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Drogue Deflections in Low Speed Unmanned Aerial Refuelling

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Abstract

In this research paper the implications of Unmanned Aerial Vehicles (UAV) being refuelled in flight by another UAV is addressed for specific requirements relating to aerodynamics and flight stability. Low speed flight, less than 150KTS, introduces unique flight and stability problems that can be exacerbated by weather conditions. The methods suitable for refuelling have been researched and presented in previous papers by the authors and drogue systems are justified as being operationally feasible with significant aerodynamic characteristics. Nevertheless, these drogue systems do have flight stability problems needing addressed. Not least of these stability problems is docking when weather conditions are less than optimal. In this research the data for Wind tunnels and Computational Fluid Dynamics are used in an Experimental Design system based on a full factorial orthogonal array. The data generates statistical values offering designers and users of UAV that require refuelling a unique insight for allowing operational usage in weather conditions previously problematic. This increase operational possibility extents not only the range but regions where weather might influence deployment of UAVs

Keywords: UAVs, refuelling, Low speed aerodynamics Experimental Design.

1. Introduction

In the last 10 years the use of Unmanned Aerial Vehicles (UAV) has expanded exponentially, furthermore, they have become accepted as a technology that offers boundless opportunities at high technical levels. They have progressed from those that fly within visual sight to those that are operated from the opposite side of the world. Of course, this does not address the practical implications of flying in controlled air space and near misses have been recorded, McAndrew & Moran (2013).

One of the very unique aspects of UAVs, small, light and cheaper than conventional aircraft is also one of its principal weaknesses. The lack of space limits the range they can fly and as these UAVs have been limited by range due to their low speed, McAndrew & Witcher (2013). One way to increase the range is by refueling in operational use. Previous papers have addressed the implications and applications of refueling. Here the focus is towards the design and considerations of drogues and how best to minimise drogue deflection (docking) when refueling.

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2. Drogue refueling

Drogue refueling is where the receiver docks with the deliverer of the fuel. The drogue is the interface device deployed. In Figure 1 below it shows the deliverer and receiver and the drogue. This drogue is deployed from the deliverer and extended rewards in the free air flow to a position sufficiently behind that does not cause aerodynamic considerations and the drogue remains relatively static for the receiver to dock. As with any flow in air there is a tendency for movement and this movement can inhibit if not prevent docking in severe cases.

Figure 1: Receiver docked to drogue

Aerodynamics and atmospheric pressures will influence the free movement of the drogue. These parameters are beyond the direct control of the process, McAndrew et al. (2014). To establish the direct influences of the design the thre principal parameters selected for consideration were: speed, lenth of the droge from the refueler (extended position) and mass of the drogue itself, Anderson (2005). To investigate these parameters an three factor, two positional full factorial array was proposed. This would not only investiaget the influence of each factor, it would also establish if any interactions were present. With a two level design of experiment it is critical to determine the input values of each. Too close together and no insight to full use, too far apart and the extrapolation is superflouous. In table 1 below the parameters selected are shown along with their values.

Table 1: Factor values and units

	Low	High	
A	100	130	Speed, in knts
B	10	15	Length, in m
C	12	16	Weight, in kg

In table 2, below, it shows the full array for this full factor where it balanced to produce an orthogonal array of values where there is an equal probability within each column as there is within each row. Thus a non-parametric set of results for analysis of data. Each value in the main array is assigned a negative (-) or positive (+) value corresponding to the data shown in table 1.

In the left hand column each experimental run from y_1 to y_8 and represents the eight experimental settings. The 5^{th}, 6^{th} 7^{th} and 8^{th} columns are the signage for any interactions between each input factor and another (two level interactions) and the 8^{th} for any three level interactions. Each value is divided by four in order to average the values in the positive and also negative. In effect these column numbers show the difference between the average of the four positive numbers and the average of the four negative numbers. The larger they are the most probability of a statically significant effect. Likewise, the closer to zero it suggests they have negligible influence on the outcome. Generally (ref) three level interactions are very unlikely to have an influence and this is kept in the experiment as a benchmark comparison. Some experiments use this column for a forth factor and thus a half full factorial array is developed and increase error but widens scope of comparisons, Bertin & Cummings (2008).

In the final four columns are the recorded values for each experimental run (rows 2 to 9) of deflections in the x-axis (repeated 5 times) and its corresponding standard deviation, σ_x and y-axis deflection with its standard deviation, $\sigma_{y.}$ The bottom row, labelled L is calculated by determining the difference between the average low level and the average of the higher level. Equation 1 displays such for Column A. The combination of – and + signs follows that in the column from top to bottom, Box & Norman (2007). Each Factor and Interaction column has its unique formulae. These are subsequently used to calculate the values for the last four column results that are analysed and presented. Having repeated runs allows for comparisons between experiments and more importantly within experiments. This is addressed and compared later with the N Score plots. For now, each sample is five and the standard deviation is σ_{N-1} to represent the discrete statistical sample used.

Table 2: Formatting guidance

	A	B	C	AxB	BxC	AxC	AxBxC	$\bar{x}$	σ	$\bar{y}$	σ
y_1	-	-	-	+	+	+	-	1200	80	800	60
y_2	+	-	-	-	+	-	+	1400	100	950	85
y_3	-	+	-	-	-	+	+	1300	90	900	80
y_4	+	+	-	+	-	-	-	1500	110	1000	90
y_5	-	-	+	+	-	-	+	800	60	650	40
y_6	+	-	+	-	-	+	-	900	70	700	50
y_7	-	+	+	-	+	-	-	850	65	675	40
y_8	+	+	+	+	+	+	+	950	75	750	50
L	L_A	L_B	L_C	L_{AB}	L_{BC}	L_{AC}	L_{ABC}				

$$L_A = \frac{-y_1+y_2-y_3+y_4-y_5+y_6-y_7+y_8}{4} \quad (1)$$

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2.1 Results from the full factorial array

It is shown below in Table 3 it is divided into sections, x deflections, y deflections, σ_x and σ_y values for the data. The left hand column is listed chronologically from L_a to L_{abc}. The second column lists in this order the results obtained and these results correspond to the first column of each four sections. The next column sorts them from lowest to highest. This is on the assumption of the Central Limit Theorem, CLT, where we are reviewing to separate the random variations to spurious ones that explain the vast variation. An ANOVA was calculated to determine the expected outcomes. The i column iterated the sorted outcome and f_i the median probability score for individual probability, not division of probability in equal measure to accommodate the first value can happen at t=0 and not 14.28 (100 divided by 7) O'Conner (1992).

Table 3: Individual results for each column and output

	$\bar{x}$	Sorted	Expected	i	f_i	$\bar{y}$	Sorted	Expected	i	f_i	σ_x	Sorted	Expected	σ_y	Sorted	Expected
L_A	150	-475	-1.36449	1	0.086207	93.75	-218.75	-1.36449	1	0.086207	15	-27.5	-1.36449	13.75	-33.75	-1.36449
L_B	75	-50	-0.75829	2	0.224138	56.25	-31.25	-0.75829	2	0.224138	7.5	-5	-0.75829	6.25	-6.25	-0.75829
L_C	-475	-25	-0.35293	3	0.362069	-218.75	-18.75	-0.35293	3	0.362069	-27.5	-2.5	-0.35293	-33.75	-3.75	-0.35293
L_{AB}	0	0	0	4	0.5	-6.25	-6.25	0	4	0.5	0	0	0	-3.75	-3.75	0
L_{BC}	-25	0	0.352934	5	0.637931	-18.75	18.75	0.352934	5	0.637931	-2.5	0	0.352934	-6.25	3.75	0.352934
L_{AC}	-50	75	0.758293	6	0.775862	-31.25	56.25	0.758293	6	0.775862	-5	7.5	0.758293	-3.75	6.25	0.758293
L_{ABC}	0	150	1.364489	7	0.913793	18.75	93.75	1.364489	7	0.913793	0	15	1.364489	3.75	13.75	1.364489

This data is analysed in the following sections with N Score plots as it highlights the variations that are normally distributed or not. A Normal distribution will have an average of zero and standard deviation of 1. If this is plotted then those influenced more by the CLT will lay closer to a straight line passing through zero (average) and 0 (standard deviation). Alternatively, the further they are from a straight line they are more spurious results that cannot be explained by randomness either within the samples or between the samples. Thus it can be concluded that they are the significant values influencing the output variations that are shown.

3. Normal Probability plots of data outputs

Normal Probability plots demonstrate visually and numerically the separation of normally distributed and spurious outputs. Figure 2 is for the data set allied to the x axis movement of the drogue. There are seven plots that correspond to the seven columns in the full factorial array. Basing the origin of (0,0) a projected line can be seen that would encompass the majority of the points. This line clearly demonstrates C as an outlier to the others and it significantly accommodates for the majority of the variation.

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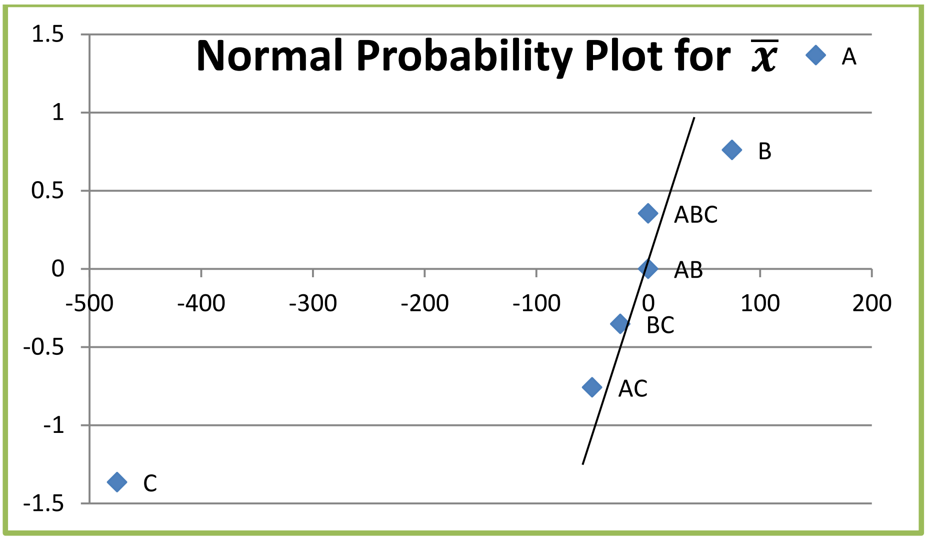

Figure 2: N Score plots average in X axis

It is worth nothing that the (0,0) line also has A relative far away, not as significantly, sufficiently far enough to be able to say that it too has an input to the total variation. Starting with this it can be hypothesised that the drogue movement weight is significant and the heavier the weight the more reduction in free movement. In addition, as the speed increases this too assists in reducing. Inversely, the length of the drogue from the aircraft is not influential to a significant level. None of the interaction plays any significant role, which is surprising given that A and C are both. However, given it is when they are closer to maximum individual values they have their greatest influence. Noting ABC is close to the centre supports the validation of not significantly active.

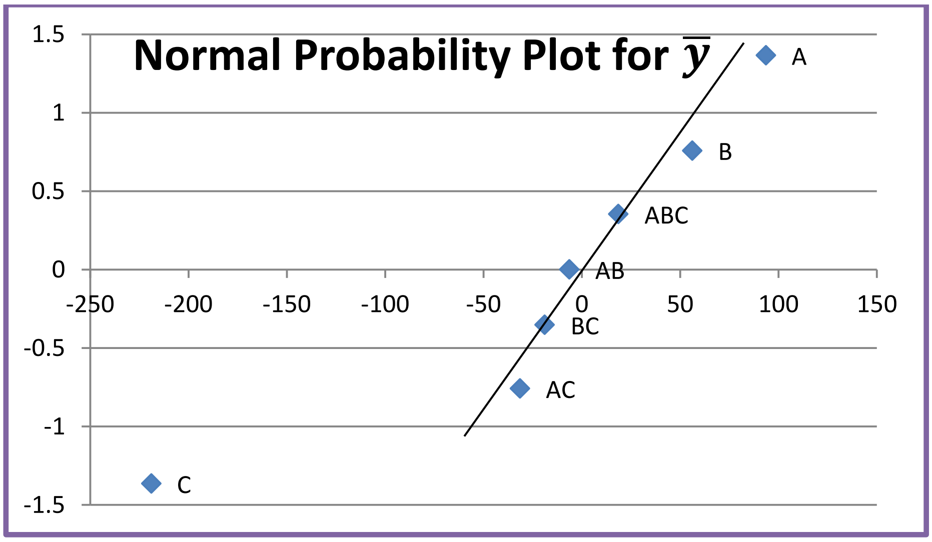

Figure 3: N Score plots average in Y axis

The variations for the Y axis deflections show a similar trend tho those for the X axis deflection. This may seem a natural response; it must be noted that Dutch Role is more influential in the X axis and there could be

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other factors that have influenced, McAndrew & Navarro (2014). In figure 3 factor C is still the largest influence, factor A also and this time factor B has a greater significance. The inter-relationship will be covered more in the discussion of figures 4 and 5 where the variations within samples are addressed in greater detaial. This data also shows that there are no interactions that are influencial.

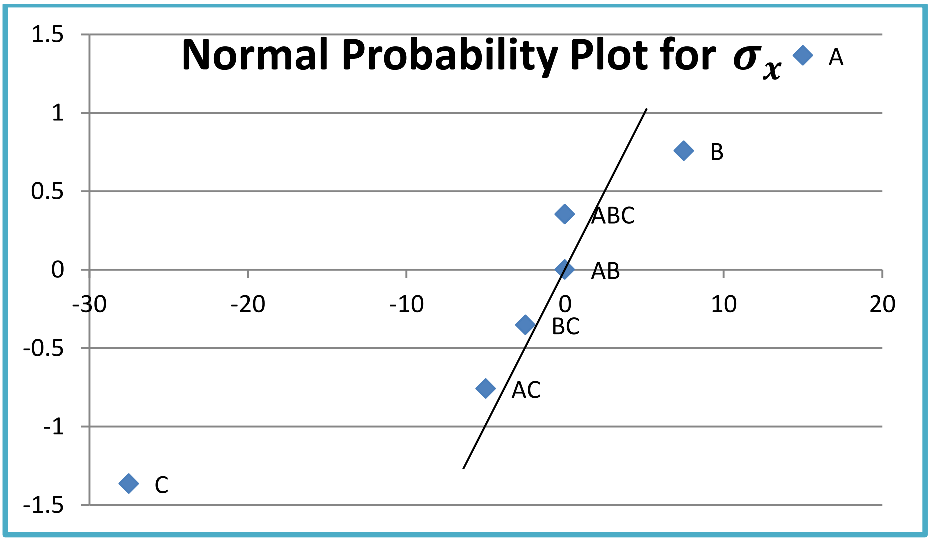

Figure 4: N Score plots standard deviations in X axis

Standard deviations of each experiment considering the X axis are based on a sample of five. Unlike the N Score plots above for the X and Y axis deflections that have various reasons and factors the there is only one factor, C, that is influential in explaining the variation of the drogues movement, Nair (1992). This is by far the greatest influence in variations within each sample and no other factor or interaction has any principal affect. All the other variation can be explained by the randomness within the sample, Leon et al (1987). Below, in figure 5 shows the corresponding values for the standard deviation of the Y variations. This too follows a pattern in logic and results for the data expressed within the individual samples, and the individual implications and results are discussed further on the following page. These results need to be reviewed in isolation and also in comparison of their total implications from the total array of all experiments.

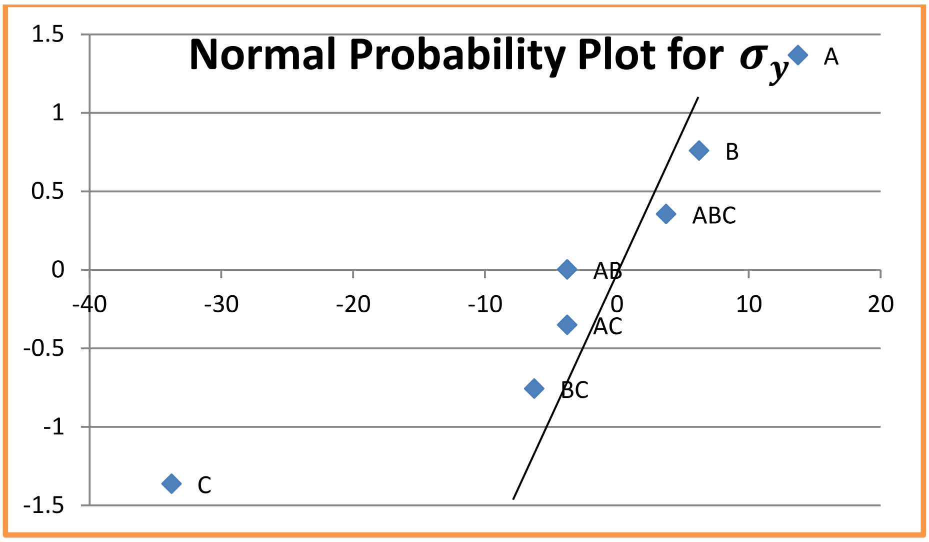

Figure 5 N Score plots standard deviations in Y axis

Variations in the Y axis experience a somewhat similar trend to that in the X axis with the addition of the A factor being of a minor significance. This parallels the trend of the deflections in the X and Y axis and factor A only seems significant in the Y axis where there Dutch Role affect if minimal. These results do not focus to answer this problem, only they now highlight what is happening.

Factor B, the distance the drogue is trailing from the deliverer seems of minor importance. This is a paradox in terms of operation as the longer the distance the move movement is available. Clearly the overarching influences of speed and weight counter act this factor, more so in the X axis.

4. Analysis

4.1 X Axis

In this axis the greatest deflections were recorded, averaging over 1m with standard deviations being greater also than the Y axis. Examining the data in detail it highlights that as factor A, increases the values are at their greatest. Factor B also indicates that higher values are obtained. Therefore applying the reverse logic to minimise the deflections Factor A needs to be minimised, factor B also to be minimised, and factor C maximised, for the X axis deflections to be kept at its lowest level. No interactions are accounted or influence the results.

4.2 Y Axis

Deflections are at their greatest for the Y axis when factor A and factor B is at their greatest values and factor C at its lowest. Inversely, the minimum deflections occur when they are at the optimum (minimum the best) in line with that needed for minimising the X axis deflection. Unlike the deflections for the X axis the or two factors have a greater influence in this axis. There are still no interactions to note and the majority of factors and interactions only influence deflections in the randomness of their values.

4.2 Combined Affect

Experimental arrays combine all inputs to determine their significance of the outputs. Minimum deflections for the X and Y axis do not conflict and mirror the requirements needed. The greatest influences are the firstly the factor C, the weight of the drogue. Next follows the speed and finally the distance trailing from the deliverer. Optimum setting is factor A negative, factor B negative and factor C positive. That means the setting should be as close to the settings used in the experiment, see table 1. Thus, a lower speed, shorter length, and heaviest weight is the focus for flight operations with minimal external influences on the deflections. With this array it is not significantly robust to extrapolate the results as they are based on only two levels that have no data from the points plotted. An array with multi-level is needed to fully evaluate.

5. Conclusion

The results from this study have shown that there is one significant input factor that influences the movement in the X and Y axis, the weight of the drogue. The greater the weight of the drogue the lower is the deflections in the movement for docking. Inversely, the distance the drogue is left trailing behind has negligible affect and only accounts for those by randomness in values. Factor A, in the Y axis had an influence in reducing the deflection; although, the aerodynamic reasons why are not clear from this study and will be reviewed in further studies.

A unique and not predicated at the onset was that there was no interaction at two or three levels. This does allow for the next set of experiments to focus on multi-level and Factor input to determine if the responses between settings are linear or curved. This will enable predicting setting levels. Results have suggested optimum settings for the parameters used and application are based on two level linear responses.

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A Brief Author Biography

1st Dr Ian R. McAndrew – has been in academia for the past 25 years, building on his industrial experience and used this to develop his extensive knowledge of aerodynamics in subsonic and sonic flight. Dr McAndrew has published widely and been involved with many PhDs in both Europe and USA. He is the author of two books and in excess of 20 international conferences and journals. His current research is with a focus of low speed flight requirements in refuelling of Unmanned Aerial Vehicles in flight. He is currently the Department Chair of Graduate Studies for Worldwide at Embry Riddle Aeronautical University (ERAU).

2nd Elena Navarro – has been working with ERAU since 2008, first as an adjunct instructor. Between 2010 and 2013 she served as a Director of Academics at several USAF bases in Germany. Currently, she is a Full Time Faculty within the College of Arts and Sciences. Elena Navarro has both her undergraduate and graduate degrees in Computer Science from Riga Technological University of Civil Aviation. She has taught various undergraduate Computer Science courses at the New Mexico State University, where she also worked as a tutor for all Math courses. Elena has hands on experience with substantial programming and application development at Latvian Environment, Geology, and Meteorology Agency. She has co-authored several publications for conferences and journals. Her current research focuses on the construction and analysis of data from factorial experiments. Elena is also assisting on the numerical side of several aerodynamic research projects and works supporting research in the University where computing and numerical analysis is needed.

3rd Dr Ken Witcher – aviation experience includes 20 years of service in the United States Air Force. During this time, he served as superintendent of an operational test and evaluation squadron and field training detachment chief for F-15, F-16, F-22, H-60, A-10, MQ-1, and MQ-9 aircraft. He also served as a team member of the United States Air Force Air Demonstration Squadron, *Thunderbirds*. Subsequently, he joined Embry Riddle Aeronautical University (ERAU) as Faculty, Director of Academics, Program Chair, and now Dean of the College of Aeronautics, which is responsible for the largest Graduate and Undergraduate aviation degrees from the world's only dedicated aviation university. Dr Witcher's areas of research interest are in effective use of airport capacity and integrating Unmanned Aerial Vehicles (UAV) into commercial airspace.