# Integration of new conceptual design for VTOL UAV with multi-level optimization

Cite as: AIP Conference Proceedings **2425**, 380002 (2022); https://doi.org/10.1063/5.0081408
Published Online: 06 April 2022

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# Integration of New Conceptual Design For VTOL UAV With Multi-Level Optimization

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**Abstract.** As the combination of FW(Fixed-Wing) and VTOL(Vertical-Taking-Off-and-Landing) UAV (Unmanned Aerial Vehicle), the hybrid drone is more accepted as its multipurpose application. With the aid of CFD method for test and RSM (Response Surface Methodology) for optimization, this article presents new concept of canard wings that were integrated to the fuselage of the UAV. It combines the conventional delta wing with winglet and the canard configuration. Based on the requirements and the limitations of the design, the lift was optimized and distributed respectively to the main wing (90~95%) and to the front wing (5~10%). Multi-level optimization approach using RSM was developed for the optimization. At the first level, we optimize the delta wing, then a second level is applied to evaluate the final design of the canard wing from the previous step. By comparison with the initial design, this concept provides enough lift with less drag in cruise model. Besides, the control surface of the canard wing in the front could replace the tail wing that was used for trimming and dynamic controls which turns the drone into a tailless vehicle which reduce also the weight of the UAV.

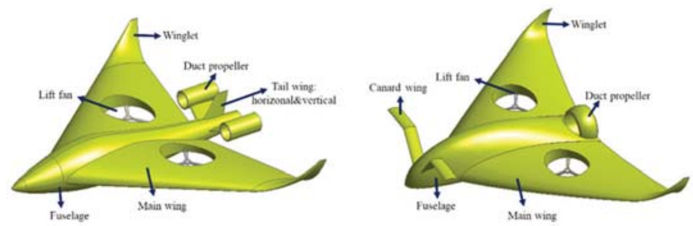
## INTRODUCTION TO HYBRID UAV

Unmanned Aerial Vehicles[1] are becoming increasingly vital and indispensable in more widely domains such as agriculture, logistics, intelligence, surveillance and reconnaissance (ISR), power transmission line inspection, environmental monitoring, aerial mapping and meteorology, border patrol and security defense, Hybrid UAV is characterized with both the ability of Fixed-Wing and Vertical-Taking-Off-Landing vehicles, which inherits both of their advantages[2]. Although suffering from the disadvantages of complicated mechanical system and additional dead weight, the Tube-fan is still viewed as one of the most promising hybrid UAV benefiting from the high payload capacity and excellent aerodynamics during cruise flight.

## NEW CONCEPTUAL UAV DESIGN

Starting from the initial conceptual design (see FIGURE 1.a)[3], two canard wings were integrated in the fuselage and the propulsion in the back were reduced to just one engine (see FIGURE 1.b) with a small changes on the central body shape.

*International Conference of Numerical Analysis and Applied Mathematics ICNAAM 2020*
AIP Conf. Proc. 2425, 380002-1–380002-5; https://doi.org/10.1063/5.0081408
Published by AIP Publishing. 978-0-7354-4182-8/$30.00




(a) (b)

**FIGURE 1.** (a) premier conceptual design and (b) new The conceptual design with canard configuration

As the low aspect-ratio delta wing results in the poor aerodynamics performances, the lift capacity would be reduced with limited principal dimensions, which are important to have good portable advantage and easy taking-off and landing space requirement. According to the conventional configuration of the fixed-wing, the tail wing always has to produce negative vertical force to respect the trimming purpose, which leads to the dilemma that the delta wing must produce additional positive lift to keep balance. The canard configuration was raised just with the invention of the first modern plane of Wright Brothers and it's still widely preferred in the modern fixed-wing plane, particularly in modern military air vehicles which take advantage of low trim drag and excellent manoeuvrability at high attack angle. The canard configuration (**FIGURE 1**.b) is taking into our new conceptual design with respects to some requirements such as: the maximum taking-off weight that should be over 30kg at cruise speed $V = 60km/h$ . length and width less than 2 meters to have a good portable capacity. In addition to the fact that the minimum drag improves the aerodynamic performance, wings should have the lightest weight[4]. At cruise speed, multi-objective optimization of the global problem can be stated as follows:

$$\begin{cases} Minimization\ of\ \{F_x \cdot M_w\} \\ \qquad s.t. \begin{cases} F_y \geq 150N \\ s_p \leq 1m \\ L_c \leq 1.5m \end{cases} \end{cases} \quad (1.)$$

*Where $s_p$ means the span width of one wing, $L_c$ means the length of the airfoil at the chord, $s_w$ means the area of the wing, $M_w$ means the weight of the wing, meanwhile $F_x$ and $F_y$ are respectively the drag and lift of the wing structure.*

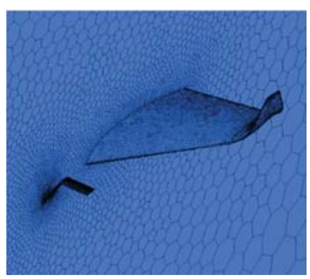


**FIGURE 2**. Mesh for CFD analysis with grid quantities equal to $1.57e^6$

To obtain precise results with less calculation resources, the grid independent verification is carried out to choose a propriate mesh strategy for the CFD simulation. Fortunately, since the mesh region of the delta wing by previous research is inherited and only the differences of the mesh in the region of canard wing would be considered and compared, particularly to evaluate the influence and interference between both wings. According to minimize size of the canard wing, 3 different meshes strategies were studied differing in the grid quantities at $1.17e^6$, $1.57e^6$ and $2.44e^6$ at the cruise speed V with SST-kw turbulent model. Referring to the lift and drag results, the differences of the lift turn out 0.14% and 0.01% and that of drag turn out 0.31% and 0.21% while enlarging grid number to 1.34 and 1.55 times respectively. The optimal mesh (see FIGURE 2) is adopted in the CFD simulation to offer more virtual results with more detailed finite volume to investigate on the flow around the wing.

## MULTI-LEVEL OPTIMIZATION STRATEGY

Considering the model characteristics of the delta wing and canard wing, there are dozens of parameters related to the CAD design, in which 9 parameters are choses as the optimised variables[5]:

A. The delta wing : 1) the incident angle $\alpha_{in1}$, varied from 4° to 6° according to test experiences; 2) the chord length $L_{c1}$, varied from 1.3 to 1.5 meters respecting the design limitations; 3) the span of delta wing $s_{p1}$, varied as 0.8 to 0.9 meters to leave space to the winglet; 4) the ratio of tip/chord of the plain wing $\lambda_1$, varied from 0.4 to 0.6 according to design experience ; 5) the ratio of tip/chord of the winglet $\lambda_{sw}$, varied from 0.2 to 0.4 according to design experience.
B. The canard wing: 6) the incident angle $\alpha_{in2}$ , varied from $\alpha_{in1}$+0° to +2° according to test experiences; 7) the chord length $L_{c2}$, varied from 0.1 to 0.2 meters to keep quite enough distance from disturbing the delta wing ; 8) the span of the upward part $s_{p2}$, varied from 0.5 to 0.7 meters to keep a reasonable distribution of lift and drag; 9) the height of the upper part $h_{up}$ to avoid the structural stabilize.

Due to the time consuming, response surface method (RSM) is defines based on a second-order functional to fit the relationship between the single response $y$ and design matrix with input variables $(x_1, x_2, \dots, x_k)$ with unknow parameters $\beta_{ij}$ of the RSM[6]:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \varepsilon \qquad (2.)$$

That can be also written under matrix notation as below:

$$y = \boldsymbol{x\beta} + \varepsilon \qquad (3.)$$

*where $\boldsymbol{x}$ is a function of location which is regarded as the design space of DOE as well as $\boldsymbol{\beta}$ should be calculated by ordinary least squares (OLS). In addition, ε is the term of random error (Zero at simulated points).*

The optimization of the response surface is carried out in four parts. 1) Building of the design space, 2) List of DOE, 3) Establishment of RSM: by adopting some suitable algorithms and respecting given criterium, the response surfaces are computed using the response values obtained in DOE and 4) Optimization of response values: after verification and modification of the response values referring to a few new experimental cases, which apply for estimation of the precision of the RS, the final optimized values are obtained[7]. To minimize the number of experiments and accelerate the progress of optimizing searching, Central Composite Design (CCD) was selected. In order to choose the best response surface, the genetic algorithm is applied for the building of the population using different response surfaces which would be solved in parallel. Taking both the accuracy and the robust of the response surface into account, each type of response surface adopts the appropriate fitness function to determine the yield range of best approach[8]. Integration with different meta-models, the genetic aggregation[9] applying in the response surface is expressed with the ensemble of their weighted average. The genetic aggregation is capable of select and build the most suitable response surface automatically corresponding to the output parameters. With 9 parameters, Design Of Experiments (DOE) turn quickly to time-consuming problem[11]. Even with all the results obtained by the DOE, the three goals make it quite uncertain and confusing to choose the appropriate optimum criteria, particularly concerning the possibility that there would be some conflicts among these three goals[12]. In order to simplify the optimization calculations, two hypotheses that respect the actual designs and fabrication conditions[8, 10, 11] are considered: We assign equal weight for each objective function. Both the drag and the weight of the delta wing are much larger than those of the canard wing. Benefiting from these two assumptions, the multi-objective optimization problem can be converted into two sequential mono-objective optimization problems (see Equation (4) and (5)).

$$\begin{cases} Min\ G_2(\alpha_{in2}, L_{c2}, S_{p2}, h_{up2}) \\ s.t.\ F_y(\alpha_{in2}, L_{c2}, S_{p2}, h_{up2}) \geq F_y' \end{cases} \qquad (4.)$$

$$\begin{cases} Min\ G_1(\alpha_{in1}, L_{c1}, S_{pw1}, \lambda_1, \lambda_{sw}) \\ s.t.\ F_{y1}(\alpha_{in1}, L_{c1}, S_{pw1}, \lambda_1, \lambda_{sw}) \geq F_{y1}' \end{cases} \qquad (5.)$$

*$G_1$ and $G_2$ are defined as the goal functions respectively in delta wing and canard wing: $G_1 = F_{x1} \cdot s_{w1} \cdot L_{c1}$ and $G_2 = F_x \cdot s_{w2} \cdot L_{c2}$. Where $F_{y1}'$ and $F_y'$ are respectively the minimum lifts of the delta wing and total lift.*

During the model design process, some parameters are defined directly with recommendation values offering by traditional design manuals or restriction conditions, while the others are picked up to be optimized with respecting the previous researches and design experiences. In general, there are 9 uncertain parameters are selected to be optimized, meanwhile whose maximum and minimum given values are already constrained by the design conditions respectively.

# RESULTS

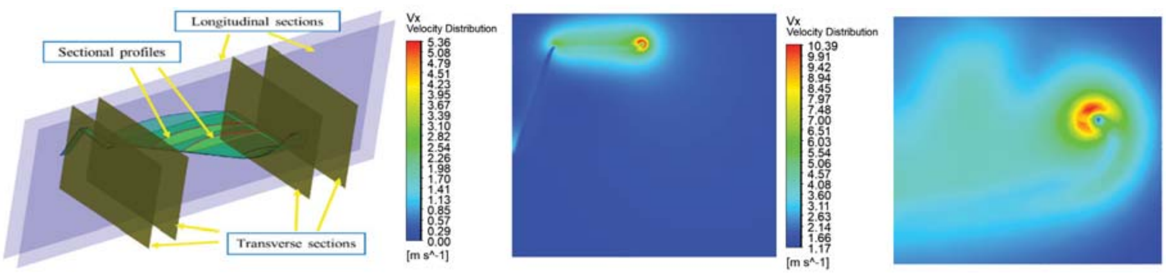
The strategy of multilevel optimization starts by the optimization based on 5 parameters that is carried on to determine the shape of the delta wing with respect to the lift goal of delta wing; Then, we apply the second optimization based on 4 parameters in canard modelling to reach the final design.

**TABLE 1.** The optimized parameters of the wing

| | Variables | Candidate Values |
|---|---|---|
| Delta wing | Incident angle $\alpha_{in1}$ | 6.9969° |
| | Chord length $L_{c1}$ | 1.3036m |
| | Span of wing $s_{p1}$ | 0.8520m |
| | Ratio of plainwing tip $\lambda_1$ | 0.4251 |
| | Ratio of winglet tip $\lambda_{sw}$ | 0.3819 |
| Canard wing | Incident angle $\alpha_{in2}$ | 7.5149 |
| | Chord length $L_{c2}$ | 0.1000m |
| | Span of wing $s_{p2}$ | 0.6450m |
| | Height of upper part $h_{up}$ | 0.5519m |

Results of aerodynamic performances are given below (see **TABLE 1TABLE 1** The optimized parameters of the wing). Compared with the assumption in Sections "*Distribution of lift*" in the delta and canard wings, where the lift of delta wing $F_{y1} = 145.13$N and of canard wing $F_{y2} = 10.05$N, is proved to respect the optimal criteria of the optimization problem (Equation (1)) as follows.

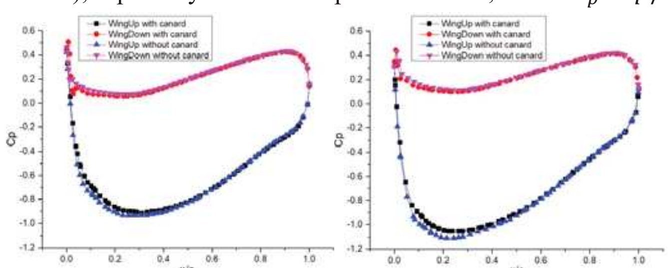
$$F_{y1} + F_{y2} - 50\% F_{y2} = 150.16 > 150N \quad (6.)$$




(a) Sectional planes (b) Contour with canard at cut at X2 (c) Contour with canard at cut at X4

**FIGURE 3**. Velocity distribution at the final design at the 2[d] (b) and 4[d] (c) cross sections (see (a)

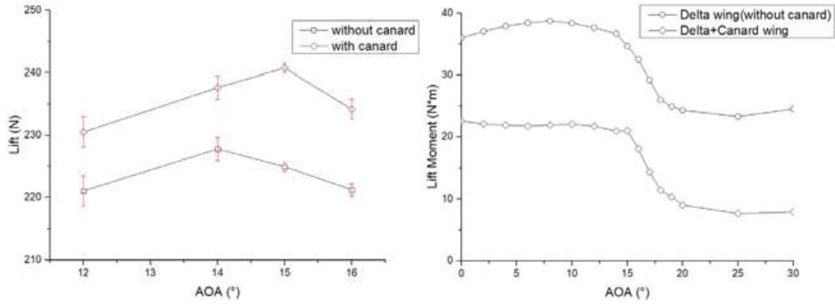
The slight interference of the canard wing can also be demonstrated by the pressure coefficient on the air-foils of delta wing which are still at the span range of the canard wing as Z1 and Z2 (the 2 parallel sections see **FIGURE 3**). Although a little less than that without the canard wing, the curves $C_p - x/c$ of the delta wing behind the canard wing remain almost same(see **FIGURE 4**), especially at the latter part of the foil, where $C_p = p/\frac{1}{2}\rho v^2$.




(a) airfoil at Z1 (b) airfoil at Z2

**FIGURE 4.** $C_p$-$x/c$ on the profile of the delta wing at Z1 and Z2 with/without canard.

Furthermore, the interference of canard on the delta wing could be slightly at high attack angle as well. The distributions of vector around the delta wing behind the canard wing at Z1 and Z2 planes are compared as following (see **FIGURE 5**.a and **FIGURE 5**.b), which turns out to be nearly identical with that without canard. Therefore, it can be proved and demonstrated that the canard wing would help prevent the wing into stall station with a gentler change.




(a)Lift-AOA (b)Lift Moment -AOA

**FIGURE 5.** Lift and lift moment of the wing with/without canard at different *AOA*

## CONCLUSION

To improve the performance of the novel tube-fan hybrid UAV, the canard configuration is successfully introduced and added in the conceptual design. Multilevel optimization approach was proposed coupled with RSM and DOE. To respect the design goals and limitations, certain coefficients are defined to evaluate the criterion in terms of the least cost desired. By comparing between with and without canard wing at different attack angles, it's testified that the optimized design of the wing has achieve the lift improvement with only slightly interference by the canard wing.

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