Factors Influencing Paper Airplane Flight

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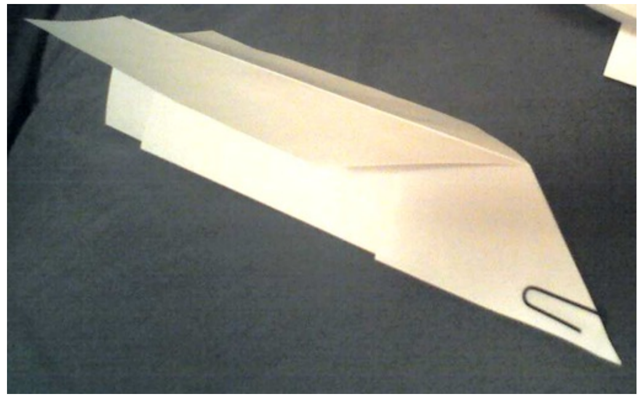
Description

An experiment was designed to test the flight of paper airplanes. Four factors would be used and maximum flight distance would be measured as the response. A fractional experiment was performed, as no three or four factor interactions were expected, allowing for half the number of runs. This would require research into possible confounding, however. Four trials were performed for each run, and the average used as the response.



Standard fold plane, one paper clip, wing down, printer paper.

Four planes were made, two out of each type of paper, with one of each in the standard and one in the jet fold design. The tail fins were cut on all four planes, and flipped up or down as needed. The paperclip, also, was added or removed as needed.

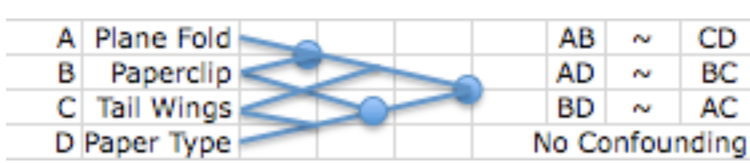
Factors and Levels

The first factor (A) was airplane fold design, with a “Standard” plane (-) and “Jet” (+) as the two levels. Factor B was the number of paper clips used on the nose, with the two levels being zero (-) or one (+). Factor C was the tail position, a 1” flap at the rear of the plane, folded either down (in line with the fuselage) (-) or up (+). Finally, factor D was notebook paper (-) or printer paper (+). These factors were chosen because they were thought to have greatest influence on the flight, and were easiest to control in the experiment. Additional factors, such as launch force, could have been chosen, but would require significant effort to attempt to control.

Jet plane, no paper clip, wing up, notebook paper.

Expected Interactions

Expected interactions were predicted, and an affinity diagram made to plot them (shown right). In combination with the table of confounding terms for a 2^{4-1} experiment, found in the textbook, it was determined that no confounding



should occur. The expected interactions were: Plane Fold and Number of Paper Clips; Plane Fold and Paper Type; and Number of Paper Clips and Paper Type. These interactions were chosen as the plane fold affects the wing surface area and plane aerodynamics, and both number of paperclips and paper type affect plane weight (printer paper is thicker and larger, weighing more than notebook paper). Aerodynamics, lift, and weight are all heavily integral to plane flight, and interactions between these factors were thus expected.

Array

The experiment array was built using the factors to be used and expected interactions, and the responses filled in. Confounding interactions are also shown at the bottom of the array. The run order was randomized to avoid a build up of noise. For each run, four trials were made, only the average of them is shown below.

tc	STD	RDM	A - Fold	B - Clips	C - Tail	D - Paper	AB	BD	AD	Distance
(1)	1	4	(-) Std	(-) 0	(-) Down	(-) Note	+	+	+	34
a(d)	2	3	(+) Jet	(-) 0	(-) Down	(+) Printer	-	-	+	181
b(d)	3	8	(-) Std	(+) 1	(-) Down	(+) Printer	-	+	-	199
ab	4	5	(+) Jet	(+) 1	(-) Down	(-) Note	+	-	-	146
c(d)	5	1	(-) Std	(-) 0	(+) Up	(+) Printer	+	-	-	75
ac	6	7	(+) Jet	(-) 0	(+) Up	(-) Note	-	+	-	231
bc	7	6	(-) Std	(+) 1	(+) Up	(-) Note	-	-	+	228
abc(d)	8	2	(+) Jet	(+) 1	(+) Up	(+) Printer	+	+	+	170
also measures:			BCD	ACD	ABD	ABC	CD	AC	BC	

Confounding

As a fractional experiment was performed, confounding of factors and interactions must be considered. Using the table of interactions for a 2^{4-1} experiment from the textbook (p. 119) and the affinity diagram above, all factors and expected interactions were listed and checked for confounding. Factors confounded only with three factor interactions, which were not expected, and expected interactions did not confound with each other. Interactions that confound with each factor/interaction can be seen in the last line of the experiment array, shown above.

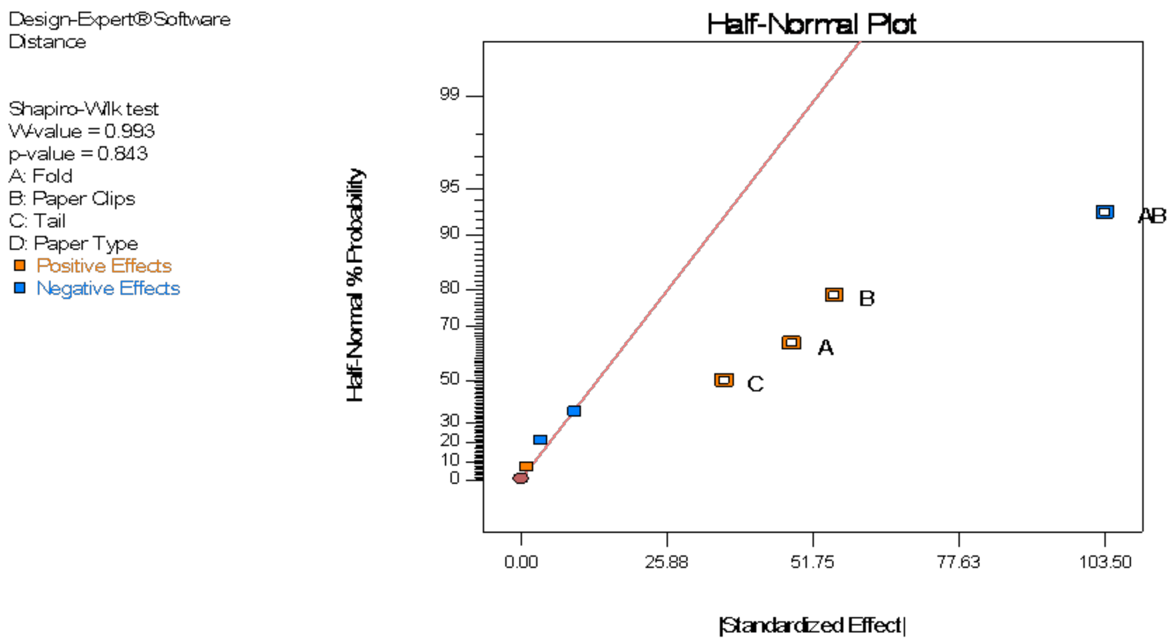
Should any interaction occur unexpectedly (i.e. The CD, AC, or BC interaction), the effects of it would be included within the confounding interaction, inflating its value. This could cause two insignificant interactions to combine into a single apparently significant interaction. This is not expected to have occurred in this experiment, however.

Response

The experiment's response was maximum flight distance, as measured in inches, averaged over the course of four trials per run. Distance was measured from the line where the plane was thrown to the point where the plane first touched the ground. If a plane stopped upon touching the ground, the front most point was used. If a plane continued to slide across the ground after landing, the impact point was used. If a plane drifted significantly right or left of the straight line, the trial was discarded and retried. A new trial was made also if the plane impacted any objects during flight, or if the flight distance was thought to be "abnormal" (significantly more or less distance than other flights of the same run).

Analysis

Results were entered into Design Expert software for analysis. Significance of factors and interactions was determined based on the Half-Normal Plot and ANOVA table shown below.



The half normal plot shows the factors and interactions present in the experiment, and plots them. Items furthest form the normal line (on right) are most likely to be significant, while items that closely follow the normal line are more likely to be insignificant. Significant items are labeled (AB, B, A, C) while the insignificant items are not. By choosing those items most likely to be significant in the half-normal plot and checking the ANOVA table below, the significant factors can be ascertained.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	34785	4	8696.25	126.03	0.0011
A-Fold	4608	1	4608	66.78	0.0038
B-Paper Clips	6160.5	1	6160.5	89.28	0.0025
C-Tail	2592	1	2592	37.57	0.0087
AB	21424.5	1	21424.5	310.5	0.0004
Residual	207	3	69		
Cor Total	34992	7			

As shown on the ANOVA table, factors A, B, and C all have less than 5% probabilities of not being significant (.38%, .25%, and .87% respectively). Additionally, the AB interaction has only a .04% probability of being insignificant. All other interactions, and factor D, had p values greater than .05, and were deemed insignificant.

Modeling

A linear model was generated by the Design Expert software as well. It is:

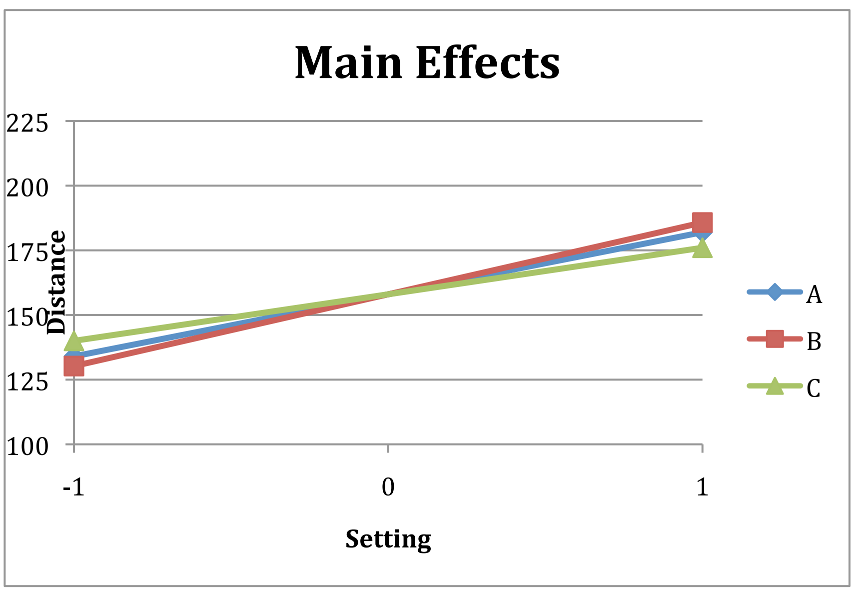
$$distance = 158 + 24A + 27.75B + 18C - 51.75AB$$

Using this model and the graphs below, maximum and minimum values can be found.

In addition, the equation can be solved for a known distance if desired. Such solving, however, is not possible in this circumstance, as all four factors are categorical. This makes it impossible to utilize the levels that would be obtained, such as a fraction between a standard and jet fold.

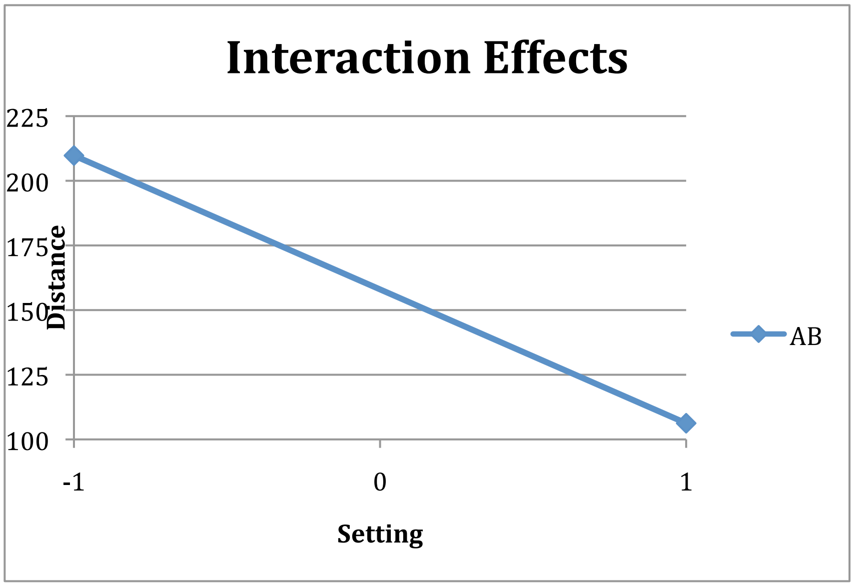
The confirming run, discussed later, utilizes this model. The y-intercept of 158 will be found below as the intersection point of lines on both the Main Effects and Interaction Effects graphs.

Effects graphs were created to visualize the significant data. The main effects graph below shows the significant factors, and allows visualization of their slopes. In this way, the effects of each factor can be better seen, as well as differences between them.



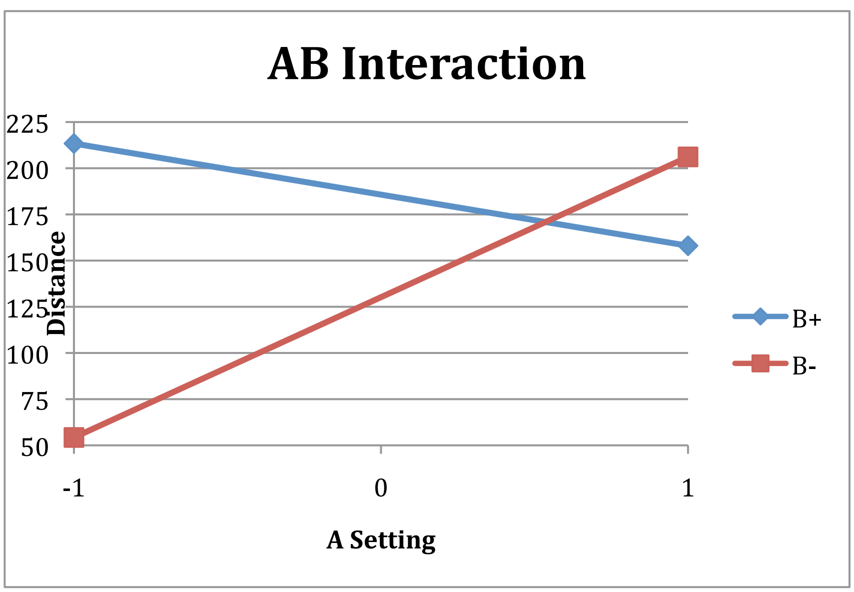
Factor B has the greatest slope, and is therefore the most significant. Factor A is next, followed by factor C. As factor D is not significant, its slope would be still less were it graphed. The intersection point appears to be ~160, which equates to the y-intercept, as discussed above. As all four factors are categorical, values between the two levels are not possible. The line is continuous only for visualization.

The interaction effects graph shows the significant interactions and allows comparison of them to each other as well as to the factors on the main effects graph. For this comparison, however, both graphs must have the same scale, as these do.



As can be seen, the slope of the AB interaction is very great, indicating a strong significance. If the other interactions were plotted as well, they would have small slopes (as they are not significant) and would intersect at ~160 (the y-intercept).

The Interaction Plot shows the interaction of two factors and the values obtained at each of their levels. This allows visualization of both levels for both factors, as well as estimation of intermediate levels.



The AB Interaction Plot above shows that furthest distance can be obtained from the A- and B+ settings.

Utilizing the information from the graphs above, a confirming run was made, as presented below.

Factor	Name	Sig?	Setting	Comments
A	Fold	Yes	(+) Jet	AB Interaction Plot
B	Paper Clips	Yes	(-) Zero	AB Interaction Plot
C	Tail Position	Yes	(+) Up	Main Effects Graph
D	Paper	No	(-) Notebook	More readily Available

Levels for factors A and B were found using the AB Interaction Plot, and factor C from the Main Effects Graph. The Interaction plots must be looked to first, as using the Main Effects Graph for factors A and B would have instead provided a confirming run of B+. As factor D was not shown significant, its setting was chosen to be notebook paper, as it generally easier to find, though situations may vary.

Using this data and the linear model, the maximum theoretical distance can be obtained.

$$\text{max distance} = 158 + 24(+1) + 27.75(-1) + 18(+1) - 51.75(+1)(-1) = 224 \text{ inches}$$

This value, however, is not equal to the maximum value obtained in the experiment (231) due to likely to noise in the experiment.

By reversing the levels of the significant factors, a minimum value can also be found.

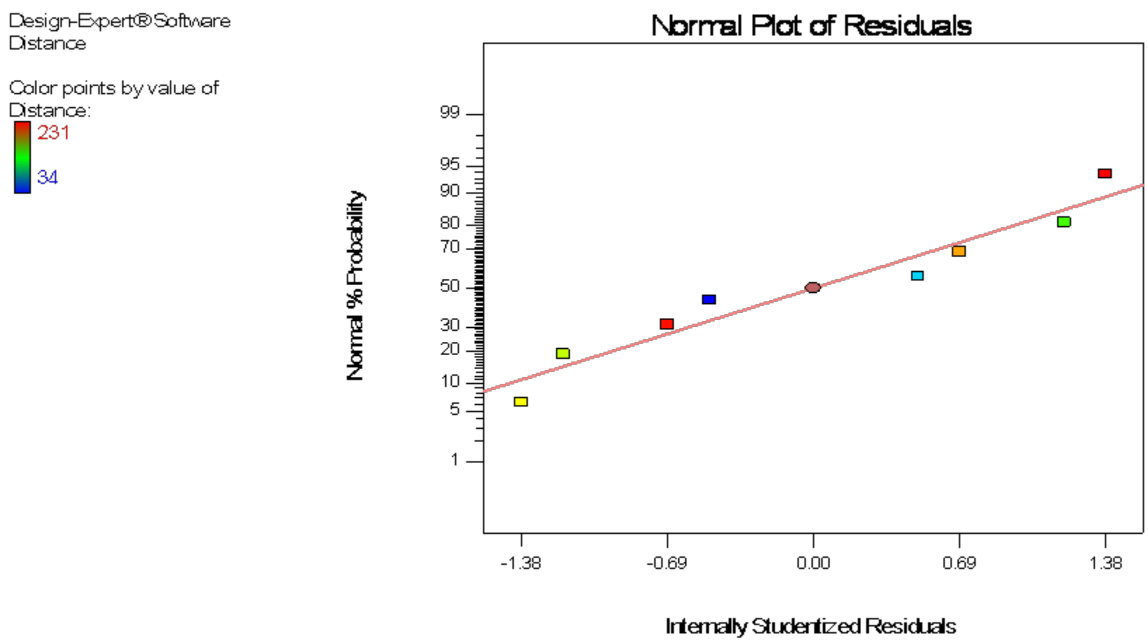
$$\text{min distance} = 158 + 24(-1) + 27.75(+1) + 18(-1) - 51.75(-1)(+1) = 195 \text{ inches}$$

Note that this value is even more different from the actual minimum value of 34. Again, this is due to noise in the experiment, not accounting for non-significant factors and interactions, and noise in confounding interactions.

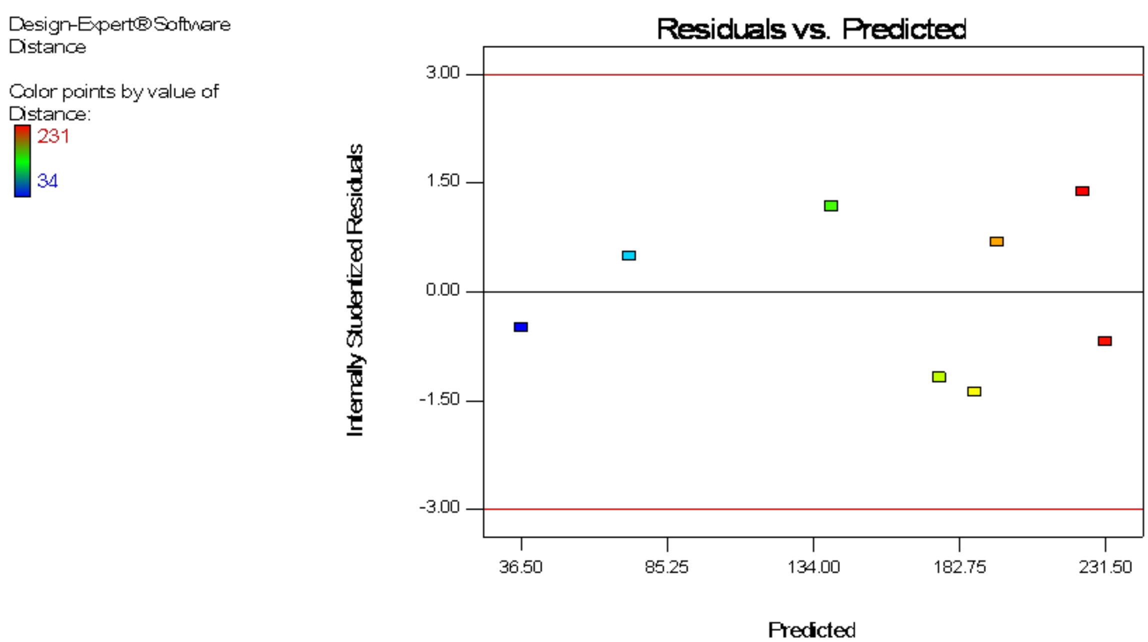
Diagnostics

Diagnostics were run in Design Expert to verify the integrity of the data. Two diagnostics were run, a normal plot of residuals and a comparison of residuals to predicted values.

The Normal Plot of Residuals (on next page) plots the responses along a line of probability. The points should closely follow the line. Points that differ greatly from the line should be considered suspect, and possibly bad data. All values in this experiment closely hug the line, and are likely good data.



The Residuals Versus Predicted plot plots the responses between + and – three sigma lines. Points that are outside the lines are considered suspect and may be poor data. All data obtained in this experiment appears to be good.



Noise and Outside Influences

Due to the nature of the experiment, outside interference and noise were a significant issue. Small variations between the four planes made caused variations in flight, as did crumpling of the nose with continued impacts. Small air currents through the test area also caused differences in flight distance and path. Throw was inconsistent between trials and runs, as it is a human controlled factor. A mechanical throwing rig would have helped decrease some noise, but would be impractical to build for the scale of this experiment. Additionally, testing in a more controlled environment would have decreased air currents, but it was believed that these would be minimal in the chosen area.

Several trials that had abnormally long or short distances were redone to combat noise. As well, trials that drifted off course and would be difficult to determine actual distance were ignored.

Within the experiment, even insignificant interactions do include some noise, which is carried over to the confounding interaction of factor. This causes more noise within a fractionated experiment than would be seen in a full-factorial. As the main factors were only confounded with three factor interactions, such noise should be minimum. Among the two factor interactions, however, the confounding two factor interactions may present more significant amounts of noise, as may be the case in the AB interaction.

Conclusions

It was found that the most significant element was the AB interaction, as it had a greater slope than did any other element. This may be due to confounding with the CD interaction as well as noise present in the experiment and from outside sources.

Of the expected interactions, one was significant. It cannot be ascertained if any unexpected interactions were significant as they all confounded with expected interactions.

The best design for greatest distance was found to be a plane folded as a Jet, with no paperclip at the nose and the tail in the up position, with paper type not significant.

Further study could be focused on deviation from course, to see if a particular design is more likely to drift to the right or left of a straight line. In addition, the data from this experiment could be analyzed to study variation, to find if a particular design produces more variability or consistency in flight distance over others.