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Optimization of the winglet geometry of a small airplane-type UAV wing

This study provides an analysis of the impact of key geometric parameters of winglets on the lift-to-drag (L/D) ratio for airplane-type UAV. The results of this analysis, conducted using Statgraphics Centurion, are presented and discussed.

The development of unmanned aerial vehicles (UAVs) has accelerated significantly due to improvements in structural materials and technologies that allow for lightweight and durable vehicles with improved aerodynamic performance. Modern design approaches include the use of composite materials and additive technologies to optimise trough shapes, bringing them closer to the optimal aerodynamic shape, which reduces drag and increases manoeuvrability. One of the key elements may be the use of winglets, which reduce inductive drag, thereby improving flight efficiency [1-2].

Winglets, as part of the wing structure, play an important role in improving the aerodynamic characteristics of the UAV. They help to reduce vortex wakes at the ends of the wings, which in turn reduces fuel consumption or battery charge and increases the range of the vehicle. Thanks to this design solution, UAV can not only perform their tasks more efficiently, but also demonstrate better performance and stability during flight in severe weather conditions [2].

The winglet, which has been given the name Zirael and its modifications, is discussed below. The Zirael is mounted on an airplane-type UAV. The wing tip used has been modified according to the number of parameters (Fig.1) [3].

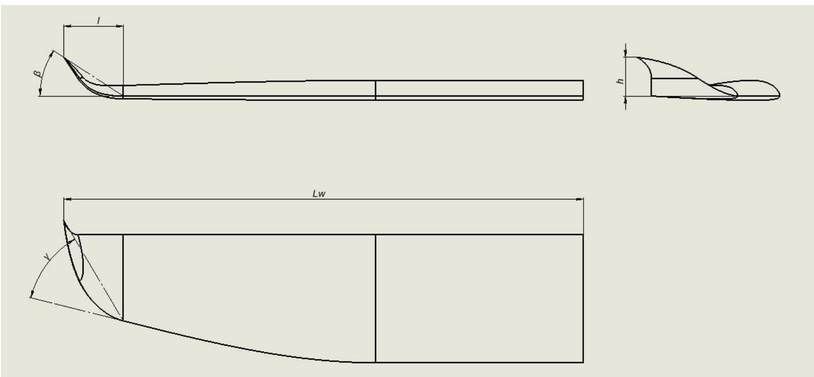

Fig. 1. “Zirael” winglet

The wing area (*S*) and the wingspan (or half wingspan - *Lw*) are important parameters that determine the total lift force generated by the aircraft. In the case of winglets, changes in wing area can have a significant effect on lift over drag (L/D) ratio.

Winglet angle (β) plays a key role in reducing wing tip vortex and reducing inductive drag. Changing the winglet angle affects the distribution of airflow around the wing.

The height (h) of the winglet and winglet length (l) determines their effects on the airflow and pressure distribution over the wing. A higher height can improve flight characteristics by allowing better airflow at the wing tips and reducing vortex impact and improving the overall L/D ratio of the UAV.

The winglet shear angle (γ) determines how the winglet interacts with the airflow and can be tuned to maximise efficiency and minimise drag.

Modifications to the Zirael winglet were carried out to optimise its aerodynamics for specific UAV applications. The simulation provided lift and drag data for each modification. The modifications made to the winglet geometry allowed a more accurate determination of how different configurations affect aerodynamic efficiency. Results of simulations for different modifications of winglets are represented in Table 1.

Table 1.

Geometrical parameters and results of the L/D simulations

Modification	*S*, m2	*Lw*,m	*β*	*h*, mm	*l*, mm	γ	L/D
Z1	0.330918	1.229	38.1	106.38	135.67	46.43	12.27
Z2	0.33269	1.239	36.14	106.38	145.67	44.65	12.34
Z3	0.331879	1.235	36.37	104.04	141.29	45.42	12.31
Z4	0.331951	1.235	36.26	103.93	141.71	45.35	12.33
Z5	0.331446	1.232	38.92	112.04	138.76	45.87	12.29
Z6	0.331049	1.23	40.7	117.41	136.51	46.48	12.31
Z7	0.331943	1.235	33.05	92.17	141.66	45.36	12.36
Z8	0.331338	1.235	33.1	92.26	141.52	47.8	12.45
Z9	0.331387	1.235	33.1	92.26	141.53	45.38	12.487

Subsequent analysis of the effects of the listed parameters was given in the Statgraphics Centurion program, which has a powerful toolbox for multi-regression analysis, allowing the construction and evaluation of models where one dependent variable is related to several independent variables. The program supports variable selection methods, analysis of model quality using statistical measures, and verification of model assumptions through residual analysis. It also allows us to examine interactions between variables (Table 2) and provides graphical representations of the results (Fig.2). Additionally, Statgraphics Centurion supports modelling of nonlinear effects and forecasting based on the created models.

Table 2.

Analysis of the impact of geometric characteristics on the L/D Ratio

Parameter	Estimate	Standard Error	T-Statistic	P-Value
CONSTANT	101.185	47.7696	2.11819	0.1683
S	-238.025	41.9508	-5.67391	0.0297
Lw	-5.21206	40.0649	-0.13009	0.9084
β	-0.264432	0.109383	-2.41749	0.1368
h	0.0690253	0.0289191	2.38684	0.1397
l	-0.000857901	0.0483269	-0.017752	0.9874
γ	-0.0193519	0.00954345	-2.02776	0.1798

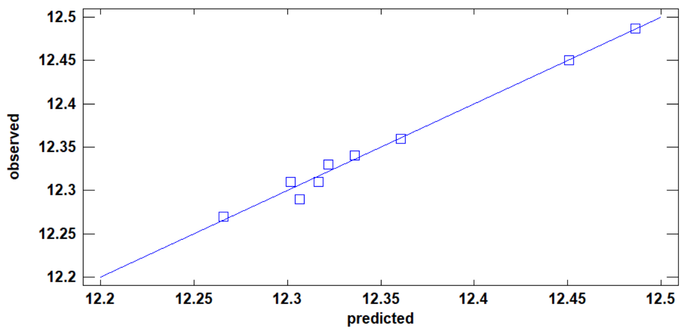

Fig.2. Relationship between observed and predicted values

$$L/D = 101.185 - 238.025 \cdot S - 5.21206 \cdot Lw - 0.264432 \cdot \beta + 0.0690253 \cdot h - 0.000857901 \cdot l - -0.0193519 \cdot \gamma$$

R-squared = 98.85%

R-squared (adjusted for d.f.) = 95.41 %

The results of analysis show that the R-squared value of 98.85% for the equation (1) indicates that the model explains a substantial portion of the variability in L/D. The adjusted R-squared, which accounts for the number of predictors, is 95.41%, reflecting a robust model fit.

Analysis of Variance (ANOVA) results indicate that the independent variables collectively contribute to explaining the variance in the *L/D*.

The T-statistic measures how many standard deviations the coefficient differs from zero. The larger the absolute value of the T-statistic, the less likely it is that the

coefficient is zero by chance, indicating a significant relationship between the predictor and the dependent variable.
The P-value tests the null hypothesis that the coefficient is zero (no effect). A low P-value (typically <0.05) indicates strong evidence against the null hypothesis, suggesting that the variable is a significant predictor of the dependent variable.
According to the data presented in Table 1, the variable *S* has a significant impact on the *L/D* with a P-value of 0.0297, indicating its strong impact. In contrast, the variables *Lw* and *l* show very low T-Statistics and high P-Values and are not statistically significant. They could be excluded from further analysis for simplification (Table 3).

Table 3.

Analysis of the impact of key geometric characteristics on the L/D Ratio

Parameter	Estimate	Standard Error	T-Statistic	P-Value
CONSTANT	96.0949	8.37065	11.48	0.0003
S	-243.149	24.2306	-10.0348	0.0006
β	-0.237375	0.021452	-11.0654	0.0004
h	0.0619155	0.00617548	10.026	0.0006
γ	-0.019549	0.00686849	-2.84618	0.0466

The output shows the results of fitting a multiple linear regression model to describe the relationship between L/D and 4 independent variables.

$$L/D = 96.0949 - 243.149 \cdot S - 0.237375 \cdot \beta + 0.0619155 \cdot h - 0.019549 \cdot \gamma$$

R-squared = 98.80%
R-squared (adjusted for d.f.) = 97.61 %

The new results demonstrate an overall improvement in the statistical significance and reliability of the model estimates:

Every parameter, including the constant, showed improvement in the form of lower P-values and higher T-statistics compared to the previous model. This indicates better predictability and reliability of the estimates. Parameters β, h and γ have changed their influence from insignificant to significant, indicating an improvement in model specification.

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