Proceedings of the Canadian Society for Mechanical Engineering International Congress 2021
CSME Congress 2021
June 27-30, 2021, Charlottetown, PE, Canada

Multidisciplinary Analysis Program for Light Aircraft (MAPLA)

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Abstract— The proposed semi-empirical Multidisciplinary Analysis Program for Light Aircraft "MAPLA" is particularly developed for the analysis of light, general aviation, propeller-driven, airplanes with a future perspective for the design of Urban Air Mobility (UAM) air vehicles. MAPLA is developed in MATLAB and includes four primary disciplines for analysis: Aerodynamics, Propulsion, Performance and Stability and Control. Specialized for light, single- and twin-engine propeller-driven airplanes, available state-of-the-art analytical procedures and design data collections have been combined and modified in a unique compatible method and automated in MAPLA. The proposed multidisciplinary aircraft analysis platform is developed to be used for several objectives and aims to enhance the light aircraft design and development, flight tests and flight plan optimization. It is also a good source for educational purposes.

Keywords- Light Aircraft Design, Multidisciplinary Design Optimization, Aerodynamicsm, Semi-empirical Methods, Trajectory Optimization, Handlig Quality

I. INTRODUCTION

Prior to the advent of computers, aircraft design was mainly based on the simplified, largely empirically-based methods for initial sizing and trade studies before the first layout. These quick answer methods are based on previous designs. Semi-empirical methods estimate aerodynamic characteristics of an airplane based on data compendia of flight tests and wind tunnel tests of similar aircraft. In this approach, the aerodynamic characteristics of the airplane are modelled via structures based on theories and engineering methods. Afterwards, variables of the structures are achieved by flight test and wind tunnel data in terms of semi-empirical equations, tables, graphs and charts. This method relies on experimental tests more than analytical methods [1-2].

Although methods used in the process of aircraft design have changed over the years, the general idea behind this work has remained the same: to offer the end-user a cost-effective, high-quality design that meets the mission requirements. The most prominent advantages of semi-empirical methods are the simplicity, lower cost and time for calculations, and acceptable accuracy of results in the flight envelope. These features make it possible to achieve the sensitivity of results due to the geometric parameters, aerodynamic characteristics and flight conditions in the preliminary design phase [3].

Recently, computing power enhancement has allowed the use of complex analytical calculations in an early conceptual design phase to assist the designers to assure the true work of each discipline playing a role in the aircraft design process including aerodynamics, performance, propulsion, structures as well as stability and controls. In addition, a higher fidelity computing analysis tool would be available using more accurate computing analysis methods that can provide an answer with ~ 80% accuracy using the initial structure achieved from the first layout. On one side, this would allow the designers to optimize their design in a very early stage and do not face unwanted changes within the preliminary and detailed design phases. On the other side, using multi-fidelity calculations, the required time for computation can be decreased while the desired accuracy is guaranteed. Consequently, the actual flight test can be planed for the proposed aircraft after the accuracy of the results guaranteed using the multi-fidelity analysis tool [1].

Recent aircraft design and development processes focus on "Design for Affordability" which denotes that the design and evaluation of a system is no longer solely a function of the mission requirements or product characteristics. Instead, it is an integration of a multi-discipline cycle towards lowering cost while maintaining the balance between mission capability with other system effectiveness. This decision-making process defines the balance between the benefit and cost as a measure of value. The variation of the knowledge about design, freedom for modifications and cost commitment is shown for design cycles at the end of the 20^{th} century against future designs in Figure 1. As can be seen, the design freedom was rapidly decreasing while the knowledge about the design was slowly increasing for design procedures prior to the 20th century. This is while, thanks to the current computing power and the enhanced semi-empirical methods, with more knowledge in the early stages enough freedom is available now to optimize the aircraft prior to the manufacturing, even in the detailed design phase thanks to the high-fidelity computations [4-7].

This work was supported by Mitacs through the Mitacs Accelerate Program (reference number: IT16648) and Columbiad Launch Services Inc.

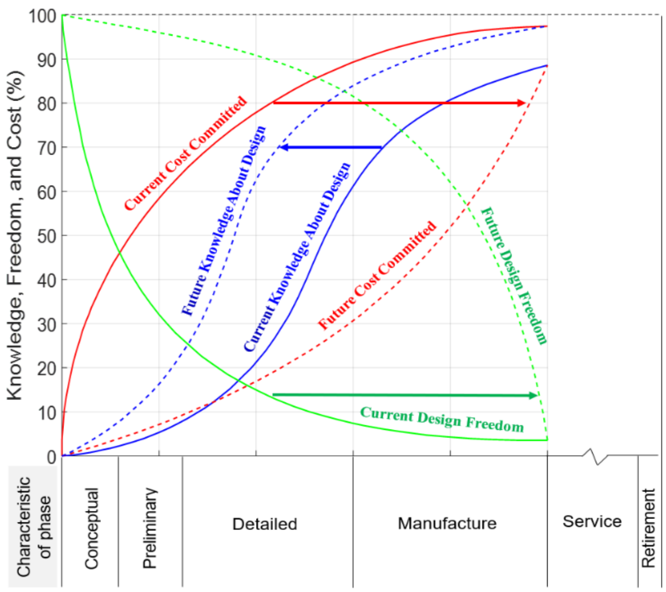

Figure 1. Life-Cycle design stages [4]

The knowledge gained by companies through their earlier designs is also a key player in lowering the associated cost of a new design. A good example of using previous experiences in the aircraft design process to lower the required time for the development of the next product is the Diamond DA-62 aircraft which is a five- to seven-seat twin-engine propeller-driven aircraft. The development process took almost six months and was originally developed based on the single-engine Diamond DA-50 aircraft. This trend shows that how much previous experiences and semi-empirical computations can enhance the entire aircraft design process and lower the required time between the project's kick-off to the maiden flight [7-9].

The final step to prove the maturity of an aircraft is to accomplish flight tests that should be done under various environments and flight conditions to demonstrate levels of acceleration and structural/aerodynamic loads [10]. One of the main reasons for such a costly and time-consuming process is to obtain the corresponding certifications of the type to assure the safety of the new aircraft. This is why, it took more than three years for the DA-62 series to reach the production phase after its maiden flight [8-9]. Consequently, still, more needs to be done to decrease this period as well. For light aircraft, two well-known certification types are available including, EASA CS-23 and FAR Part-23 [11-12].

Figure 2. Two different aircraft designed by Diamond company where a. DA-50, is a single engine aircraft b. DA-62, is a twin-engine aircraft designed based on the DA-50 within 6 months [8-9]

The main objective of this research is to provide a multidisciplinary platform for aircraft analysis. The primary disciplines include Aerodynamics, Propulsion, Performance, Flying Quality, Sensitivity and Flight Simulation. The proposed platform has been developed such that not only it can be used for design and development purposes but also flight tests as well as for operational and educational purposes. Accordingly, it can be used for design optimization purposes in the conceptual and preliminary design phases of an aircraft to speed up the design process and help designers to find the most optimum design. Also, in order to assist manufacturers in the flight test phase, the proposed tool after validation via actual flight tests results can be used to lower the amount of effort, time and money a company has to spend to complete the actual flight test phase and obtain the corresponding demanding aircraft certificates. Furthermore, airlines can benefit from this tool and use it for trajectory optimization purposes as most of the aircraft pilot manuals lack enough information and need supplementary data generation. Additionally, the propulsion module with the capability to analyze the future UAM concepts allows the designer to have a good estimation of solar energy characteristics in the multidisciplinary design environment. Finally, as this software is defined based on the most recent researches and publications, it is a good source for academic institutions to use the platform along with their textbooks to allow students to be familiar with the design and development process of a light aircraft.

MAPLA can fill the gap between the conceptual and preliminary design phases to the detailed design phase and flight test of light aircraft to lower the amount of effort, time and money a company has to spend in providing a new light aircraft to the market.

II. Methodology

As mentioned, the primary disciplines of MAPLA are Aerodynamics, Propulsion, Performance, Flying Quality, Sensitivity and Flight Simulation. Each module will be working separately and in connection with others, depending on the purpose of the analysis. Additionally, the modular approach will allow the user to connect MAPLA to other modules that can be developed in parallel to enhance the performance of the tool.

A. *Aerodynamics*

The "Aerodynamics" module consists of longitudinal and lateral-directional subprograms. In each subprogram, power-off static stability and control derivatives are initially estimated for various aircraft parts including the wing, fuselage, nacelle, horizontal tail, vertical tail and high-lift surfaces. Then, total power-off static stability and control derivatives are obtained by combining the contributes of the part derivatives. Afterwards, the dynamic characteristics of the aircraft are estimated based on the static derivatives. Finally, the power-on parameters and propeller effects are estimated based on the existence of semiempirical methods. The layout of the Aerodynamics module is presented in Figure 3.

In our previous work [13], the aerodynamics module has been developed based on the work done by NASA [14-15]; however, in order to generalize the platform and enhance the work particularly for light aircraft, some changes have been made:

- Maximum lift of the twisted wing
- Zero-lift pitching moment of the twisted wing
- The drag of the twisted wing
- The high-lift surfaces
- Lift of the horizontal tail and elevator surfaces
- Drag of the control and high-lift surfaces

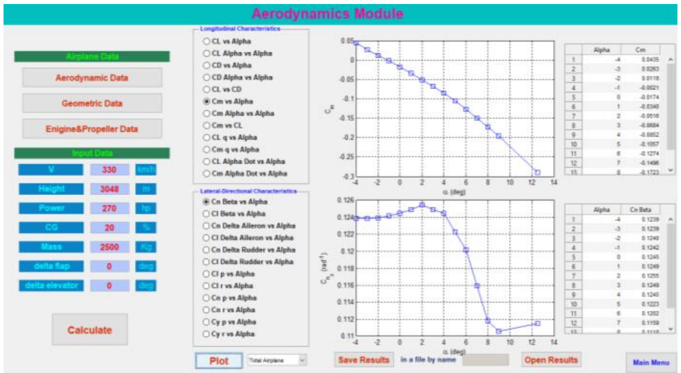

Figure 3. The layout of the Aerodynamics module

B. *Propulsion*

The "Propulsion" module provides information about the propeller effects on the aircraft design and engine specs including both fuel-powered and electric aircraft analysis. It is expected to use this module for analyzing different aircraft types including UAM vehicles as well. For propeller effect analysis, an engineering approach is proposed to analyze the asymmetric blade thrust effect with the help of analytical and semi-empirical methods. It is shown that the contribution of the asymmetric blade thrust effect in the lateral-directional stability of multi-engine propeller-driven aircraft is significant particularly in critical flight conditions with one engine out of service. Also, in some cases where the engines are rotating in one direction, the asymmetric blade effect has substantial effects on the handling quality of the aircraft even in normal flight conditions. Overall, due to the significant contribution of this phenomenon in the lateral-directional stability of propeller-driven airplanes, it is important to consider it in the design of the vertical stabilizer and rudder. The resulting analytical method has been used to determine the vertical tail incident angle and desired rudder deflection in accordance with the most critical flight condition for two different cases and validated to assure the accuracy of the result.

C. *Performance*

The "Performance" module provides information about the mission performance of the aircraft. The performance module is required to estimate the operating speed and cruise altitude of the aircraft at a given weight. Accordingly, required data for steady and accelerated level flight characteristics, flight envelope, climb and ceiling as well as range and endurance graphs are generated. This module can be used for the trajectory optimization of flight routes along with the weather information for different altitudes and specific times and airspace to enhance airlines' flight plan. An example of a flight planning optimization will be discussed in the results section.

D. *Stability and Control*

The "Stability and Control" module contains three subprograms including Flying Quality, Sensitivity and Flight Simulation. The Flying Quality subprogram, as shown in Figure 4, estimates the aircraft trim characteristics in all flight conditions and aircraft configurations and provides the corresponding handling quality level for different longitudinal and lateral-directional modes. By changing mass, inertia, geometry, aerodynamic derivatives and center of gravity (CG), the designer can evaluate the handling qualities of the aircraft. With respect to Figure 5, the Sensitivity subprogram provides sensitivity analysis for different aerodynamic characteristics and flight conditions in longitudinal and lateral-directional modes. Finally, the Flight Simulation subprogram provides 6 degrees of freedom (6-DOF) flight simulation using simulated atmosphere, power, equations of motion, aerodynamics, gravity and mass and inertia as shown in Figure 6 to study the behaviour of the aircraft in different flight conditions.

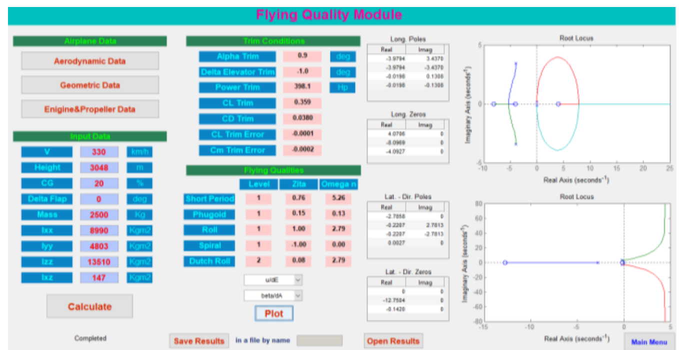

Figure 4. The layout of the Flying Quality subprogram

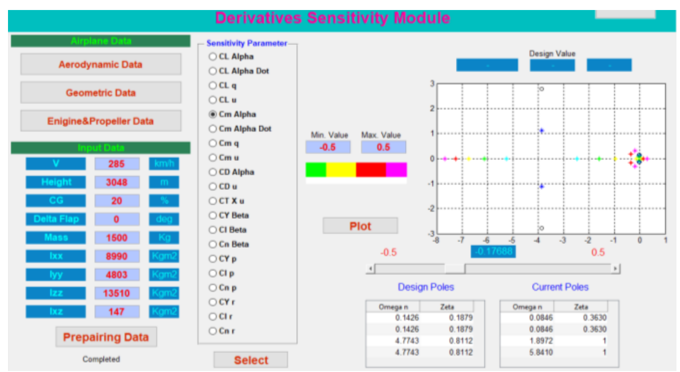

Figure 5. The layout of the Sensitivity subprogram

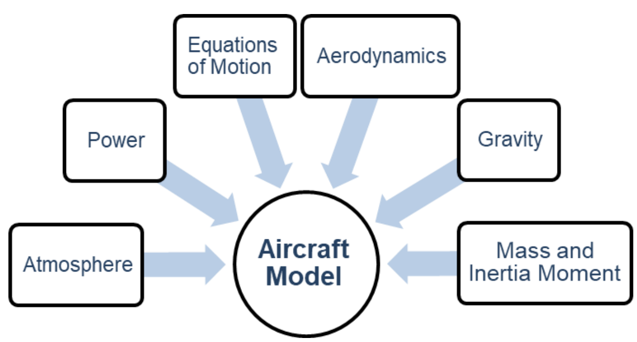

Figure 6. The architecture of the Flight Simulation subprogram

E. Multidisciplinary design optimization

Numerical optimization approaches have substantial capabilities to solve multidiscipline problems. Multidisciplinary design optimization (MDO) focuses on the use of numerical optimization in the design of systems with a number of subsystems or disciplines. The main reason for using MDO is that the performance of the system is related not only to the act of each individual discipline but also to their interactions. With the help of MDO in the early design stages, one can simultaneously enhance the design and decrease the time and cost of the entire design cycle [16-18].

MDO has specific features for problem formulations and these features are related to the cost objective and feasibility of the application. In MDO, the constraints and objective functions are stated as functions of design and state variables. As an example, let's assume a simple MDO case with two disciplines and see how the formulation of a problem can be expressed as follows [18]

Design variables: b_1, b_2 (1)

State variables: $z_1 = h_1(b_1)$, $z_2 = h_2(b_2)$ (2)

Objective: to minimize $\begin{Bmatrix} f_1(b_1, z_1) \\ f_2(b_2, z_2) \end{Bmatrix}$ (3)

Constraints: $\begin{Bmatrix} g_1(b_1, z_1) \\ g_2(b_1, z_1) \end{Bmatrix} \leq 0$ (4)

where subscripts 1 and 2 are the discipline number. In Equation 1, b is the design variable vector, and it can be expressed as local design variable vectors (b_1, b_2). In Equation 2, g is the constraint vector and it can be divided into local constraint vectors (g_1, g_2). h_i is the analyzer of the discipline number i and z_i is the state variable vector as the results of the ith analyzer. In Equation 3, f is the objective function vector and it can be expressed as local objective functions (f_1, f_2). The same approach can be taken for cases with higher disciplines.

Several evolutionary methods have been developed to solve global optimization problems. Among them, all stochastic algorithms with randomization and global exploration are referred to as metaheuristic algorithms [19-20]. In this study, the focus is on the metaheuristic algorithms, particularly genetic algorithm (GA) and particle swarm optimization (PSO); both of them are evolutionary heuristics which are using population-based search algorithms. They both move from a set of the population to another set of populations in a single iteration with expected progress using deterministic and probabilistic algorithms.

III. RESULTS

A. Aerodynamics

The Aerodynamics module has been validated via wind tunnel test data for a scale of 1:3 and compared to the estimations provided by the United States Air Force Stability and Control DATCOM (Data Compendium) and a VLM (Vortex Lattice Method) -based method [13]. The results indicated that the proposed solution is able to determine the aerodynamic characteristics of light aircraft in an acceptable range of accuracy for preliminary design purposes from zero-lift to stall conditions in all configurations.

B. Propulsion

The analytical method of the propulsion module has been used to determine the desired vertical tail incident angle and the required rudder deflection in accordance with the most critical flight condition for two different aircraft with general characteristics provided in Table I. Table II and Table III present the weathercock stability results against required rudder deflection and vertical tail incidence, respectively. Table II provides information about the required rudder deflection where aircraft 1 is equipped with two 180 hp engines and flying in one engine inoperative (OEI) situation at the minimum control speed. The required rudder deflection based on the stall angle of the aircraft at 12 degrees is equal to 22 and the same value has been proposed for this aircraft by the manufacturer [15-16]. This is while, Table III shows results for Aircraft 1 and Aircraft 2 in cruise flight conditions. In order to size the required incidence angle of the vertical tail, one can refer to the trim flight condition in the cruise flight. For the case of aircraft 1, the angle is equal to 1.38, the corresponding value for the angle of incidence will be very small and equal to 0.066 deg. As aircraft 1 uses a zero-incidence angle for the vertical tail, one can say that for this particular aircraft the incidence angle can be considered equal to zero [15-16]. Therefore, for aircraft 1 in cruise flight condition, the pilot can compensate the corresponding side force due to the asymmetric blade thrust using a small angle of the tab control surface. Now, let's consider Aircraft 2 equipped with a more powerful engine with 300 hp per engine. Side force coefficients for the various angles of attack and the required incidence angle are presented in Table III. Having the results for the side force coefficient, and the corresponding trim angle for aircraft 2 which is equal to 2 deg, one can determine the required incidence angle for the vertical tail which is equal to 0.32 deg. The proposed angle for aircraft 2 is comparable to an existing Baron G58 aircraft which has almost the same characteristics and using a small incidence angle for the vertical tail [22].

TABLE I. GENERAL CHARACTERISTICS OF THE AIRCRAFT USED FOR VALIDATION OF THE PROPOSED METHOD FOR ESTIMATION OF ASYMMETRIC BLADE THRUST EFFECT [15,16,21]

Parameter	Aircraft 1	Aircraft 2
Engine Type / Power (hp)	Lycoming IO-320 / 160 hp	Continental IO - 550C / 300 hp
Propeller Model	Hartzell (HC-E2YL-2A)	McCauley
Stall Speed (Km/hr)	130	135
Cruise Speed (Km/hr)	250	330
Wing Area (m^2)	16.54	18.5
Wing Span (m)	10.97	11.53

TABLE II. SIDE FORCE COEFFICIENT AND THE REQUIRED RUDDER FOR COMPENSATION WHILE THE AIRCRAFT IS FLYING IN OEI AND CLIMB CONDITION

Angle of attack (deg)	Cn (OEI)	δ_R (OEI)
-4	-0.020437	19.06
0	-0.021386	19.48

4	-0.022621	20.23
8	-0.024133	21.3
12	-0.025914	22.67

TABLE III. SIDE FORCE COEFFICIENT AND THE REQUIRED VERTICAL TAIL INCIDENCE FOR COMPENSATION WITH BOTH ENGINES OPERATING IN CRUISE FLIGHT CONDITION

	Aircraft 1		Aircraft 2	
Angle of attack (deg)	**Cn**	**i_v(deg)**	**Cn**	**i_v(deg)**
-4	0.000355	0.194	0.0015	0.64
-2	0.000177	0.096	0.00076	0.32
0	0	0	0	0
2	-0.000355	-0.096	-0.00076	-0.32
4	-0.000177	-0.194	-0.0015	-0.64

C. Performance

Here, an example of the flight planning results for the required fuel and total flight time using the flight performance data from a Beechcraft Baron G-58 light aircraft at a specific time and flight route is presented [21]. The aircraft performance data is taken from the pilot flight manual and the corresponding route and weather data is based on a standard flight from Thunder Bay, Ontario, Canada to Sioux Lookout, Ontario, Canada as shown in Figure 7.a and b, respectively [23-24]. Figure 8.a and b show the corresponding required fuel and total flight time, respectively for various altitudes.

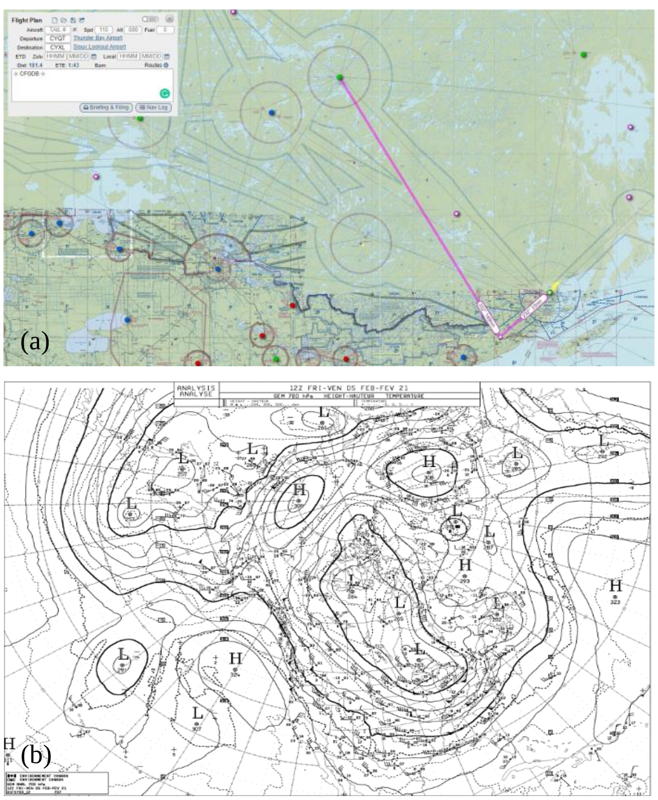

Figure 7. Flight planning using a. pre-existing route information [23] b. weather data [24] for a flight from Thunder Bay, Ontario, Canada to Sioux Lookout, Ontario, Canada.

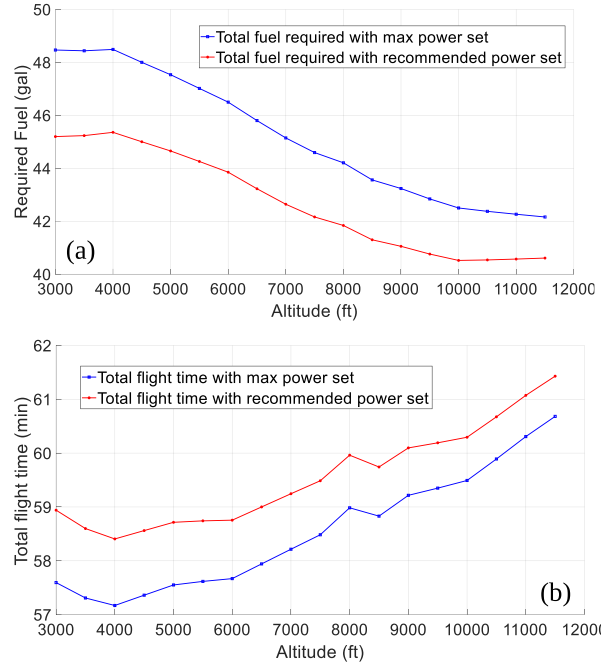

Figure 8. Results for a. the required fuel and d. the total flight time using a twin-engine propeller-driven light aircraft for a flight from Thunder Bay, Ontario, Canada to Sioux Lookout, Ontario, Canada.

D. Stability and control

The handling quality of the aforementioned twin-engine, propeller-driven light airplane in Table I, Aircraft 2 has also been investigated. With respect to the cruise flight condition, the aircraft has been trimmed first for the longitudinal motion and then the flying quality characteristics have been investigated. The longitudinal trim data are presented for the proposed airplane in Table IV. With respect to the trim condition, the flying quality characteristics have been investigated and presented in Table V. As can be seen, the Dutch-Roll mode is in level 2 and in our previous work, MDO was implemented with the help of multi PID controllers and enhanced the Dutch-Roll mode level while keeping all other flying quality characteristics in level 1 [25].

TABLE IV. PROPERTIES OF THE INVESTIGATED TRIM CONDITION

Parameter	Value	Unit
α_{trim}	0.9	deg
$\delta_{e_{trim}}$	-1.0	deg
P_{trim}	398.1	Hp
$C_{L_{trim}}$	0.36	-
$C_{D_{trim}}$	0.038	kg

TABLE V. PROPERTIES OF THE INVESTIGATED LONGITUDINAL TRIM CONDITION

Flying Quality Characteristic	Level	ξ	ω_n
Short Period	1	0.76	5.26
Phugoid	1	0.15	0.13
Roll mode	1	1.00	2.79
Spiral mode	1	-1.00	0.00
Dutch-Roll mode	2	0.08	2.79

E. MDO

As discussed earlier, the flight planning results provided for the required fuel and total flight time of a Beechcraft G-58 aircraft using different disciplines: the aircraft performance data, the corresponding route and the weather information. For an airline, it is very important to find the optimum case for each flight and relying on these results. In this case, one can implement MDO techniques and come up with the best solution in accordance with the objectives which are minimum required time and/or minimum fuel consumption. Figure 11 shows the corresponding optimum results for a typical flight from Thunder Bay to Sioux Lookout on a specific day.

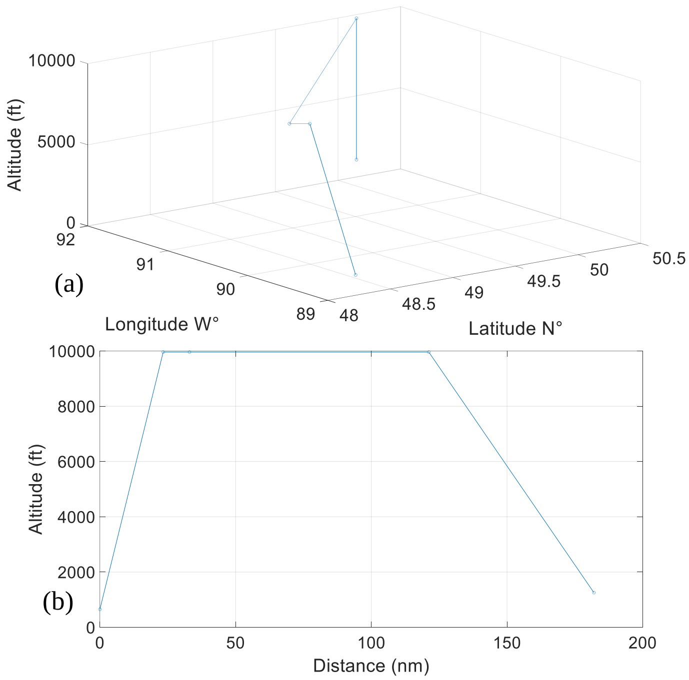

Figure 9. a. 3D flight path and b. mission profile for an optimum flight plan of a Beechcraft G-58 aircraft

IV. CONCLUSION

In conclusion, in this work an enhanced semi-empirical multidisciplinary program for design optimization of light, general aviation, propeller-driven aircraft is proposed. MAPLA has four primary disciplines for analysis: Aerodynamics, Propulsion, Performance and Stability and Control. Specialized for light, propeller-driven airplanes, available state-of-the-art analytical procedures and design data collections have been combined and modified in a unique method and automated in MAPLA. Initial investigations showed that the proposed solution is able to determine the aerodynamic characteristics of light aircraft in an acceptable range of accuracy in various configurations. The proposed software developed to be used for multi objectives including but not limited to design and development, flight test, operational and educational purposes.

ACKNOWLEDGMENT

This work was supported by Mitacs through the Mitacs Accelerate Program (reference number: IT16648) and Columbiad Launch Services Inc.

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