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A Taguchi Based Iterative Wing Structural Design for A Low Speed, Hybrid UAV

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Abstract
An iterative structural design process for the conventional, composite wing of a low speed, hybrid Unmanned Aerial Vehicle (UAV) is presented in this paper. The relevant design goals are light weight, strength and stiffness derived from the customer specifications, conceptual design and STANAG-4671 airworthiness standards. To achieve the design goals, a modified Taguchi model was applied in conducting iterative Finite Element Analysis of the loads and stresses on the wing model, using ABAQUS CAE. In this analysis, the pitch of the rib and thicknesses of the spar and skin were applied as control factors in three levels, leading to an L9 orthogonal array. Mass, maximum deflection and Tsai-Hill failure index of the wing structure were measured as responses. The result shows that varying the skin thickness had the most impact on the wing mass, failure index and maximum deflection. The design goal of wing mass- less than 2.5kg, deflection of 10% and Tsai-Hill failure index value- less than 1 were achieved after 9 iterations.

Keywords: *Aerospace, Analysis of Mean (ANOM), Analysis of Variance (ANOVA), control factors, detailed sizing, fixed wing, rapid design, quality loss function, Tsai-Hill Failure Index, Unmanned Aerial Vehicles (UAV), wing deflection.*

1.0 INTRODUCTION

The success of Unmanned Aerial Vehicles (UAV) as a robust platform for surveillance, remote measurement and courier has led to its proliferation in the last two decades. From the inception of the war against terror in the early 2000's to the COVID-19 crises of 2020, its design and application evolved rapidly with consumer demands for more range, endurance and payload carrying capacity [1]. Satisfying this performance demands for UAVs and aircraft in general has led to several research into aerospace materials and optimal design.

UAV wings are designed to generate lift sufficient to sustain the entire structure in heavier than air flight. According to [2], wing design involves trade-offs between lift, structural strength, stiffness and weight. Other design considerations include ease of manufacture, ease of transportation, set-up time and maintainability. The design for operational flexibility and easy transportation led to modular compact designs while posing the problem of designing for rapid set-up [3]. Also, the materials, technology or manufacturing process required to produce the most efficient design may be cost ineffective, restricted or unavailable.

On the other end of the design dilemma is the need to rapidly design, develop and test UAV concepts to meet quality parameters prescribed by customers and airworthiness certification standards. According to [4] typical approaches to product design includes the Build-Test-Fix approach, One Factor at a Time, Full Factorial Design and the Taguchi Method. The most efficient of these methods in terms of cost and time is the Taguchi method also referred to as the robust design method [4-6].

Other statistical and probabilistic methods have been applied in design, such as Monte Carlo method detailed in [7-9]. The probabilistic design frame work presented by [10] considered requirements for reliability, manufacturability and cost in the design optimization of a wing spar. Approaches that integrate probabilistic constraints into the parameter design in Reliability-Based Design Optimization (RBDO) process were proposed by [11], [12]. These methods improved the efficiency of the RBDO process.

In this study, detailed sizing and stress analysis of the composite wing structure of a low speed UAV was done in ABAQUS FEA environment. A Taguchi method was applied in varying the rib pitch, skin thickness and

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spar thickness. For each iteration the wing mass, maximum deflection and failure index were measured as responses.

2.0 THEORETICAL BACKGROUND

The approach is based on methods developed by Genichi Taguchi for improving the quality output of manufacturing processes and for determining the impact of variations on the outcome of a design process [4], [5]. Taguchi evaluates the quality of a product based on the variance observed between the response (quality characteristics) measured and the target, expressed as a quality loss function:

$$Q = 10\log 10\left[\frac{\mu^2}{\sigma^2}\right] \quad (1)$$

where μ is the desired quality characteristic and σ^2 is the variance. The ratio of the square of the response to the variance is referred to as the signal-to-noise ratio (SNR) [5].

In the design of experiments, Orthogonal Arrays (OA), are derived as smaller sample representation of the entire sample space based on the degree of freedom [13], [14]. Interpretation of the result is done statistically by Analysis of Mean (ANOM) [14], [15] and Analysis of Variance (ANOVA) to determine optimum combinations of variables and the factor having most contribution to the outcomes.

In this research, the quality characteristics of the wing were selected as mass, failure Index and maximum deflection. Rib thickness was fixed, while skin thickness, spar thickness and rib pitch were varied as control factors in 3 levels or variation.

3.0 FINITE ELEMENT ANALYSIS MODEL DEVELOPMENT

The model is a fixed wing for a UAV with Maximum Take Off Mass (MTOM) of 25kg. It is expected to cruise at 22ms^{-1} at an altitude of 3,048m. With a wing mass budget of 2.5kg, the wing is in 3 modules of 1100mm length, summing to 3300mm span. Table1 shows relevant parameters of the fixed wing.

Table 1: Conceptual model of the Fixed wing

Parameter	Unit	Value
MTOM	Kg	25
OEM	Kg	20
Wing Mass	Kg	2.5
Planform Area	m^2	0.9
Airfoil		MH-32
Root chord	m	0.32
Tip chord	m	0.176
Span	m	3.3
Cruise speed	ms^{-1}	22
Maximum Speed	ms^{-1}	30
Cruise Altitude	m	3,048

Figure 1 shows the plan view of a hybrid UAV. In this configuration, a boom passes through the central wing module. It carries 4 Vertical Take Off and Landing (VTOL) motors and connects the V-tail to the wing.

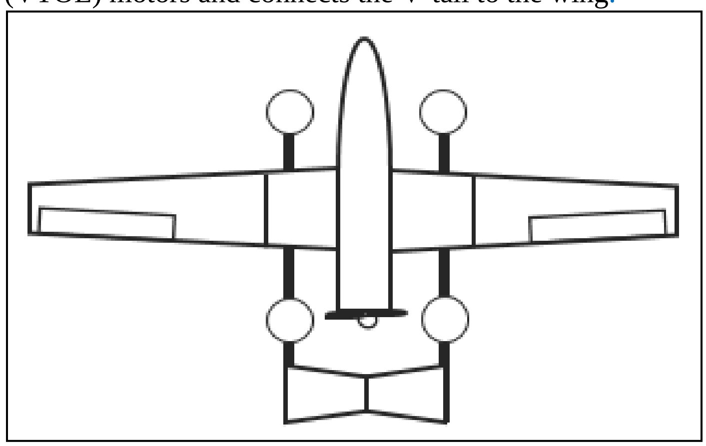

Figure 1: Hybrid UAV wing configuration

3.1 Materials Selection

The considerations for material selection were tensile strength to weight ratio, stiffness to weight ratio, and resistance to corrosion. In this regard, carbon fiber and foam composites are the materials of choice for design of UAVs. In this study, the aerospace composite materials adopted are as detailed in Table 2.

Table 2: Mechanical properties of the materials

Mechanical Property	Unit	Hexply8552 Wing Skin	AS4/3501-6 Spar & Ribs
Longitudinal Young's Modulus	GPa	172	181.9
Transverse Young's Modulus	GPa	10	11.4
Longitudinal Shear Modulus	GPa	5	8.6
Poissons Ratio		0.3	0.224

Mechanical Property	Unit	Hexply8552 Wing Skin	AS4/3501-6 Spar & Ribs
Longitudinal Tensile Strength	MPa	3039	3200
Longitudinal Compressive Strength	MPa	1669	2200
Transverse Tensile Strength	MPa	50	64.3
Transverse Compressive Strength	MPa	250	232
Shear Strength	MPa	79	45.7
Ply Thickness	mm	0.125	0.184
Density	Kg/mm^3	1580	1700

Source [16]

3.2 Wing Layout and Sizing

Idealizing the wing as a single unit, the FEA model was created as a semi wing span with a single spar placed at 30.2% of the wing chords in order to achieve the maximum spar height for the airfoil section. A false spar placed at 68% of the chord provides support for aileron hinge reactions. For an initial design baseline, span-wise positioning of ribs was at wing tip, wing root and 1100mm from wing tip. The Initial spar, rib and skin thickness was set at 1mm as shown in Table 3.

Table 3: Initial structural member sizes

Structual Member	Ply thickness (mm)	Layup	Thickness (mm)
Spar	0.125	[0,45,90,0]s	1
Skin	0.125	[0,45,90,0]s	1
Ribs	0.125	[0,45,90,0]s	1
False Spar	0.125	[0,45]s	0.5

3.3 Ultimate Load and Boundary Conditions

At 3.8g pull down manoeuver, a critical load of 570N, was derived using steps detailed by [17], and STANAG 4671 airworthiness certification standard. This was applied at the wing tip of the semi span model, while 27N boom reaction was applied at the point of boom-wing interface as seen in Figure 2. The wing root was fixed such that the wing semi span is cantilevered.

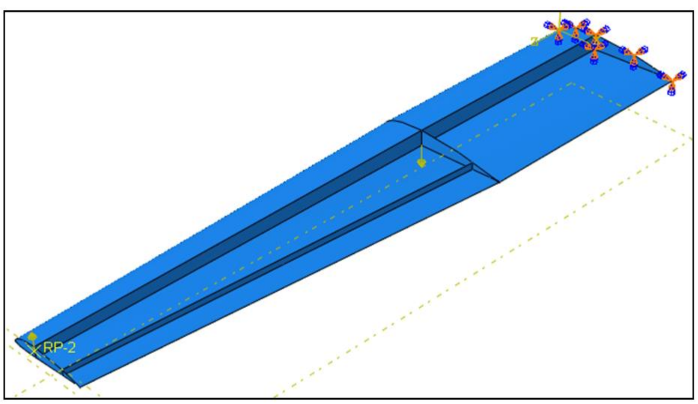

Figure 2: Baseline semi-span model

4.0 FINITE ELEMENT ANALYSIS

4.1 Application of Taguchi in the FE Analysis

To achieve a robust design, quality parameters adopted as design factors were mass M, Tsai-Hill Failure Index F.I and deflection as % of semi span δ. These were evaluated against design targets below:

M_o= 2kg, Design brief; ≤ 2.5kg [18]
$F.I_o$ = 0.8, Standard; < 1.0 [19]
δ_o = 0.1 or 10% Standard; 5% to 15% [20]

The matching signal to noise SN ratios for the i^{th} quality response are expressed as

$$\eta = -10\log_{10}(M_i - M_o)^2 \quad (2)$$

$$\eta = -10\log_{10}(F.I_i - F.I_o)^2 \quad (3)$$

$$\eta = -10\log_{10}(\delta_i - \delta_o)^2 \quad (4)$$

These equations are adapted forms of Taguchi model for 'the smaller the better' SN ratios detailed by [4], [5].

To set up the analysis, 3 control factors varied in 3 levels were set so as to limit the tests to 9 iterations. Table 4 shows the design factors and levels while the resulting L9 orthogonal array obtained using the array described in [4] is shown in Table 5.

Table 4. Control factors and level

Control Factors	Levels		
	1	2	3
Skin thickness (mm)	1	0.75	0.5
Spar thickness (mm)	1	0.75	0.5
Rib pitch (mm)	200	400	500

Table 5: L9 Orthogonal Array

Experimental run number	Control Factors		
	Skin thickness (mm)	Spar thickness (mm)	Rib Pitch (mm)
1	1	1	200
2	1	0.75	400
3	1	0.5	500
4	0.75	1	500
5	0.75	0.75	200
6	0.75	0.5	400
7	0.5	1	400
8	0.5	0.75	500
9	0.5	0.5	200

Mean signal to noise ratio of the responses for each control factor is modelled as:

$$SN_{Li-skin} = \frac{1}{3}\sum \eta_{Li-skin} \quad (5)$$

$$SN_{Li-spar} = \frac{1}{3}\sum \eta_{Li-spar} \quad (6)$$

$$SN_{Li-rib} = \frac{1}{3}\sum \eta_{Li-pitch} \quad (7)$$

Where η_{Li} is the signal to noise ratio of the FE analysis in which the ith level was applied. This was computed for the responses F.I, M and δ.

A sample calculation for F.I is given below by referring to Table 5 and 7.

$$SN_{L1-skin} = \frac{1}{3}\sum \eta_{L1-skin}$$

$$SN_{L1-skin} = \frac{1}{3}(7.6 + 7.92 + 7.89)$$

$$SN_{L1-skin} = 7.8\text{db}$$

This value is shown in the mean SNR chart in Fig. 3 for the skin at Level 1

Similarly, for the spar at Level 1,

$$SN_{L1-spar} = \frac{1}{3}\sum \eta_{L1-spar}$$

$$SN_{L1-spar} = \frac{1}{3}(7.6 + 11.18 + 40.92)$$

$$SN_{L1-spar} = 20\text{db}$$

5.0 RESULTS AND DISCUSSIONS

Table 6 and 7 show the responses and SN ratio for each of the FEA iterations.

Higher SN ratios indicate a lower gap between the actual response and the desired value.

Table 6: Response of the FEA

FE Analysis No.	FEA Results		
	F.I	Max Deflection (mm)	Mass (kg)
1	0.383	79.8	3.22
2	0.398	82.83	3.1
3	0.397	83.56	3.04
4	0.524	87.23	2.44
5	0.53	88.36	2.48
6	0.466	89.71	2.36
7	0.791	156.9	1.77
8	0.947	165.1	1.7
9	0.991	163.4	1.74

Table 7: Signal to Noise Ratio

FE Analysis No.	SN Ratio (db)		
	F.I	δ(max Deflection/semi span)	Mass
1	7.60	25.74	-1.73
2	7.92	26.06	-0.83
3	7.89	26.13	-0.34
4	11.18	26.53	7.13
5	11.37	26.66	6.38
6	9.53	26.81	8.87
7	40.92	46.18	12.69
8	16.65	84.35	10.46
9	14.38	60.27	11.63

The 7th analysis presents results with the highest signal to noise ratio for F.I and mass responses (Table 7), while the highest SN ratio for deflection was recorded in the 8th. This is a strong indication that the desired solution set for skin thickness, spar thickness and rib pitch exist within the neighborhood of the combinations of control factors and levels used in FE analysis no. 7 and 8. To further aid the determination of the final design, the mean SN ratios for the design control factors were considered (Figure 3, 4 and 5).

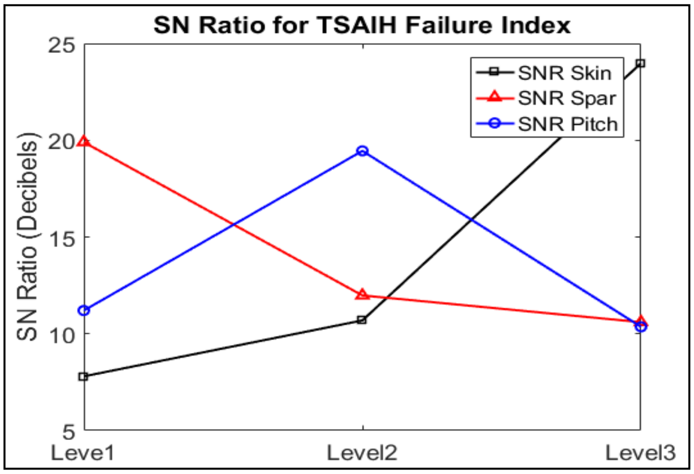

Figure 3: Mean Signal-Noise Ratio for F.I response

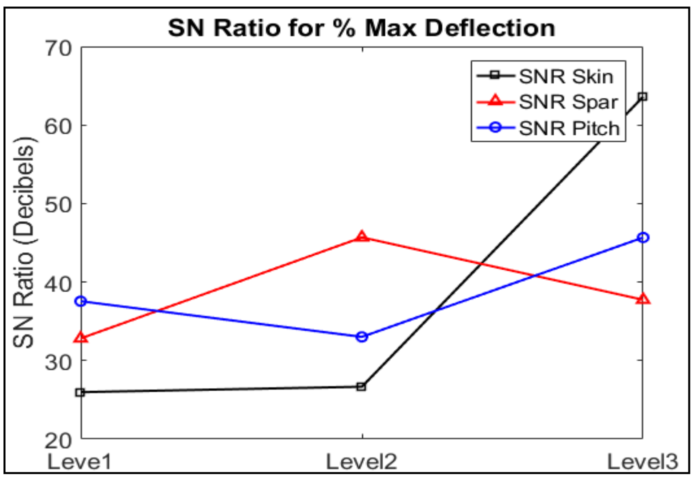

Figure 4: Mean Signal-Noise Ratio for δ response

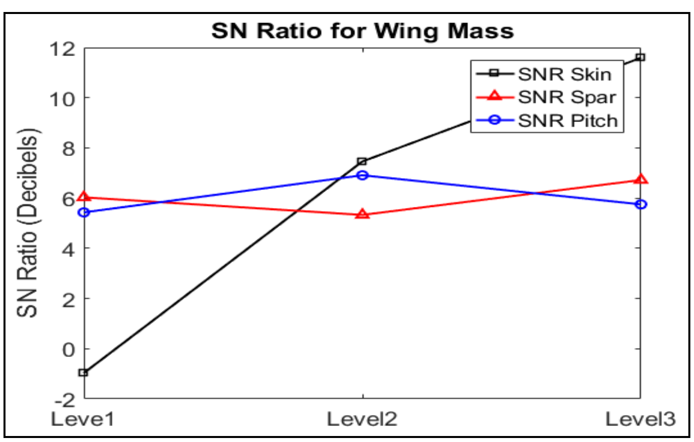

Figure 5: Mean Signal-Noise Ratio for full Span Wing Mass

From the charts of the mean SN ratio, the thickness of the skin is shown to have the most significant impact on the Tsai-Hill failure index (Figure 3), maximum wing deflection (Figure 4) and wing mass (Figure 5). Next is the spar thickness, while the pitch of the rib has the least impact on the responses. This result is consistent with previous findings [21].

Level 3 skin thickness and Level 1 spar thickness gives high mean SN ratios for Tsai-Hill failure index. These levels where chosen for the final model. The highest rib pitch mean SN ratio is observed as about 45db under deflection at Level 3 (Figure 4), hence this was retained for the final design.

Table 8: Final design values for the wing structure

Control factor	Level	Design Value (mm)
Skin thickness	3	0.5
Spar thickness	1	1
Rib pitch	3	500

A FE analysis to evaluate the response of the selected design was conducted. The final design has a Failure Index of 0.92, percentage deflection of 9.5% and wing mass of 1.75kg. The model and final results are shown in figures 6, 7 and 8.

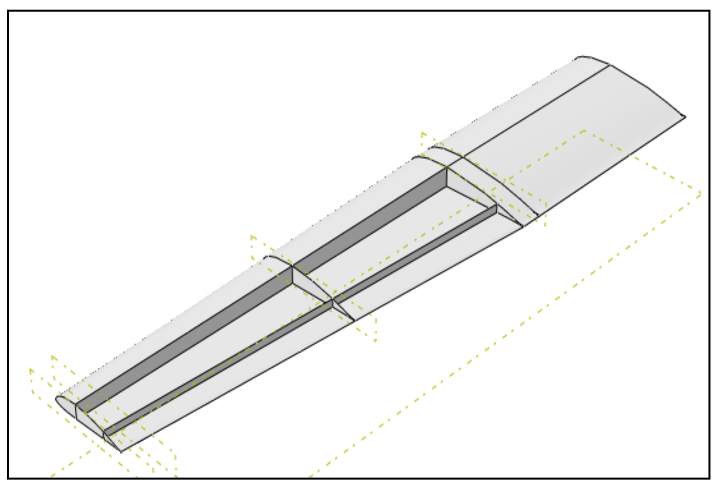

Figure 6: Model for final design FE Analysis

The results obtained demonstrate the suitability of applying Taguchi method in the design of UAV wing structures which by extension can be applied in the design of tail planes and fuselage. However, in order to simplify the method, the impact of variations in ply angles as thicknesses were varied across the 3 levels was not studied. This may affect the result.

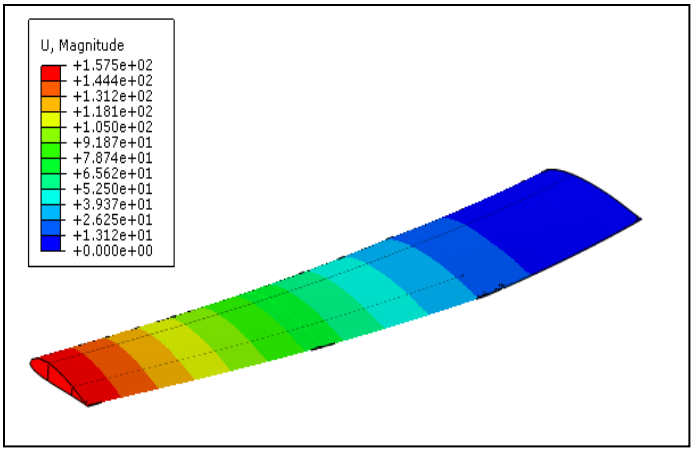

Figure 7: Magnitude of Wing Deflection -Max 157.5mm

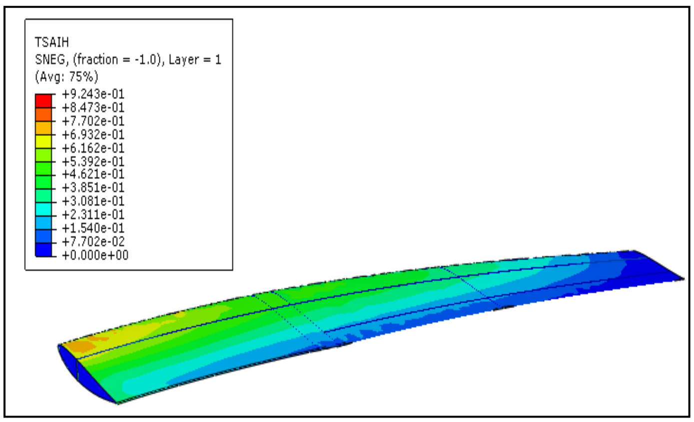

Figure 8: Tsai-Hill Failure Index- Max at 0.92

Table 9: FEA Results for Final Wing Design

	F.I	**Max Deflection (mm)**	**δ**	**Mass (kg)**
Actual	0.92	157.5	9.5%	1.75
Target	0.80	165.0	10.0%	2.00

6.0 CONCLUSION

A 3 factor, 3-level Taguchi Method, adapted to the design of the wing structure of a low speed UAV was presented. Finite Element Analysis conducted on models of the 9-step iterations showed that plausible results for structural design targets were achieved within the 9 steps as opposed to infinite iterations of a build-test-fix approach or 27 iterations for a full factorial design approach. This becomes relevant in the industry for rapid design, testing and deployment of UAVs that meet certain customer and certification requirements. A consequent result of this approach is the savings in computational time and cost.
For further research, the authors recommend a study on the impact of varying the ply angles as a control factor on the design response.

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