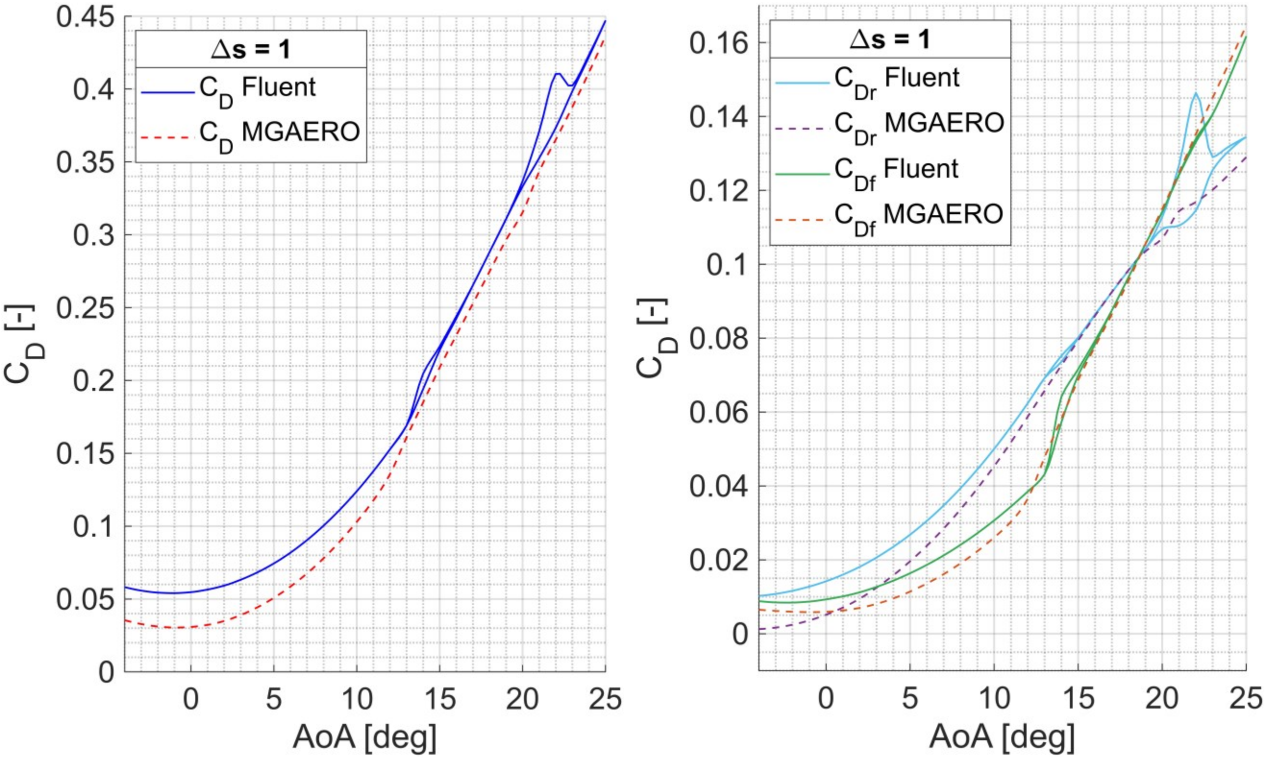
As for C_D, MGAERO gives significantly lower drag than Fluent which is expected for a simpler software (with Fluent being based on RANS equations and MGAERO – on Euler's equations). However, it is not the case for C_{Df} at higher AoA. The reason behind this is probably because upwash from the rear wing reduces front wing's drag coefficient. This effect is captured by Fluent, but not by MGAERO. This confirms the conclusion that MGAERO manages to correctly model the effects of the impact the front wing has on the rear wing, but not the opposite. The conclusions from comparison are the same for $\Delta s = 0.54$ and $\Delta s = 1.8$.



(a)

(b)

Figure 9 – Percentage difference between results for $\Delta s = 1$ in (a) lift, (b) drag.



(a) (b)

Figure 10 – Drag coefficient comparison for $\Delta s = 1$: (a) total, (b) components.

Even though C_L and C_D for both software are fairly similar, the lift to drag ratio (L/D) varies significantly (Figure 11). To understand where these differences come from, analysis into what influences L/D the most for two different AoA ranges was conducted with conclusions shown in Figure 11. L/D for Fluent was calculated from average coefficients, because the differences between maximum and minimum are negligible. The main factors contributing to L/D are different between two software for AoA below $12°$ while for higher AoA in both cases the main contributor is C_D. As a result, L/D for low AoA differs significantly between both models, but above $12°$, similar values are reached. The biggest problem is that the optimal AoA (i.e. corresponding to the highest L/D) is not the same for both models. At the same time, it must be highlighted that since the configuration is strongly coupled, L/D would change for the equilibrium, but that is not the subject of this paper and as such, it will not be further considered.

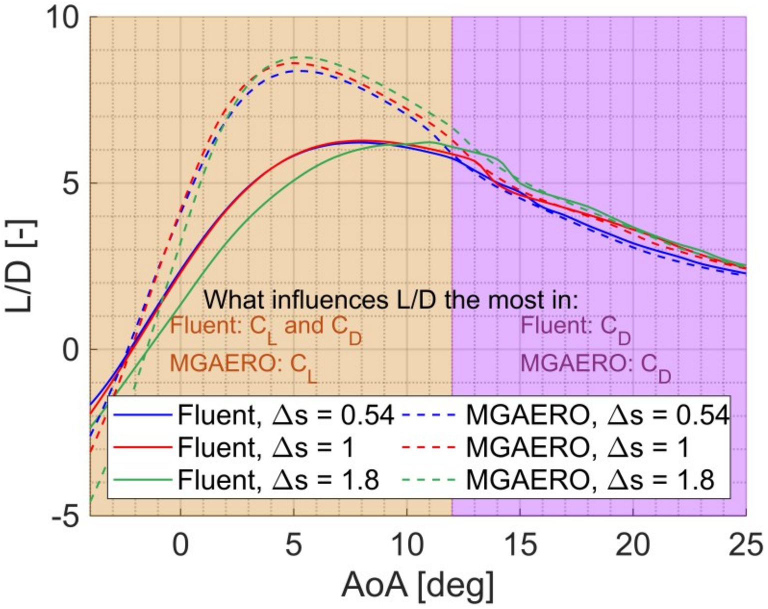


Figure 11 – L/D ratio

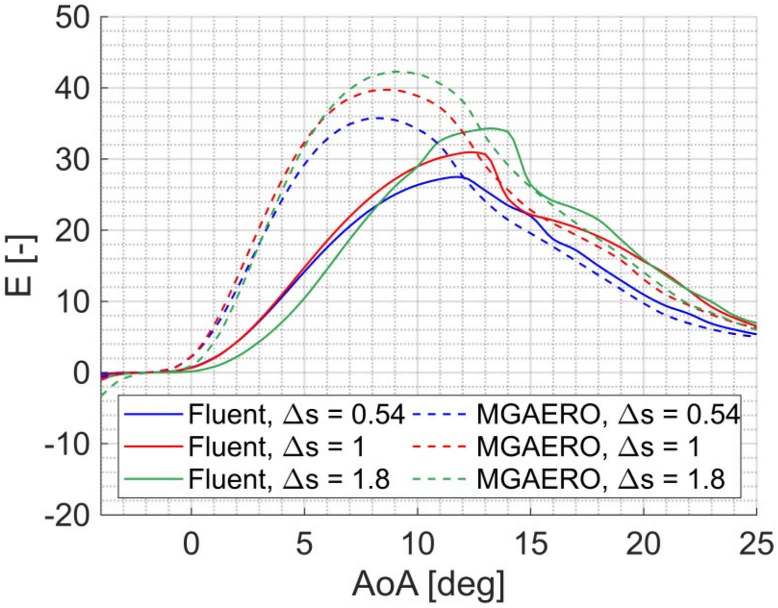


Figure 12 – Aircraft's demand for power.

Analogous conclusions as for L/D can be drawn for a quantity shown in Figure 18, defined as:

$$E = \frac{C_L^3}{C_D^2} \tag{1}$$

which describes the aircraft's demand for power in a given phase of flight [3]. Contrary to L/D, maximum value is clearly reached for one stagger, namely $\Delta s = 1.8$, in the case of both software.

Small differences in C_L between two models translate to similar results for C_M for AoA below $4°$, but the results quickly diverge (Figure 13). Analysing C_{Mf} and C_{Mr} shows that for both wings, MGAERO predicts higher values. Since the forces are similar between both software, the differences must stem from different centres of pressure (CoP). This prompts the hypothesis that unsteadiness in Fluent does not only affect the magnitude of the forces, but also the point they are applied at, i.e. even if an AoA seems steady because C_L and C_D do not change with time, CoP may be travelling. The same conclusions apply for all cases of Δs.

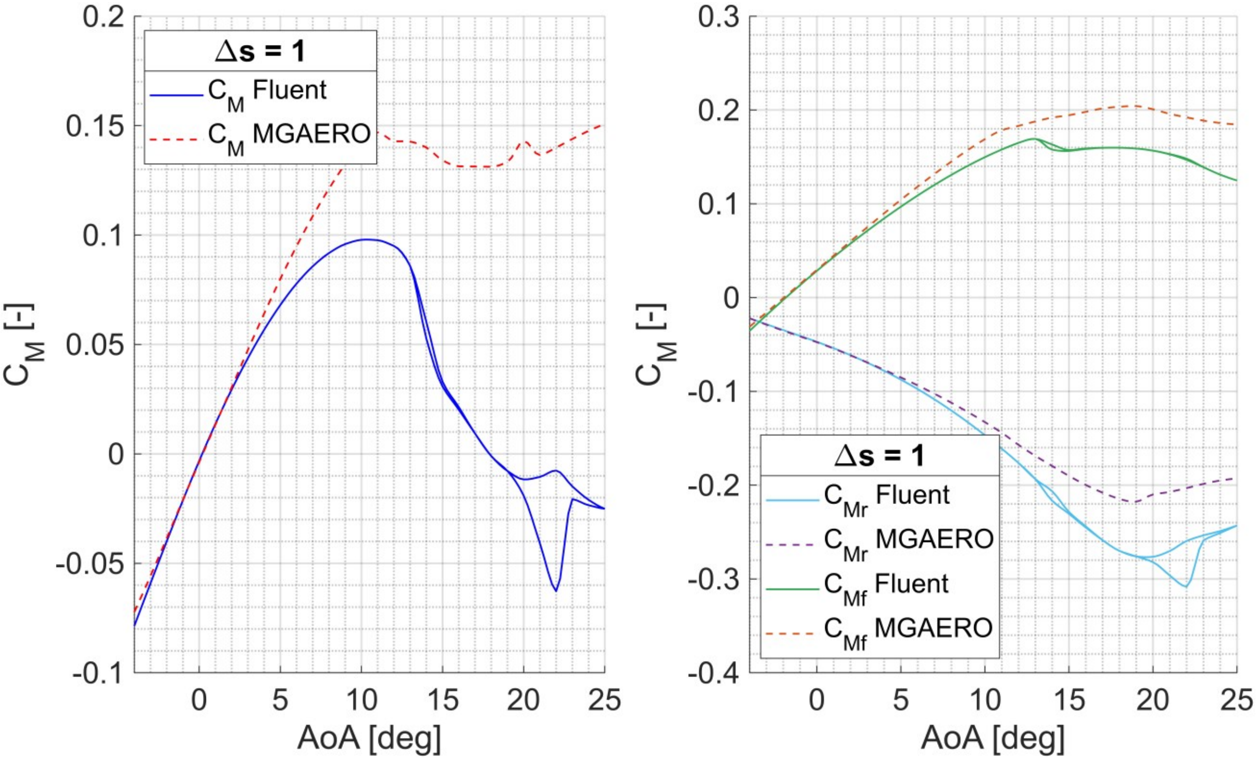
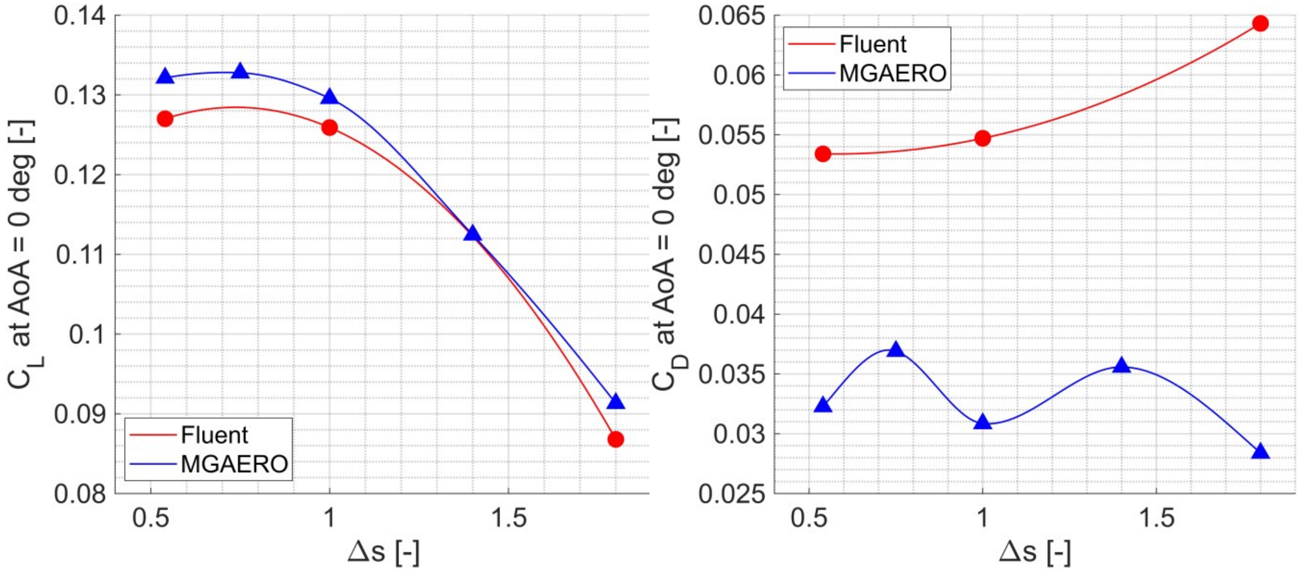


Figure 13 - Moment coefficient for $\Delta s = 1$: (a) total, (b) components.

Continuing the analysis into how the mutual impact of the wings changes with Δs, Figure 14 shows the relation between this parameter and selected results: C_L and C_D at $AoA = 0°$ and $AoA = 15°$ ($C_L(0)$, $C_D(0)$, $C_L(15)$, $C_D(15)$). Table 1 summarizes the theoretical optimal values of Δs for both models.

	$C_L(0)$	$C_D(0)$	$C_L(15)$	$C_D(15)$
Fluent	0.74	0.58	1.8	0.54
MGAERO	0.69	1.8	1.8	1.6

Table 1 – Optimal values of Δs.



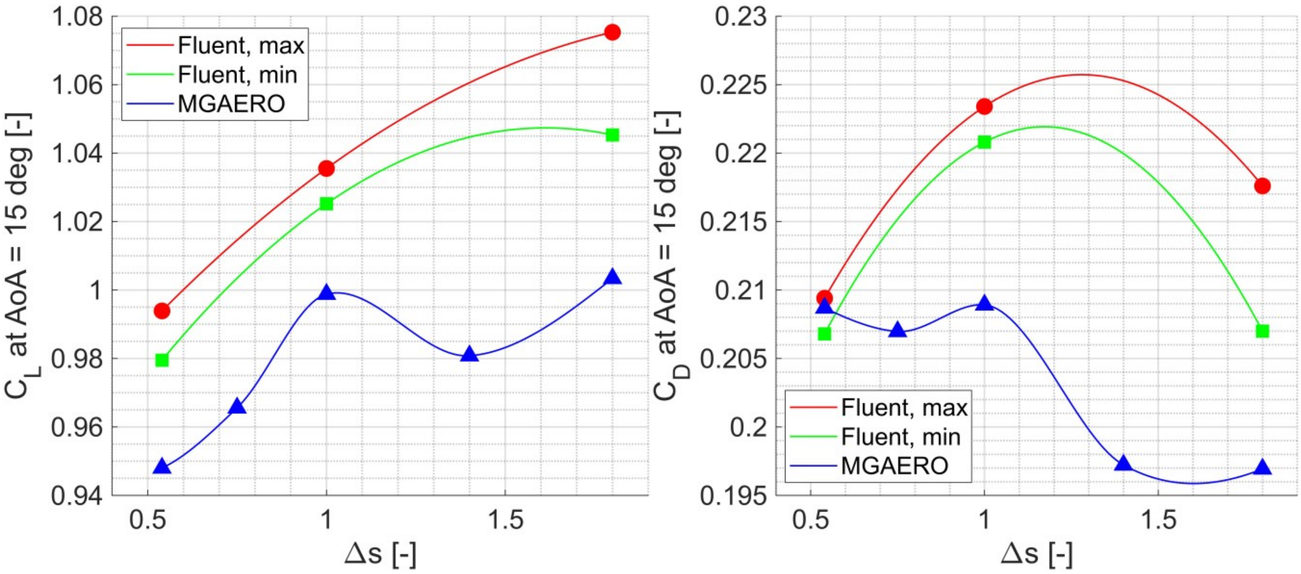
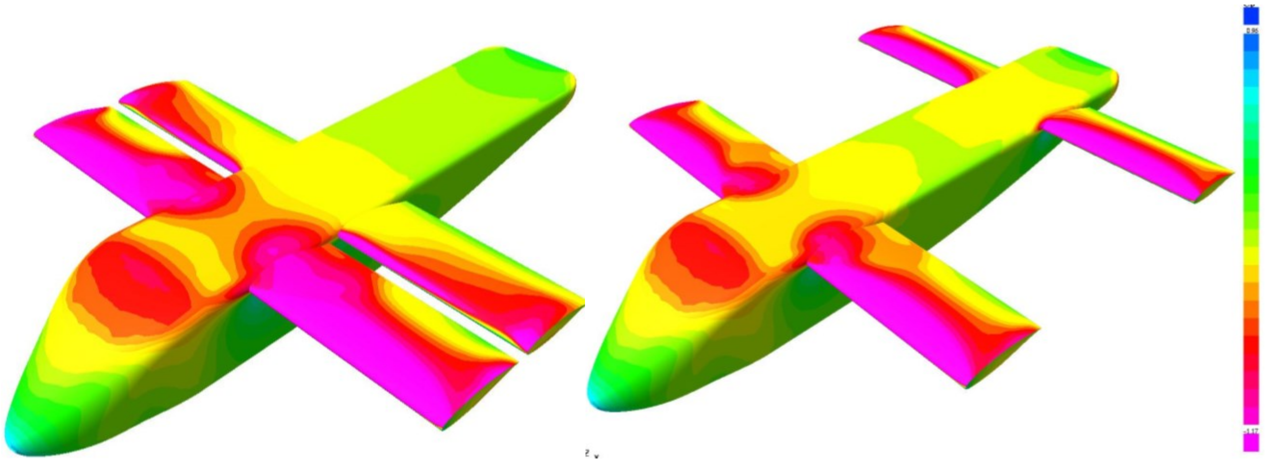


Figure 14 – Relation between selected results and Δs.

In case of $C_L(0)$, both software show close position of the wings to be optimal. For the rest of the quantities, calculations for additional Δs in MGAERO prove that the relation is not parabolic. As such, the conclusions for Fluent based on three values of Δs cannot be considered conclusive without further computations. Nevertheless, $C_D(0)$ is shown to increase with Δs by Fluent while for MGAERO, the situation is opposite. For $C_L(15)$, the trend for both software is generally the same, but for MGAERO, it cannot be answered unequivocally whether the maximum value would be reached around $\Delta s = 1$ or beyond $\Delta s = 1.8$. For $C_D(15)$ and in Fluent, both minimum and maximum Δs minimize drag, while for MGAERO only high Δs decreases drag. Based on available data, it is not certain whether minimum $C_D(15)$ for MGAERO is between $\Delta s = 1.4$ and 1.8 or beyond 1.8.

If the goal of the analysis was to optimize four quantities in Figure 14 by finding an optimal value of Δs, then for MGAERO that would be Δs around 1.8. The situation is not so conclusive for Fluent though, where lower Δs seem to be more beneficial, but calculations for more Δs are needed. Also, to reach decisive conclusions, the concept of what is optimal would need to be defined more precisely.

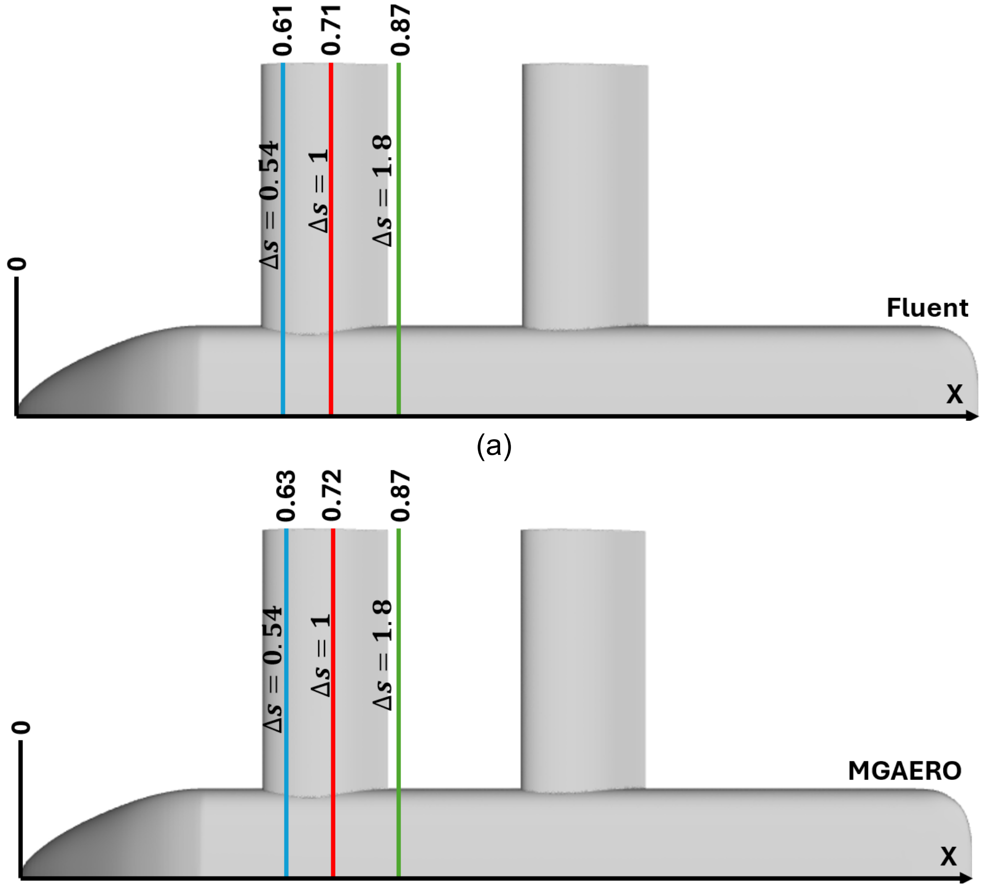
Apart from the quantitative distinction between different cases of Δs, qualitive analysis also proves how significant this parameter is. Figure 15 shows the pressure coefficient (C_P) distribution for two positions of the rear wing. From there, changing Δs visibly affects not only the rear wing, but also the front wing, while in the literature, the impact the rear wing has on the front wing is often omitted.



(a) (b)

Figure 15 – C_P distribution from MGAERO at $AoA = 15°$ for Δs equal to (a) 0.54, (b) 1.8.

As mentioned before, the position of the centre of gravity (CoG) was determined for which a safe static stability margin of 5% is achieved. Figure 16 shows how the sought CoG changes with Δs (the distances are given in meters). The differences between Fluent and MGAERO are negligible despite substantial differences in C_M. From there, it is preliminarily concluded that MGAERO would be an eligible software for conducting a dynamic stability analysis for a tandem wing.



(a)

(b)

Figure 16 – Position of CoG required for static stability margin of 5% for (a) Fluent and (b) MGAERO.

4. Summary, Conclusions and Further Work

In this paper, the aerodynamic analysis for the aircraft in a tandem wing configuration is presented. The main goal of the research was to determine whether the effects of mutual aerodynamic impact of the wings in a tandem wing configuration are modelled correctly by two numerical models (Ansys Fluent and MGAERO). Calculations in Fluent had to be conducted as transient and that led to high computational cost. On the other hand, MGAERO is less accurate, but the computational cost is much lower. The main conclusions from the analysis are:

1. Both models give similar lift for AoA up to $10°$. Beyond that transient calculations in Fluent become necessary and discrepancies between the models arise. MGAERO gives lower drag for all AoA.
2. Both models give similar aerodynamic coefficients for the rear wing for all AoA, especially the lift coefficient. As for the front wing, MGAERO predicts lower lift and higher drag, which means that it underestimates the positive impact the rear wing has on the front wing.
3. Unsteadiness in Fluent applies not only to the magnitude of the forces, but also to the centre of pressure for each wing. That causes differences in the moment coefficient between the models, but when considering the position of CoG with a safe static stability margin, both software give nearly identical results.
4. Taking into account four chosen parameters, different values of Δs are optimal for both software. To reach decisive conclusions, a more specific definition of what is optimal needs to be developed.

The differences between the results from both software highlight the need for conducting wind tunnel tests for further verification. Especially because without the third source of results, it cannot be unequivocally confirmed nor denied that results from one software are more accurate than from another. Even though Fluent is generally a more advanced software than MGAERO, it is not specialised for analysing aircrafts. As such, it may turn out that it overestimates the impact the rear wing has on the front rather than MGAERO underestimating this effect. Furthermore, more calculations from both software are needed to further study the mutual aerodynamic impact of the wings. More cases of Δs should be considered in Fluent and deeper analysis into the unsteadiness and causes behind it is required. Last but not least, the calculations for a tandem wing with flaps on both wings are planned because performance for such a strongly aerodynamically coupled configuration should be analysed under trim conditions. The model for wind tunnel tests is also going to be equipped with flaps. This will ensure proper verification and will allow to ultimately create a reliable model of an aircraft in a tandem wing configuration.

5. Nomenclature

AoA – angle of attack
C_{Df} – drag coefficient for front wing
C_{Dr} – drag coefficient for rear wing
C_D – total drag coefficient
C_{Lf} – lift coefficient for front wing
C_{Lr} – lift coefficient for rear wing
C_L – total lift coefficient
C_{Mf} – moment coefficient for front wing
C_{Mr} – moment coefficient for rear wing
C_M – total moment coefficient
CoG – centre of gravity
CoP – centre of pressure
C_P – pressure coefficient
Δs – stagger
E – aircraft's demand for power
L/D – lift to drag ratio

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