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OPTIMIZATION OF FLIGHT TIME AND DISTANCE TRAVELLED OF A STYROFOAM GLIDER

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ABSTRACT
One of the opportunities given to third-year students enrolled in the Computer-Aided Design course at UOIT is to utilize Design of Experiments and design optimization techniques to determine optimal parameter settings for best performance of an artifact. In the previous course offerings, students determined optimal designs of paper helicopters to optimize flight time, while adhering to a limited number of design constraints. In practice, though, more performance dimensions should be explored for an optimal design. This is particularly true with the design of unmanned air vehicles, which are required to have optimal range (aerodynamic efficiency for higher flight speeds), as well as optimal endurance (ability to stay aloft for extended periods of time, while operating at low speeds and low power). This paper proposes a new assignment that could be used in future offerings of the course, whereby students construct gliders out of ordinary material (Styrofoam, cardboard, etc.), and determine a wing design around a limited number of parameters that would allow the glider to fly as far as possible, as well as to stay in the air as long as possible. With the assistance of CAD software (NX7.5), students can design the various components of the glider, including the various wings to be used for the experiment, and use these designs as patterns to be cut out of the said construction material. Students will conduct flight test experiments for various combinations of design parameters, and then use statistical analysis techniques (i.e., Taguchi methods) to determine the optimal wing design of the glider.

Keywords: Design, experiments, optimization, Taguchi

1 INTRODUCTION

It is imperative that students are provided opportunities to apply robust design methods and Design of Experiments (DOE) early in their engineering academic careers in order to gain a greater sense of how a design performs under a variety of conditions, and to determine a setting of parameters that optimizes that performance subject to uncontrollable variations. For first-year students, the opportunity to utilize DOE was provided through the introduction of an assignment that charges them with designing an aircraft wing that provides an optimal Lift-to-Drag ratio [1]. Third-year students were introduced to this methodology via a paper helicopter design exercise [2]. For this research, an alternative assignment is proposed for the application of DOE in an academic setting, along with example results. Students are provided an opportunity to design, build, and test a Styrofoam glider to determine an optimal wing geometry that allows the glider to stay in the air as long as possible, while maximizing the distance travelled.

2 BACKGROUND

Design of Experiments (DOE) has been utilized in various applications in industry and research. In one application, DOE was used to improve product and process integrity [3], with Taguchi methods [4] used to find optimal factor settings for the process of radiographic quality welding of cast iron. Taguchi methods have also been utilized in manufacturing settings to optimize product quality via Taguchi's Quality Loss Function (TQLF) [5, 6]. In another application, Taguchi methods and DOE were used to optimize the assembly sequence of a product, with a toy car, a toy motorbike, and a toy boat being used as examples [7]. Other applications of DOE can be found in biological applications, such as the optimization of the production of a monoclonal antibody by a hybridoma cell line in spinner flasks [8], and in Polymerase Chain Reaction (PCR) optimization [9], used in forensic applications. With a wide range of applications of DOE available, it is imperative that students be given early hands-on exposure.

The necessity of training engineers and business managers in DOE at the university level has been well documented [2, 3], as there is a general lack of expertise in using these techniques. Also, training provided the opportunity for engineers and managers to really see the potential benefits of DOE. A simple experiment was introduced to assist engineers and managers with applying these techniques without external help [2, 10]. Other teaching approaches were developed around the most commonly used experimental designs (full factorial, screening factorial, screening fractional factorial, and Taguchi arrays), as introduced at the École de Technologie Supérieur in Montreal, Canada [11]. Another approach makes use of various existing products (such as a golf swing analyzer) to teach DOE in short training courses to personnel of varying education and experience levels [12].

This paper describes a new assignment introduced for the first time in Fall 2010 in the third-year core engineering design course (Computer-Aided Design) as an alternative to provide students with a an opportunity to apply Taguchi methods and DOE to optimize the flight time and distance travelled of a Styrofoam glider, where a closed-form solution is not readily available.

3 PROBLEM STATEMENT

Between the required knowledge of industrial engineers to understand the benefits of experimental design as a problem-solving technique, and the importance of teaching these techniques to engineers to solve quality engineering problems, there exists a cognitive gap [2]. To bridge this gap, a simple, paper helicopter design experiment was introduced, where engineers determine an optimal set of values for parameters affecting the helicopter's flight time [2, 3]. Based on this experiment, third-year UOIT engineering students determined the effects of various combinations of helicopter blade length and width on the paper helicopter's total flight time. Students optimized the helicopter design by optimization programming, software such as MATLAB®, or by analytical means (using a suggested two-parameter objective function). Bonus marks were offered to students who used Taguchi methods, utilizing the NUTEK Qualitek-4 demonstration software version [4] to accomplish this.

A performance decline from year to year of the assignment offering was observed, along with decreasing attempts to use the Taguchi methods [1]. As such, an alternative third-year assignment was introduced to students for which an analytical solution was not readily available as with the helicopter design, and where students evaluated multiple outputs for performance measurement. This way, students would be required to use the DOE methodology to arrive at the optimal design. Specifically, students were charged with the task of designing a glider, selecting a wing geometry that would maximize the glider's distance travelled, as well as the flight time (the measured outputs of the experiment which would serve as the objective functions). Using a suggested list of wing geometry parameters, students were to study the effects of varying the parameter values between at least two levels, ultimately identifying a parameter combination that would yield optimal performance for the glider. Students were to use Taguchi methods (with the help of the NUTEK software) to analyze their experimental data and identify the optimal parameter setting combination.

4 THIRD-YEAR ASSIGNMENT

For this assignment, students were given the task of designing a Styrofoam (or other suitable material) glider to maximize its distance travelled and its flight time when thrown from a height of ~2m. To accomplish this, students were to design several wings using various combinations of span, root chord, tip chord, and leading edge sweep angle. The simplest wing geometry was to be used, as shown in Figure 1, derived from an example in Ref. 13. As a starting point, students were asked to explore real aircraft to base their glider designs on (such as the Boeing 747-8 Intercontinental [14], which will be used in the example experiment presented herein).

Table 1 provides a design basis for the scaled-down glider model based on the Boeing 747-8 dimensions, showing the original aircraft dimensions, as well as the scaled dimensions. Table 2 provides values for the parameters for the wing design to be varied in the experimental trials, given at two setting levels for each parameter. Figures 2-5 show some example templates (to be used in cutting out the glider parts from ½ inch thick Styrofoam) and fully assembled glider, based on the scaled-down model, drawn in NX7.5. Constraints were somewhat relaxed to allow greater flexibility in choosing parameter combinations for the wing geometry, but students were to note the original aircraft's wing area (and scaled-down area for the glider model) for reference, choosing geometric parameters such that the resulting wing area does not deviate greatly from this reference. In this example, the scaled-down original wing area was 32625 mm^2.

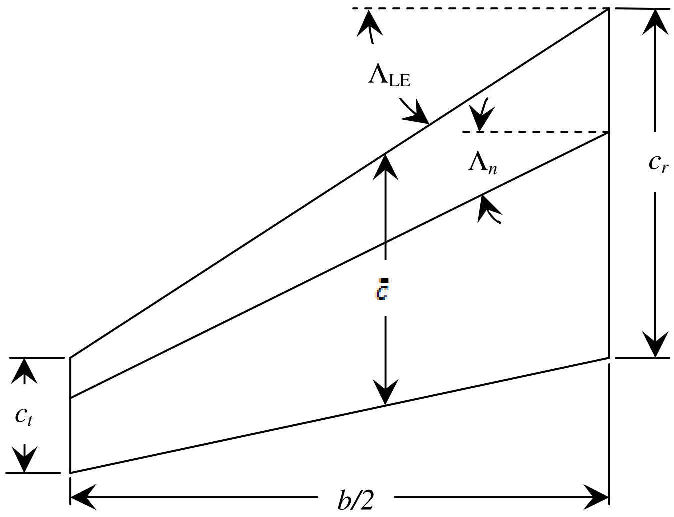

Figure 1. Wing geometry used in robust design assignment, based on Ref. 13

Table 1. Actual Boeing 747-8 dimensions and scaled measurements of Styrofoam glider.

Parameter	Actual	Scaled	Parameter	Actual	Scaled	Parameter	Actual	Scaled
Length	76.3 m	500 mm	Leading edge sweep (Λ_{LE})	42 deg.	42 deg.	Vertical tail root chord (c_{r_vt})	13.3 m	87 mm
Total height (to top of vertical tail)	19.4 m	127 mm	Horizontal tail root chord (c_{r_ht})	10.8 m	71 mm	Vertical tail tip chord (c_{t_vt})	4.6 m	30 mm
Root chord (c_r)	18.3 m	120 mm	Horizontal tail tip chord (c_{t_ht})	4.2 m	28 mm	Vertical tail leading edge sweep (Λ_{LE_ht})	51 deg.	51 deg.
Tip chord (c_t)	3.75 m	25 mm	Horizontal tail span (b_{ht})	24.6 m	160 mm	Vertical tail height	10.9 m	71 mm
Span (b)	68.5 m	450 mm	Horizontal tail leading edge sweep (Λ_{LE_ht})	42 deg.	42 deg.			

Table 2. Independent parameters to set for running computational experiments for wing design.

Parameter ID	Parameter Definition	Setting 1	Setting 2
A	b (span)	450 mm	430 mm
B	c_r (root chord)	120 mm	140 mm
C	c_t (tip chord)	25 mm	20 mm
D	Λ_{LE} (leading edge sweep)	42 deg.	35 deg.

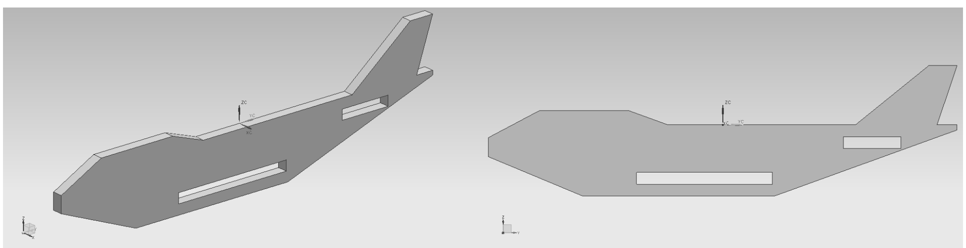

Figure 2. Glider fuselage example

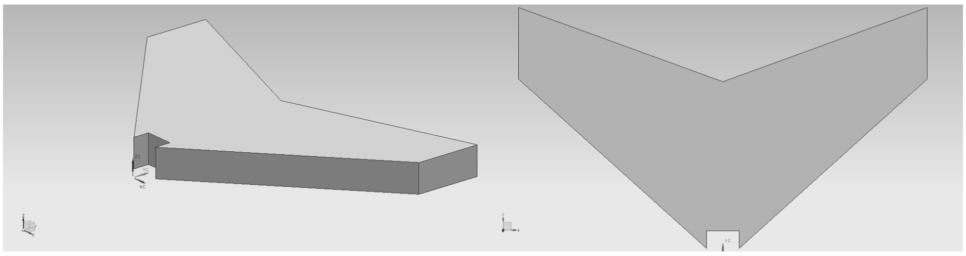

Figure 3. Glider horizontal tail example

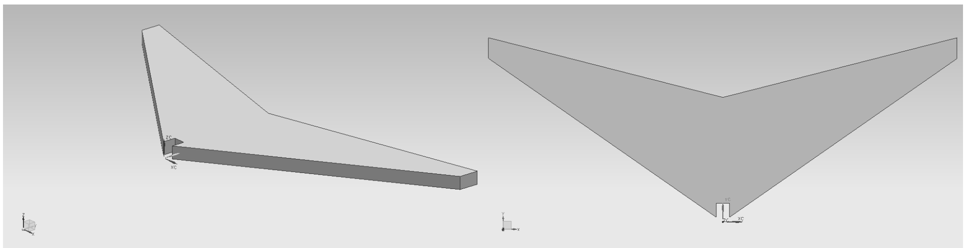

Figure 4. Glider wing example

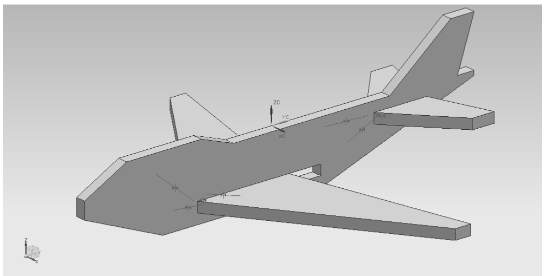

Figure 5. Assembled glider example

For the experimental trials, at least three parameter combinations were to be chosen, and therefore, three different wings constructed for each respective parameter combination. For each wing, students were to throw/launch the glider and measure the distance it travelled, as well as the time it remained in the air, doing so at least ten times for each wing design. Table 3 shows some example results of this experiment. The ‘1’ represents the parameter value at Setting 1, and a ‘2’ represents a parameter value at Setting ‘2’.

5 RESULTS

To analyze the data and determine which parameter combination for the wing design maximizes the glider’s distance travelled, as well as the flight time, Analysis of Means [4, 15] was used. The average flight time and distance travelled was taken first for all settings of parameter A at Setting 1, then at Setting 2, then for parameter B at Setting 1, followed by Setting 2, and so on. The results are shown in Tables 4 and 5. As can be seen by the results, maximum flight time and distance travelled can be achieved if parameters A and C (span and tip chord) use the first setting values, while parameters B and D (root chord and leading edge sweep) use the second setting values. This coincides with the parameter combination for the second set of 10 runs. To ensure that this combination indeed maximizes flight time and distance, a confirmation set of experiments should be performed. Also, alternative parameter combinations should be explored that were not considered in the original experiment.

Figure 6 shows a grade distribution of the previous optimization assignment (2007-2009) and the new assignment (2010). The effect on the grade distribution from the introduction of the new assignment was positive, with more grades tending to 4/4 or better. This trend may be the result of a more exciting design-build-test project, as well as requiring students to become more knowledgeable in DOE and statistical methods for analyzing the experimental data.

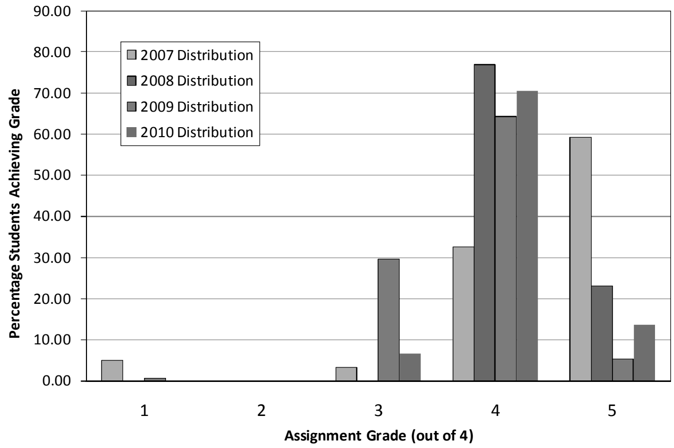

Figure 6. Grade distributions for optimization assignment

Table 3. Experimental runs for glider flight time and distance travelled for three wing designs.

Run	A	B	C	D	Flight Time (s)	Distance Travelled (cm)
1	1	1	2	2	1.56	480
2	1	1	2	2	1.25	599
3	1	1	2	2	1.37	463
4	1	1	2	2	1.48	418
5	1	1	2	2	1.25	393
6	1	1	2	2	1.49	560
7	1	1	2	2	1.42	650
8	1	1	2	2	1.48	447
9	1	1	2	2	1.43	512
10	1	1	2	2	1.42	417
1	1	2	1	2	1.72	543
2	1	2	1	2	1.6	646
3	1	2	1	2	1.44	494
4	1	2	1	2	1.59	454
5	1	2	1	2	1.59	508
6	1	2	1	2	1.57	499
7	1	2	1	2	1.21	549
8	1	2	1	2	1.62	597
9	1	2	1	2	1.19	550
10	1	2	1	2	1.48	608
1	2	1	2	1	1.02	414
2	2	1	2	1	1.4	516
3	2	1	2	1	1.4	508
4	2	1	2	1	1.53	590
5	2	1	2	1	1.14	388
6	2	1	2	1	1.24	485
7	2	1	2	1	1.26	482
8	2	1	2	1	1.1	483
9	2	1	2	1	1.4	510
10	2	1	2	1	1.13	458

Table 4. Average flight time for all parameters at Settings 1 and 2

Setting	A	B	C	D
1	1.458	1.3385	1.501	1.262
2	1.262	1.501	1.3385	1.458

Table 5. Average distance travelled for all parameters at Settings 1 and 2

Setting	A	B	C	D
1	519.35	488.65	544.8	483.4
2	483.4	544.8	488.65	519.35

6 CONCLUSION

An alternative third-year assignment was described in which students were to design, build, and test a glider for maximum flight time and distance by determining appropriate settings for the geometric parameters of the wing. Students utilized Taguchi methods to analyze experimental data from the flight trials and to determine the optimal parameter combination for the wing design, as there is no closed-form solution to the problem at hand. Sample experimental results were shown to illustrate the experimental and analysis process, from which an optimal set of parameters was determined. An improved grade distribution was also observed by the introduction of the assignment. This assignment will continue to evolve for future offerings of the third-year engineering design course and the authors welcome suggestions for improvement.

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