Conceptual Design and Optimization of 2-seater Seaplanes

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Abstract
This paper presents the conceptual design and optimization of 2-seater seaplane. A design code was developed from MATLAB with optimization toolbox. Design synthesis contains aircraft weight, performance, aerodynamics, aircraft stability, engine sizing and ship hull design according to user requirements and Standard Specification for Design and Performance of a Light-Sport Airplane. The seaplane take-off weight is used as the objective function to minimize subjected to design constraints. The optimization process makes use of the MATLAB GA-hybrid scheme (Genetic algorithm and Fmincon) which is faster and more efficient than the genetic algorithm or gradient-based approach. The optimum designs were obtained. The influences of design requirements and constraints were investigated. The outcome of the program is an optimum design of a single-engine 2-seater seaplane.

Keywords: Conceptual design, Seaplane, Optimization, GA, LSA

1. Introduction
The seaplane has been widely used in sea travel because of advantages that makes it faster than a ship and can manage to take-off and land on both ground and water, making it superior to normal aircrafts that need an airport to operate. The seaplane was invented in 1910 but after 1950 their performance has not been improved that much and the idea of designing seaplane stopped [1]. Seaplanes can be divided into two categories: a flying boat and a floatplane. In this study, we focus on the flying boat. Although there are some research studies on seaplanes, very few of them have found a conceptual design. Most of them, however, focused on improving specific areas such as surface effect [2] and water landing control [3]. Aircraft design is a multidisciplinary problem. The multivariate optimization method (MVO) [4] has been used popularly in conceptual and preliminary design stage [5-8] because of capability in searching an optimum design from a large number of design variables and non-biased design decision making. The optimization method used in this work is MATLAB GA-hybrid.
The objective of this work was to obtain an optimum design of single-piston engine of a 2-seater seaplane according to standard specification for design and performance of Light-Sport Airplane requirements [9] and study the influence of design variables and the constraints of the design.

2. Design Algorithm and Problem Formulation

The design algorithm of design synthesis analysis and optimization [10] and Design synthesis modules are shown in simplified block-diagram in figure 1. The input data is the value of design variables. These variables are the ones that affect the design and can be changed by the optimizer and fixed by variables such as range, payload, load factor, etc. After all the data was fed into the design synthesis, all values then were calculated before sending them to the optimizer.

![Figure 1. Design and optimization algorithm (left) and Design synthesis modules (right)](image)

Aerodynamics module contains aerodynamic parameters calculation such as lift coefficient, drag coefficient and air density. Aircraft performance module [11] contain cruise, ground take-off, water take-off and rate of climb. The Weight module follows Raymor’s weight equations [11]. Engine & fuselage module calculates engine and fuselage size. Stability module [12] calculates CG, static margin and trim parameters. Hull design [1] calculates the shape of the hull that is capable of taxiing and take-off from water. The water stability calculates parameter such as metacentric height in both directions.

2.1 Objective function

In this work problem, take-off weight \( w_{\text{to}} \) need to be minimized and was chosen to be an objective function \( w_{\text{to}} \) is a combination of all aircraft components weight as follows:

\[
 w_{\text{to}} = (w_{\text{pl}} + w_{\text{fus}}) + (w_{\text{l}} + w_{\text{c}} + w_{\text{e}} + w_{\text{p}} + w_{\text{f}} + w_{\text{h}}) \quad (1)
\]

where
- \( w_{\text{pl}} \) is the weight of the payload
- \( w_{\text{fus}} \) is the weight of fuselage structure
- \( w_{\text{l}} \) is the weight of wings
- \( w_{\text{c}} \) is the weight of vertical and horizontal stabilizer
- \( w_{\text{e}} \) is the weight of the airframe systems, equipment, passenger furnishing, etc.
- \( w_{\text{p}} \) is the weight of the installed engine
- \( w_{\text{f}} \) is the weight of landing gears
- \( w_{\text{h}} \) is the weight of fuel
- \( w_{\text{h}} \) is the weight of hulls structure
\(W_W\) was categorized under 2 groups which are fixed and variable in weight. The fixed weight group contains the payload and fuselage weight, calculated from design requirements which cannot be changed by the optimizer. The variable weight group contains wings, tail, system, fuel, landing gear and hull weight, which have been calculated from design variables that can be changed during the optimization process.

### 2.2 Design constraints

Design constraints are the criteria to assure that the design requirements are met. Constraints were set from designer requirements and standard specification for the design and performance of a Light-Sport Airplane. These constraints are listed as follows:

1. The estimated take-off weight must be equal to the calculated take-off weight.
2. The take-off length required for both land and water must not be longer than that specified in requirements.
3. Stall speed must not exceed the requirement.
4. The cruise lift coefficient must not be greater than the buffet limit.
5. The required power must not be greater than the available power in the cruise.
6. The seaplane static margin must be in range to be stable.
7. The seaplane must be trimmable in requirement conditions.
8. The seaplane must be stable in water.
9. All of the seaplane components must be in an allowable layout range.

### 2.3 Problem formulation

The design problem can be formulated as a general mathematical problem of optimization as follows:

Find design variables \(\alpha = \{\alpha_{\text{to}}, \alpha_{\text{a}}, \alpha_{\text{w}}, \alpha_{\text{t}}, \alpha_{\text{h}}, \alpha_{\text{e}}, \alpha_{\text{v}}, \alpha_{\text{h}}, \alpha_{\text{p}}, \alpha_{\text{s}}, \alpha_{\text{f}}, \alpha_{\text{c}}, \alpha_{\text{s}}, \alpha_{\text{sl}}\}\) (2)

Minimize: \(W_W = f(\alpha)\) (3)

Subject to:
\[
\begin{align*}
\alpha_{\text{to}} & \leq \alpha_i \leq \alpha_{\text{to}} & & i = 1, n \quad (\text{bound/side constraints}) \\
\alpha_j(\alpha) & \leq 0 & & j = 1, y \quad (\text{inequality, equality constraints})
\end{align*}
\]

where

- \(n\) is the number of design variables
- \(y\) is the number of constraints
- \(\alpha_{\text{to}}\) is the take-off weight
- \(\alpha_{\text{w}}\) is the wings' CG position
- \(\alpha_{\text{a}}\) is aspect ratio
- \(\alpha_{\text{t}}\) is the tail's CG position
- \(\alpha_{\text{h}}\) is the wings area
- \(\alpha_{\text{e}}\) is the engine CG position
- \(\alpha_{\text{v}}\) is sweep angle at quarter cord
- \(\alpha_{\text{h}}\) is horizontal tail volume
- \(\alpha_{\text{t}}\) is taper ratio
- \(\alpha_{\text{c}}\) is vertical tail volume
- \(\alpha_{\text{p}}\) is spray coefficient
- \(\alpha_{\text{s}}\) is hull slenderness ratio
- \(\alpha_{\text{f}}\) is float slenderness ratio

### 2.4 Optimization and programming

The optimization method used in this work is MATLAB GA-hybrid. The seaplane design program was coded in MATLAB included Objective function, Constraints and design synthesis modules can be linked to the Optimizer. MATLAB GA-hybrid is a scheme to optimize function by using Genetic
algorithm and another optimization method. GA can reach the optimum region quickly but slow to reach an optimum point. However, combining it with another method, which is better at finding a local optimum point, will make the optimizer faster than GA and more efficient than gradient-based optimizer. This gradient-based optimizer tends to have difficulty in finding global optimum point when the initial point is far from the optimum one. A common technique is running a few generations of GA to approach optimum area, then it uses the GA solution as an initial point for the gradient-based optimizer to search the optimum point. The Genetic algorithm [13] is an optimization method inspired by Charles Darwin’s theory of natural evolution and a part of Evolutionary algorithms. The algorithm uses the concept of a natural selection process that selects the fittest individuals to reproduce next populations by using Selection, Crossover and Mutation as three main operators.

3. Results and Discussions

3.1 Optimum design results
Mission requirements, optimization value and constraints are shown in Table 1, Table 2, and Table 3 respectively.

| Table 1. Mission requirements | Requirements |
|------------------------------|--------------|
| No. of seats                  | 2            |
| Range (nmi)                  | 354.2        |
| Ground takeoff length (ft)   | ≤550         |
| Water takeoff length (ft)    | ≤700         |
| Stall speed (ktas)           | ≤61          |
| Cruise speed (ktas)          | 98           |
| Rate of climb (ft per min)   | ≥1000        |
| Takeoff weight (lbf)         | ≤1430        |
| Static margin                | 5 ≤ α ≤ 15  |
| Propulsion                   | 1 piston engine |

| Table 2. Optimized design for a full set of the design variables | Variables | Initial value | Lower bound | Upper bound | Optimized value |
|------------------------------------------------------------------|-----------|---------------|-------------|-------------|-----------------|
|                                                                  | W_W_W     | 1200          | 1           | 2500        | 1287.04         |
|                                                                  | W         | 12            | 5           | 20          | 5               |
|                                                                  | W^2       | 157           | 100         | 300         | 179.94          |
|                                                                  | W^4/4     | 50            | 0           | 100         | 0.0006          |
|                                                                  | W         | 0.5           | 0.5         | 1           | 0.5             |
|                                                                  | W_0       | 98            | 98          | 98          | 98              |
|                                                                  | a         | 100           | 50          | 150         | 85              |
|                                                                  | b         | 8200          | 5000        | 20000       | 5000            |
In the optimization process, GA was performed first and the optimized value was used as an initial condition for Fmincon. The design variables behaviour from GA to Fmincon is shown in Figure 2.
As the results show, design-driving parameters are the rate of climb and water take-off distance because both are at the edge of the design constraints boundary (see Table 3) and affect aircraft sizing, directly. The optimizer attempts to reduce water-resistant as much as possible by reducing stall speed, increasing spray coefficient (\(k\)) and slenderness ratio (SLR) (see Figure 2). Both rate of climb and water take-off distances are constraints that determine engine size. The seaplane might be lighter if the designer can relieve the requirement from design drivers. The optimizer shows that sweep angle is not essential for a low-speed aircraft because sweep angle makes wings' structure heavier, but does not improve flight performance as shown in Table 2 and Figure 2 where the value was converged to zero. Taper ratio was converged to the minimum value to minimize wings' weight as well. The seaplane geometry base on the optimized value is shown in Figure 3 and component weight breakdown is shown in Table 4.

**Figure 2.** Optimization processing graph GA (left) and Fmincon (right)
3.2 Trade-off studies

The cruise speed and water take-off distance were selected to be studied since they are parameters which important to set mission requirements. Results are shown in Tables 5 and 6, respectively.

As can be seen in Table 5, the increasing cruise speed leads to increased required power and reducing the wings’ area, all of which prompt to higher weight and stall speed, even though the power available is higher than lower cruise speed cases but it did not affect water take-off distance, drastically.

To reduce water take-off distance effectively, stall speed was decreased by reducing the wings’ area. However, a higher wing area means a higher structure weight, which leads to result in a higher required power.

Table 5. Optimize design according to cruise speed

| V (ktas) | SW (m²) | TO weight (lbf) | P (bhp) | Ground TO (ft) | Water TO (ft) | V stall (ktas) |
|---------|---------|-----------------|---------|----------------|---------------|---------------|
| 88      | 172.6   | 1222.85         | 80.5    | 487.17         | 700           | 34.08         |
| 93      | 176.1   | 1253.12         | 82.59   | 488.35         | 700           | 34.16         |
| 98      | 179.94  | 1287.04         | 84.95   | 489.58         | 700           | 34.25         |
| 103     | 184.1   | 1324.61         | 87.59   | 490.86         | 700           | 34.35         |
| 108     | 182.37  | 1366.28         | 93.97   | 482.81         | 700           | 35.05         |
| 113     | 179.61  | 1414.88         | 102.36  | 473.43         | 700           | 35.94         |
| 118     | 177.66  | 1468.69         | 111.57  | 465.90         | 700           | 36.82         |
To verify the program, comparison to real seaplane is conducted. Progressive Aerodyne Sea Ray is a light sport amphibious aircraft, which was chosen for the comparison process. Design requirements such as cruise speed, take-off distance, load, ROC and range were determined in a range around Progressive Aerodyne Sea Ray specification. The seaplane that was obtained from the program has identical performance to Sea Ray but some characteristics were different because the design synthesis model may not be the same. These comparison results are shown in Table 7 below.

### Table 7. Comparison result

|             | Weight (lbf) | P (bhp) | SW (\(\text{ft}^2\)) | Length | b     | V stall | Ground TO (ft) | Water TO (ft) |
|-------------|-------------|---------|----------------------|--------|-------|----------|----------------|---------------|
| Sea Ray     | 1370        | 100     | 157                  | 22ft5' | 30ft10' | 42 ktas  | 350            | 472           |
| Case1       | 1331        | 105     | 165                  | 23ft   | 35ft4' | 36 ktas  | 400            | 493           |

4. Conclusion
This article presented a comparison and a trade-off study. The optimum design was obtained. The results have shown the design drivers such as rate of climb and water take-off distance that affect engine sizing and variables that were minimized to a reduced weight such as a sweep angle and taper ratio. This study will help a designer to know significant parameters and could set a proper design requirement, which lead to a lighter, and a better-optimized design.

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