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Abstract. The study of aerodynamics has been preoccupied with understanding flight at increasing speeds and ultimately supersonic. Today, this pursuit has advanced the science for both Hypersonic and Transonic flight to near Mach 1 supporting economical commercial flight operations. This research presents the data from a Taguchi array on low speed with twin wing designs to establish the design parameters for their use in low speed and high altitude. Also presented is how aerodynamic advantages can be achieved through understanding the interactions of parameters and their use. This is compared to operational effectiveness when applied to remotely piloted aircraft that are not constrained by direct requirements. The research concludes with suggestions for improved designs and further work that may enable higher altitudes with low speeds.

1 Background

There has been a collective effort since the Wright Flyer's first flight to fly faster, higher and further. This was achieved with advances and developments in design and improved propulsion systems through the 1960s. In a few decades, aviation progressed from the Wright Flyer to jet passenger aircraft, Comet, TU 104, B 707 and finally Concorde. Now, supersonic flight on a commercial basis is no longer possible, efficient transonic commercial speeds are the aims for manufacturers, and economical considerations drive designs and operations [1]. Most modern defence manufactures strive to achieve stealth and unmanned flight where the aircraft will no longer be limited by g-forces a pilot can withstand. It could be argued current aviation philosophies are at a cross-roads in direction. There are developments for space travel tourism and hypersonic flights to reach anywhere on the globe within 2 hours. Unmanned Commercial flight is also a real possibility [2].

With Unmanned Aerial Vehicles (UAV), the traditional development rules have changed and requirements need to align with current design capabilities. In this paper the theory, or lack of theory, relating to bi-planes aerodynamics and stability at low speeds is addressed and explores how legacy theories do not consider current design capabilities. Bi-planes were used as the ability to create lift was not as efficient as current designs and the materials available were limited. Having two wings offered extra lift for the weight of the aircraft and overcome the engine power concerns and limited propeller theory.

Early Bi-planes were still working with the infancy of aerodynamics and often limited by the propulsion systems weight and capability. Eventually, multi-engine concepts were recognised as way to overcome reliability concerns. A twin-wing can generate more lift in certain phases of flight; it also has disadvantages from the construction perspective. In Fig. 1, below, the construction is shown of the Bi-plane and the methods to make the structure rigid are clearly shown with the struts between the two wings [3]. These struts cause excessive drag and limit maximum speed. One major advantage that twin-wing has over the modern mono-wing it the low speed and manoeuvring stability in turns, where drag is not greatly influential. Bi-plane fighters were still in use at the start of WWII as combat tactics mainly focused on out-manoeuvring the enemy [4]. There were fighter successes against faster monoplanes; however, the operational ceiling became their aerial weakness for attack where the ability to turn in a smaller circle lost its advantage.

Figure 1. A classic twin-wing designed aircraft.

A standard feature of all twin-wing aircraft is that the top wing is off-set forward (negative stagger), see Fig. 1 above. This stagger is for several reasons: first to allow the pilot to see the ground when taxing and on approach to landing. Secondly, to allow the pilot to get into the cockpit; and finally for the pilot to see above and around for all stages of flight. The latter was critical in the early fighters as if spotted first you were vulnerable. Stagger was, however, a weakness. The extra drag from this configuration reduced the top speed and the stall speed was increased, which was a reason for many crashes by early inexperienced aviators. Given all aircrafts were designed and manufactured in this manner, then these disadvantages disappeared.

2 Evaluating Wing Designs

Early aerodynamics focused on obtaining more speed resulting in the actual behaviour at low speeds not being thoroughly documented. It was always the goal to fly faster and initial developments achieved this aim quickly. Further, aerodynamics has not been concerned with low speeds and certainly not twin-wing. This research is investigating if twin-wing designs can be a realistic solution for UAVs to generate sufficient lift at low speeds for high altitude flight. As the roles and possibilities of UAVs expand, this is an area where solutions are needed and current theory does not offer practical solutions.

Given modern materials for monoplanes can produce a twin-wing without the needs for struts, an experimental design approach is suggested to determine what are the advantages or disadvantages for wing stagger, height, and operations. There are four principal inputs, shown in table 1: the height of the top wing above the lower, the staggering of the top wing, speed of flight and altitude of flight. The wing selected for modelling is NACA6412, primarily as this can be validated against the CFD model (Micro CFD®) and it is a classic wing profile. As little or no theory is obtained for these parametric designs, a three level parameter was selected that requires a Taguchi L9 array, shown below in table 1. Using three level will enable the result to determine if any non-linear responses are established and what might be the response, i.e., a curve.

Table 1. Parameter settings and values.

	Low (1)	Medium (2)	High (3)	
A	0.7	1	1.3	Height as % of Chord
B	-0.5	0	0.5	Off-set as % of Chord
C	0.3	0.325	0.35	Speed Mach
D	3000	5000	8000	Altitude ft

Taguchi's L9 array is statistically indeterminate; it is of a high resolution that does not model for interactions between any of the factors at two level. This research is primarily concerned with the principal factors, and further research for interactions is planned.

3 Methodology

An experimental array is a design matrix to maximise the possibility of determining the way inputs (factors) have on output. In this array (L_9), no interactions are considered among the parameters as these are based on Bernoulli's principle where static and dynamic pressures are related to the speed of the airflow on the upper and lower surfaces of the aerofoil. If interactions are to be included, then a separate array is needed [5]. The CFD runs (rows) were completed in numerical order, the first experiment was a single wing NACA6412 to validate the result of a wind tunnel test with respect to Mach, Density, Pressure and Temperature. Table 2, below, shows the L_9 array and results. The maximum lift and drag are the two outputs shown in the final column of the table.

Table 2. L_9 array and output results.

A	B	C	D	Max lift	Max drag
1	1	1	1	18	15
1	2	2	2	19	15
1	3	3	3	21	14
2	1	2	3	19	15
2	2	3	1	20	16
2	3	1	2	22	14
3	1	3	2	19	17
3	2	1	3	21	16
3	3	2	1	23	15

Lift and drag in N/dm^2

An L9 array has nine experimental runs, not repeated, as this is a computer-generated model not susceptible to variation. CFD simulation cannot offer variables and thus the range, standard deviations, and ultimately signal to noise ratios are not able to be established. Each run generated a maximum lift and drag value for the design. As no operation of an aerofoil will generate a constant pressure underneath, as on the upper surface, the combined output of the pressures are averaged to give a defined lift value for that unique experiment. The drag is directly proportional to the calculations and directly stated as an output. Hence, a high confidence from the datum run comparing to a wind tunnel set up, as discussed earlier. These calculations of the effective lift and combined drag respectively, at each set up, are shown in the last two columns of table 2. The distribution of these (speed, density, pressure and temperature) were modelled to determine the complete influences. These are explained and discussed fully in the following section, as Mach, density, and pressure; all inter-related though Bernoulli's equation [6]. Classic aerodynamics does not model temperature in this equation, it does, however, influence lift and drag significantly in certain situations and has to be included as directly proportional to lift and drag. The tunnel length modelled was 12.5 m and boundary conditions for 2D modelling are shown in Fig. 7 below.

4 Results and Discussions

Experimental run two, where the wings are without stagger and closest together, is shown below in Fig. 2, pressure distribution is displayed in the figure below. Dark blue indicates low pressure and green, yellow and orange indicate higher pressure levels. Clearly, the higher pressures are needed under the aerofoil and lower above to generate lift.

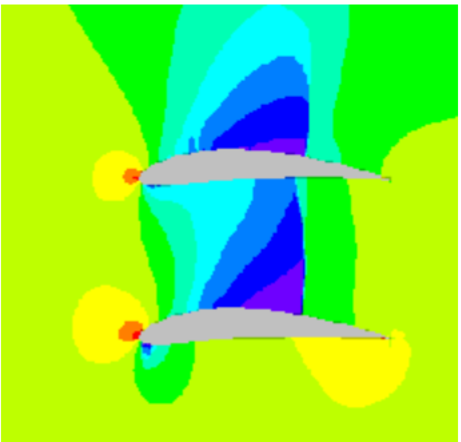

Figure 2. Pressure distribution for run two.

This clearly shows the upper pressures from the bottom wing are influencing the lower surface on the upper wing. In effect, the lift generated by the upper wing is considerably reduce from its theoretical maximum. The leading edge with its high pressure is in effect reducing the total lift as this design of aerofoil has most of the leading edge on the upper profile.

If the negative stagger is modelled under the same parameters, the results are shown below in Fig. 3. This time the upper wing will influence (reduce) the possible theoretical lift of the lower wing. The upper wing exhibits classic pressure profiles for lift [7]. Downwash pressure from this profile is altering the pressure on the lower and very little lift generated by the aerofoil [8]. Its combined pressure lift is considerably lower than what theory suggests and could, under certain conditions, act more as a spoiler (down force) than an aerofoil.

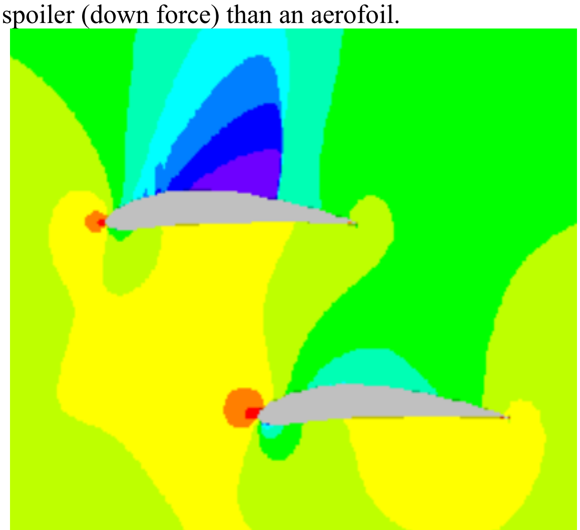

Figure 3. Negative stagger influence.

Stagger has a significant influence on the lift generated, and also the legacy drag from these parameters. It is the extent from the other inputs that need evaluation. The height is of interest as if infinite then there would be zero influence on the output lift and drag. That is not a design solution for this research question.

Each column needs evaluating on its own and in combination. If column A is used as an example, the average of the outputs at each of the three levels is needed. Thus at level 1 the average is (18 + 19 + 21/3) = 19.3. Fig.s 4 & 5 shows the summary of each column for lift and drag respectively. The summary of all for lift is shown below in Fig. 4.

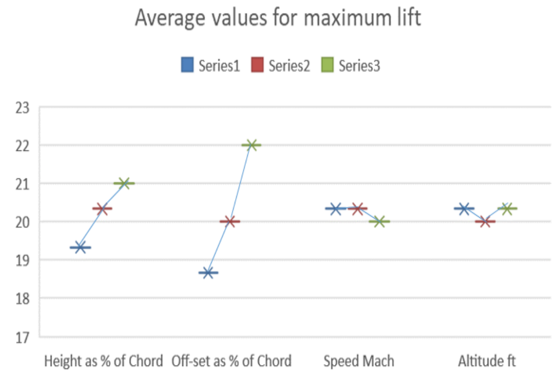

Figure 4. Summary of Lift for each column.

Fig. 4 above shows clearly that as the height separation between the wings becomes larger the lift generated also increases; it could be linear in response outside this range. It could be assumed this height increase is not an influence rather, at lower speeds, the wash down effect from the upper wing has no negative impact on the pressure distribution [9]. Likewise, off-set (stagger) is worst when negative, it improves if directly above but increases the most when a positive stagger A and B suggest high separation and positive stagger are the favourable settings.

Speed has a significantly lower influence with the lift being limited from the positive stagger by a small percentage. Altitude is not significant in these ranges and it might be shown statistically that variation is random and not spurious. Overall, the off-set (stagger) is critical and the separation less critical.

Fig. 5 shows the evaluations for the drag influences from this experiment. Each point is calculated as an average in the same format as for the lift, and average of the three values for each setting. It is presented in the same format as for lift.

Consider the setting with the highest drag and lowest lift, run 7. This is where the difference between average lift and drag is at its smallest level [10]. This is where the height is at the maximum, off-set is negative stagger, speed was set high and the altitude at medium. The negative stagger performance could have been predicted, the height is perhaps more enlightening, and the lesser influences are dependent on possible interaction. It is not possible to determine from this experiment and the outputs. Interaction analysis requires a separate experiment. It does suggest that the settings are sensitive to individual values and could easily change the positives to negatives, which is lower lift and increased drag. The opposite of the focus of this research. For example, if lift is sensitive to speed, any increase in headwind could result in loss of altitude.

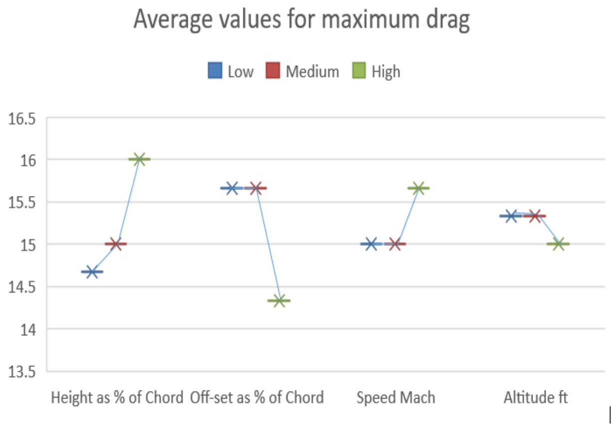

Figure 5. Average values for maximum drag.

Height separation does not appear to be linear. The height increase may produce more lift, but it is also producing higher drag, the instant advantage is tempered by this disadvantage. However, the stagger is of more interest [11]. Whilst the negative and zero stagger play no significance in reducing drag, the positive stagger has a disproportional influence on the reduction of drag that appears far more than the induced drag from height separation – this seems at first contradiction to theory.

Increasing the air speed increases drag just as increases in altitude naturally reduces drag as the air becomes thinner and lower friction [12]. These latter two are not significant in influence as the height and stagger, in the same way as is for lift; the sensitivity of each on the principal inputs needs to be known.

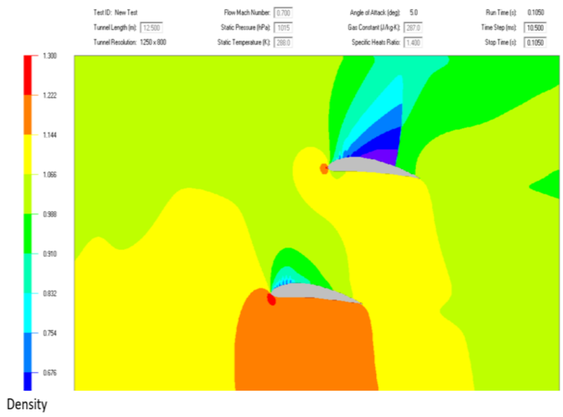

Figure 6. Optimum setting – Density.

When the heigth between the two aerofoils are maximum, see Fig. 6 above, with a positive off-set the influence of one on the other wing is drastically reduced. First, the lower one is almost totally unaffected from the upper, the density difference is greater and that remains constant at these speeds for the length of the underside. Secondly, the upper wing has a low density compounding the difference between the top and bottom. Finally, the difference in density between the two wings is relatively consistent and allows for the two wings to be accepted as not significantly influening each other. Removing this interference is key to lift at altitude where the air density is lower and pressure resulting will be closer between the surfaces and the wings.

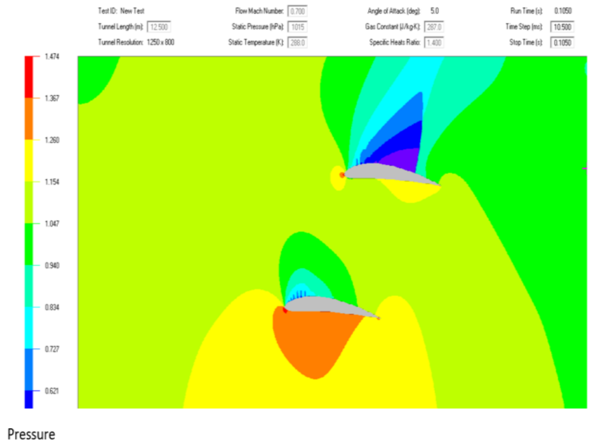

Figure 7. Optimum setting – Pressure.

The pressure distributions shown in Fig. 7above, that the density influences the pressure directly and follows that of Bernoulli's equation [13]. Most importantly is the consistency of pressure between the upper surface of the lower wing to the underneath of the upper wing. Other settings have been directly influenceing this channel between the wings to the detriment of generating pressure. It would appear that the height setting may be close to optimum; although that needs to be verified by further defining. The positve stagger being correct is reinforced further by observing the response values shown in Fig. 4.

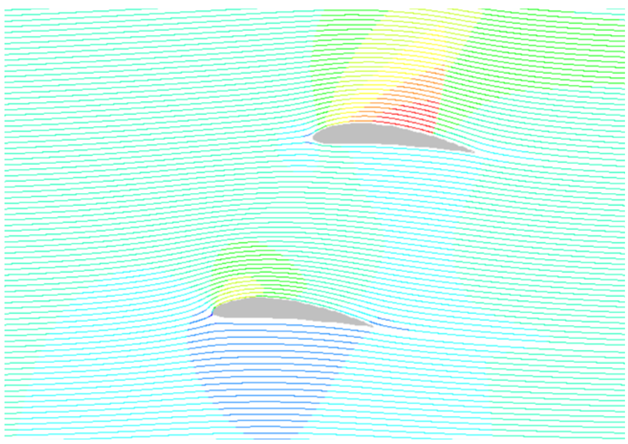

Figure 8. Streamlining of optimum setting.

Streamlining, as shown in Fig. 8 above, of the flow also supports the findings, particularly the downwash of each wing will not cause flow restrctions when combining for a long distance behind the aircraft. Thus, the drag will not be as great as otherwise expected. It is further supported with the response rate show for off-set in Fig. 5. When this is compared in conrast to the lowest lift but highest drag the influences compond on the wings to cause negatives in flow both about and between the wing positions [14]. Even though the hight is maximum the lift offered by twin-wings in this case is neglable in compasion, see Fig. 9 below. The sensitivity is also high from small changes to the stated inputs used.

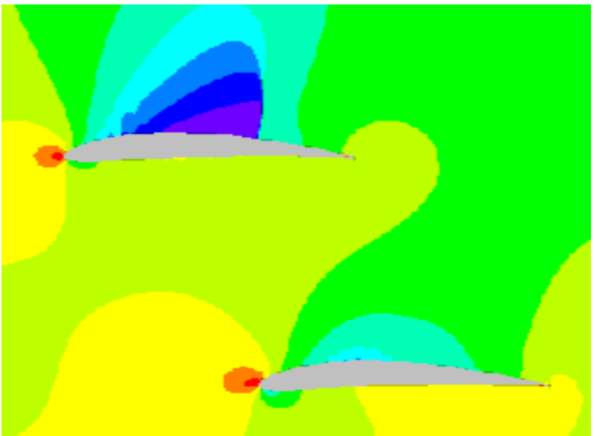

Figure 9. Lowest lift to drag ratio pressure.

Taguchi's experimental arrays offer insights to soulutions with reduced experiements, not all are able to achieve useful results as they are statistically inderterminate. Thus, to finalise and achieve maximum settings further experiements are needed. Indeed, any variations allow for signal-to-noise ratios that identify sensitiivety and if variations are random or spurious.

5 Analysis

This research has shown that of the four inputs investigated; those of the wing heights and the stagger are significant. Speed and altitude less for lift, although each can increase the overall drag, from small changes within the medium to high settings on height and stagger. Likewise, increasing lift may have significant results with moderate changes from inputs.

What is not clear is if interactions exist between any of the settings and if those of speed and altitude are sensitive or just showing random not spurious variations. The results have been validated with a datum scenario and there is a high degree of confidence in the results.

6 Conclusions and future work

This research has shown that the classic way of using a twin-wing had many aerodynamic disadvantages, even though the negative stagger was necessary for operational use. There were four parameters investigated: Height, Stagger, Speed and Altitude. Height and Stagger are the two principal influences; those of speed and altitude were secondary. The results of this research suggest that high separation and positive stagger are critical. The Angle of Attack has not been included in any of these designs and their influence is needing to be known. Future research will also focus on the exact height separation and stagger. Additionally, how any angle of incident will complement the lift whist reducing drag to achieve the highest altitudes with minimum flight speed.

Future work will model in 3D with wing tip boundaries and fuselage drag. These constraints and parameters established here will focus the variabilities to determine robust settings and prediction models.

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