Extended Abstract with Poster

Reverse Engineering through Simulation of a Conceptual Design Process of Supermarine Spitfire

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Abstract

This paper is a report documenting the experience of participating in a Senior Design Capstone course in which the Supermarine Spitfire Mk Vb was reversed engineered. Instituting multi-disciplinary analysis, first order estimations, and calculations, the design team verified the flight capabilities of the Spitfire. The final focus of this engineering was to incorporate a synthesis of all the major disciplines through Lawrence Loftin's Subsonic Aircraft: Evolution and the Matching of Size to Performance. A brief discussion of this rapid iteration process is described below and results in a sanity check for the conceptual design and reverse engineering process by creating a solution space for a typical WWII fighter mission. Proving that the Spitfire's match point lies within the admissible range of design is confirmation for the reverse engineering tools used. Through reading this report one can begin to understand the complexity of conceptual designing an airplane and the adaptation of tools used for unconventional aircrafts. This includes the aerodynamic calculations using the United States Air Force DATCOM+ tool and the modification for an elliptical wing planform. From these results an engine analysis can be developed to measure its performance. The stability and control team took the ideology behind Loftin's method and applied it to the stability and control surfaces. Creating parameters and utilizing known stability trends, the team created a solution space for the stability and control effectors. The strong analysis of the individual disciplines is combined in the end to create a solution space for the Spitfire Mk Vb which exemplifies a joint effort and creates well rounded multi-disciplinary engineers. Overall, the skills developed through the project will allow each team member to carry on techniques and knowledge to other aircraft conceptual design.

Introduction

The Supermarine Spitfire is one of the most iconic and beloved aircraft or its era, and this semester, a group of senior students was able to participate in the active learning experience of reverse engineering this exceptional airplane as a part of the Senior Design Capstone Course. The Senior Design Capstone Course compiles the years of undergraduate studies to test and approve the student's engineering abilities. Under the direction of Dr. Bernd Chudoba the senior class was tasked to reverse engineer the famous World War II fighter planes with an emphasis on using a conceptual design process. Rather than using a purely analytical reverse engineering technique, the group implemented a simulation of the conceptual design phase of an aircraft in order to recreate the Spitfire based on its performance characteristics. By breaking into the individual disciplines involved in aircraft conceptual design, the team worked to create a solution space for the sizing based on a set of performance and geometric parameters. This paper defines the overall project goals for the team, as well as the teamwork and methodology used to reverse engineer the Spitfire, and outlines the results of the synthesis of the various disciplines' results.

The Team

The Spitfire team consisted of 14 individuals separated into five main disciplines for conceptually designing an aircraft as well as a chief engineer to oversee the project. These groups are: structures, aerodynamics, propulsions, performance, and stability & control. The small team allows quick communication and cooperation between the members. A hierarchy of leadership allows the big picture of the project to be focused on through the chief engineer and the details of the aircraft to be handled by the different disciplines. This process is common for the majority of companies and especially in engineering projects, much like designer R.J. Mitchell and his Supermarine team. His leadership and design genius is an inspiration for all engineers. He has had as many failures as he has had success stories, which is an encouraging notion when looking at our own imperfections.

Project Overview

The first steps taken by the team were to perform a literature survey to create a data base of sources to provide information concerning the project. Knowledge is the key. Through collecting a large database, we can grasp a better understanding of conceptual design, reverse engineering and the Spitfire itself. Nicolai notes that the first task for designing a vehicle is to "study, evaluate and understand..."[1] We took his wisdom to heart and tried to implement this into our entire project.

The next step taken by the team was to define each discipline's deliverables. With these variables, the teams were able to create individual methodologies in order to produce their key deliverables. When combining the groups' flows, we were able to create an overall group methodology. This flow incorporates all the disciplines but simplifies the processes to create a neat organizational hierarchy. Giving each team the responsibility to define their tasks for the semester creates a sense of ownership of the project and indicates the makings of a successful group.

No matter how hard-working a team may be they still need encouragement and pressure to complete a project by a deadline. One slip up for the team was not specifically defining a timeline for the project. Had we originally created and stuck with a detailed timeline, our analysis and results would have been more in depth. Nevertheless, in the time allotted the team performed admirably, creating unique techniques to reverse engineer the Spitfire and conceptually design a propeller driven aircraft.

Challenges

Over the course of the semester numerous problems arose and had to be resolved in order for the team to function at an effective level. The management and operation of the group is another objective of the capstone course which simulates a real world engineering team. These challenges include: information transfer between groups, parameter definition and assignment, timeline of deliverables, group dynamics and participation, and depth of project analysis.
The transfer of information between the groups was sometimes delayed, which consequently lagged the project progression. Because each group had priorities of their own, the information required by others was usually deferred until a convenient time. Problems arose when initial or new deliverables were not presented in a timely manner to fit the timeline of the project. This was one area where the chief intervened and made cross discipline information a number one priority. Also, even when the needed information was delivered, it often changed as the project progressed and values were corrected or refined. Additionally, even with revisions to these values, the updates were not necessarily transferred to the appropriate departments, creating a lapse in the information flow and overall analysis process.
When we originally set deliverables for each group, we kept in mind that they might change as the project progresses. When a controversy arose concerning what group should cover a certain scope of analysis, it had to be dealt with or else a part of the project would be incomplete.

Since our project was to incorporate Loftin's conceptual design process into our reverse engineering, we tried to perform similar analysis using parameters and historical trends to size various parts of the aircraft. However, this was sometimes complicated when incorporating it into every discipline. We realized that some of the disciplines are strictly analysis and others would require more resources given in one semester to create complex parameter analysis of the aircraft.

The two sided coin of the project was the team dynamic. There were good things and bad things that can be expected when working with a group. Over the weeks, individual work ethics and participation became a point of significant concern. The differences in the level of commitment, work rate, communication, and schedules proved to be an exasperating affair. The chief designated team leads to oversee their group's work and to assess the timely manner of the work. This meant organizing discipline meetings, delegating work, and participation of individual members. Occasionally in the middle of a project, the person in charge realizes that they are not suited for the responsibilities and need to be removed from the position. Fortunately our group never arrived at this dilemma.

In the beginning of the project our team had high hopes and aspirations, but we quickly realized the constraints of resources and time. This led to problems when determining the depth of analysis desired in this reverse engineering process. Reduced order calculations provided reasonably accurate results in a short time, while some higher order analysis was needed for correct verification of the Spitfire. The solution chosen was to employ reduced order methods where it would suffice, since these were generally less resource-intensive, and resorting to the higher order methods only when absolutely necessary for accurate production of results.

Reverse Engineering

One of the biggest challenges faced, and the running theme of this project, was the integration of a conceptual design synthesis method with a reverse engineering process. Essentially, the two concepts are polar opposites of the other. As such, generating a unified method incorporating both elements involved a prolific amount of improvisation to existing analytical tools as well as producing original methods tailored to the case-specific requirements. The methodology taken for this reverse engineering process was based on the methodologies of Loftin and Roskam for fixed-wing aircraft. Loftin and Roskam use a wide knowledge base of similar class aircrafts to create solution spaces in which the airplane design can exist. We started with the basic aircraft description and configuration, similar to Loftin, but with more detail since the geometry and specifications of the aircraft we were analyzing were already known.

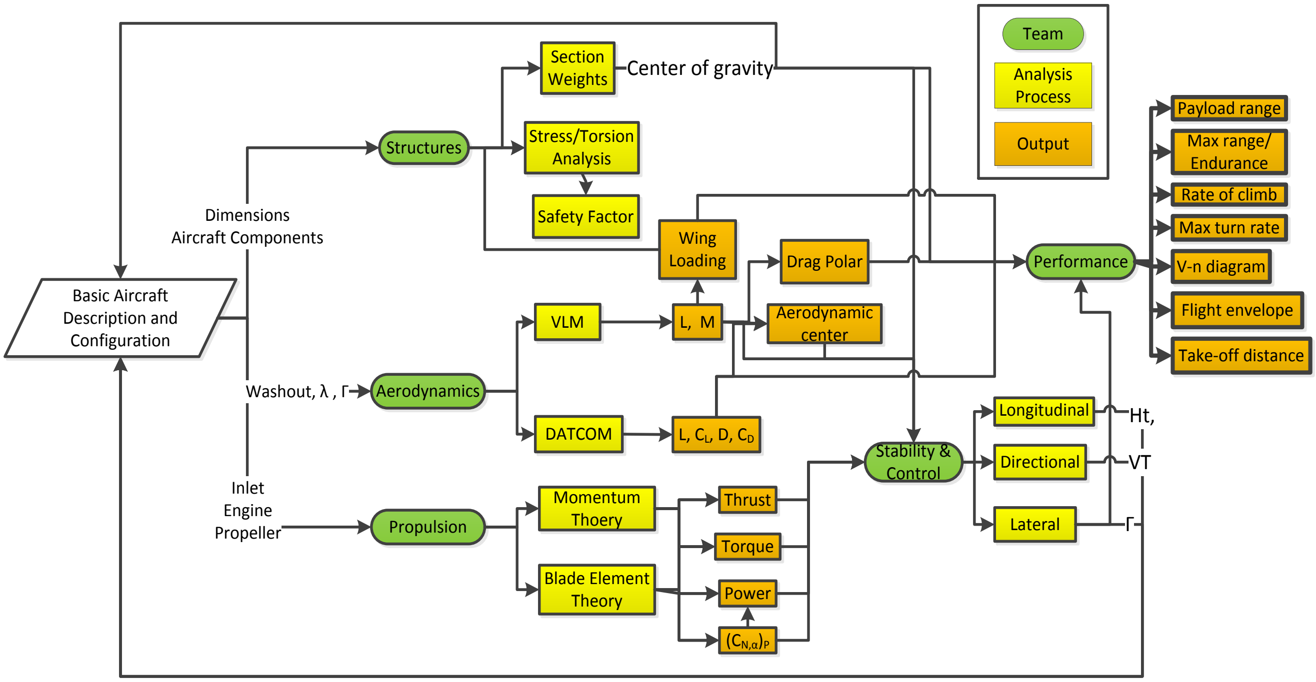

Figure 1. Group Multi-Disciplinary Analysis Methodology.

Figure 1 shows a flow chart of our designing methodology. This refined flow incorporated all the disciplines into a systematic method of iterating the aircraft design to obtain performance charts that facilitated comparison and cross-reference. This analysis involved sanity checks and then proceeded to detailed examination of the aircraft to determine if the change was beneficial or detrimental.

The group would perform optimization of the aircraft with current technology only if time permitted. Analysis of the Design Constraining Flight Conditions was our main focus and allowed us to verify the flight capabilities of the Spitfire. The successive sections detail the procedures and methods of analysis that are specific to each discipline.

Aerodynamics

The Supermarine Spitfire is known for its fighting capabilities and the Battle of Britain, but it's most notable feature is its elliptical wing. That being said, the aerodynamics team was eager to begin analysis on the aircraft and to utilize the skills gained throughout their collegiate career. The semester spent working on the project was a learning experience for the entire team because they utilized multiple aerodynamic prediction methods to determine the right aerodynamic tool that would produce accurate results. There are countless methods of calculating lift and drag on an aircraft, but all the methods have their own certain limitations. The team began to explore the various methods through a literature search. Once these methods were determined, the group of three was divided into three groups. Each person studied their designated method and improved their skillset by developing aerodynamic proficiencies while performing their analysis. The collective results of the team were used by the structures, propulsion, stability and control and performance teams, and as well in the overall Loftin analysis. Therefore, there was a great deal of pressure for the aerodynamics team to produce quick and accurate results.

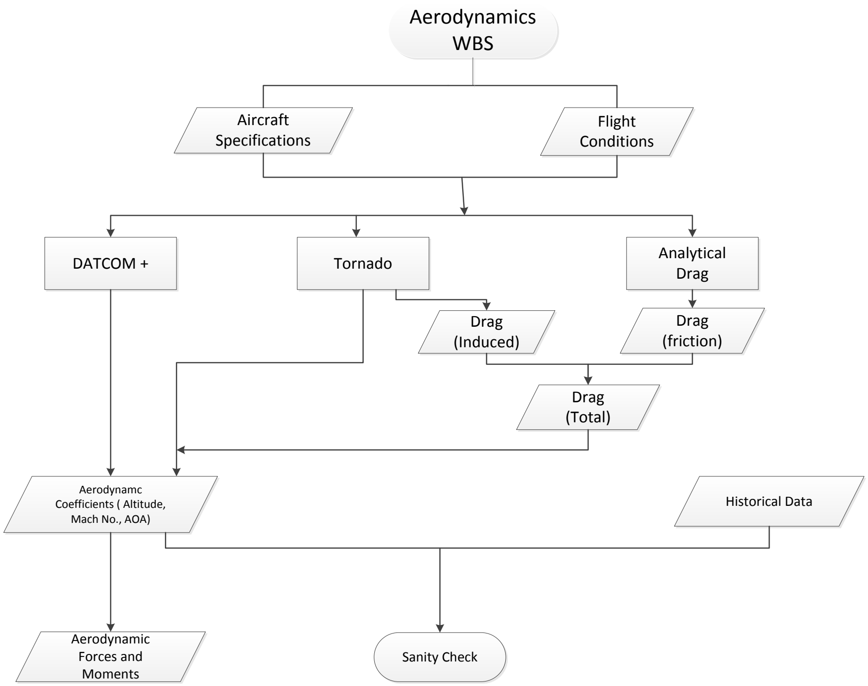

Figure 2. Aerodynamics Work Breakdown Structure.

The principal aerodynamic tool utilized for the project was DATCOM +[2], a user-friendly version of the United States Air Force Stability and Control Digital DATCOM. The program allowed for the user to define the geometry of a fixed-wing aircraft and the specifications, including the Spitfire's propeller and engine location, within an input file. The static aerodynamic and dynamic stability derivatives at various flight conditions were predicted using non-linear aerodynamics and semi-empirical calculations. A secondary method, Tornado[4], was employed to serve as a sanity check for the analysis. The program combines vortex panel method based MATLAB codes and is able to produce sufficient aerodynamic analysis to serve as a verification of the data obtained by DATCOM+. In the aerodynamics field it is often the case where engineers must perform method-switching to account for the limitations provided by the tool used. For this reason the aerodynamic team employed analytical calculations to calculate the skin friction drag, and then combined the data with the total drag obtained from Tornado to provide accurate results that could be compared with that of the primary method.

The work breakdown structure for the aerodynamics team can be seen in Figure 2. The diagram shows that the aircraft specifications and flight conditions were the inputs for the three methods used by the team, shown in the third level. The analytical drag method shows how the skin friction drag was combined with the drag results produced by Tornado to provide an accurate comparison with the results from DATCOM. The results of the tools were compared with obtained historical data to verify accuracy with actual experimental data, and then the results were exported to the other teams per specific need. The maximum lift coefficient for cruise speed was given to the Chief Engineer who used it for Loftin analysis. The aerodynamics team performed above and beyond during the project semester by generating accurate results to be used by the other design teams and by adding skills into their method's library.

Propulsion

The propulsion team was tasked with the overall analysis of the propulsion system present on the Spitfire Mk.Vb variant. The engine is sized based on power requirements for takeoff, climb rate, service ceiling and maximum speed scenarios, essentially the four main design constraining flight conditions (DCFC) for the aircraft selected. With the engine sized, the propeller geometry and aerodynamic characteristics were modeled using Reference [5]. To combine the two components of engine and propeller, the team narrowed down the analysis tools to two options; Momentum theory and Blade Element Theory.[6] The objective is to pair the engine output power and rpm with the aerodynamic characteristics of the propeller to simulate thrust production. To close the analysis loop, we had to use the aforementioned performance criteria at the DCFC to verify the feasibility and capability of the model. Essentially, the significance of this analytical and experimental data comparison is twofold; firstly it verifies that the modeled system replicates the actual system quite accurately, and secondly it shows that the overall propulsion system of the aircraft was able to achieve and surpass the performance requirements set in place by the British Air Ministry.

One of the main challenges faced by the propulsions team was the coding process whereby the blade element theory required several iteration loops to solve for required variables. This resulted in relatively long code run times thus decreasing productivity in terms of examining higher numbers of data points. The iterative process also introduced another error in the form of the propulsive efficiency being greater than unity initially, which physically is not possible. After the break tolerance for the iterations was corrected, the problem was rectified; however it remained a valid point of concern for a significant period of the project timeline.
The highlight of the educational experience specific to the propulsion analysis is the necessity an

d ability to produce a working model with the least amount of time and resources, then refining the model to where it is feasible and ideally, optimal. To be efficient in this process, a broad base of knowledge and solid command of relevant theory is crucial, however it is hands-on experience that provides the engineer with the decisive edge.

Stability and Control

The stability and control team consisted of three members, allowing the team to be split into the three sub-disciplines of static stability and control: longitudinal, lateral, and directional. Since the three sub-disciplines are relatively independent, splitting the team allowed for a more streamlined reverse engineering process and promoted high self-responsibility among all team members. Each group-member was responsible for getting the work done per their assigned sub-discipline. The disadvantage of the approach is that the entire team is dependent on each and every member of the stability and control group to finish their work. To ensure that appropriate progress was made, the stability and control team had weekly meetings to discuss encountered issues and progress.

The methodology for the stability and control team consisted of a Loftin-like design process, where inputs were parameterized, using additional information from Roskam's aircraft design series.[7] This approach was chosen to mimic the conceptual design phase of the Supermarine Spitfire. The final outputs for this approach were solution spaces that defined the sizing of the horizontal and vertical tail plane for longitudinal and directional stability, as well as dihedral for lateral stability. Solution spaces for the sizing of all primary control surfaces were also created. The solution spaces were created to see whether the Spitfire did indeed lie within the boundaries and therefore proving that the aircraft was stable and maneuverable.

Structures

The structures and performance teams both played important roles within the group by calculating and providing geometric and performance parameters to the other groups for their calculations. The nature of the analysis these groups performed meant that their calculations were primarily analytical as opposed to a simulation of the conceptual design process used by the other groups. The primary information provided by the structures group to the team consisted of the geometry of the Spitfire aircraft including the sizing of the aircraft structure along with estimations of the aircraft weight. From these measurements the team was also able to calculate the location of the aircraft's center of gravity, which was the most crucial geometric parameter for other groups' calculations. The structures team also created maps of the shear forces and moment acting along the Spitfire's wing and fuselage structures due to aerodynamic forces induced during flight. Based on these force calculations and the material properties of the aircraft, a factor of safety was able to be calculated to show that the Spitfire structure was capable of withstanding the forces induced during the most demanding of flight conditions.

Performance

The performance team relied heavily on the information being passed from the other groups in order to analytically quantify how well the Supermarine Spitfire performed. A payload-range calculation was created which allowed for analysis of the effect that the weight of the armament being carried would affect the range of the aircraft. Using the lowest payload possible for the aircraft, it was also possible to find the maximum range and endurance, or loitering time possible for the aircraft, which would have been a crucial parameter for a bomber escort mission. This analytical prediction for the range and endurance produced a range that was within 4% and endurance that was within 6% of the actual Spitfire's performance. The combat and maneuvering performance were also analyzed in the form of the aircraft's climb rate, minimum turn radius and maximum turn rate, and all three were shown to be well within the range typical of a fighter aircraft of the era. The takeoff and landing performance were analyzed by creating a V-n (velocity versus load factor) diagram which showed the load factors the aircraft could withstand over the possible range of flight velocities. Finally, the most important output of the performance team was the formation of the flight envelope which predicted all the combinations of flight velocity and altitude at which the Spitfire was capable of flying. Again this flight envelope was shown to correlate well with historical data, thus verifying that the analysis from all of the teams produced results which matched the actual Spitfire.

Loftin Verification

After the reverse engineering analysis the team was then able to simulate the sizing of an aircraft using Loftin's parametric sizing technique.[8] Any conceptual design consists of parametric sizing, configuration layout, and configuration evaluation. The parametric sizing method laid out by Lawrence Loftin gives a rapid sizing method based on existing correlations of well-known aircraft design parameters. In order to stick with the reverse engineering theme of the project, the outputs from the performance and structures groups were used in place of the empirical data that Loftin's design process generally relies on. Using Loftin's design method allows for the creation of a solution space which constrains the design's total weight, engine power and wing area.

The typical conceptual design sizing phase consists of seven distinct steps: analyze, integrate, iterate, converge, screen, visualize, and assess risk. The analysis begins with evaluating the properties, characteristics, and performance objectives with known equations from a basic engineering undergraduate degree. Many of these relations are defined by Loftin, but through our literature research and built up database we were able to verify the equations used. Next, one should build up a system of equations integrating them so major aircraft performance can be evaluated. Once the integration of parameters has been created, the following step is to iterate the method until it can converge on a specific desired value. This convergence is accomplished by constraining the combination of engine power and wing area using several performance requirements set within the design objectives.

The constraining curves used by Loftin for first order conceptual design are defined by the required velocity characteristics as well as the aircraft's takeoff/landing field performance. The resulting figure represents the screening step and leads to a visualization of the aircraft. The overall objective of the Loftin sizing method is to choose a configuration which yields the best combination of high wing loading and high power loading. Crossing these constraining curves increases the risk of flying the vehicle and is a measure of the safety of the aircraft.

As stated, the overall goal of this project involved creating valid methods for performing a reverse engineering, as well as simulating the sizing portion of the conceptual design phase of an aircraft. The successful completion of the solution space using the disciplinary results serves to fulfill both of these goals. After implementing the values obtained by the disciplines throughout the project, the solution space seen in Figure 3 was created. The solution space indicates that the actual Spitfire Mk-Vb fell within the admissible section of the matching chart, thus verifying the methods used by the individual disciplines, as well as the sizing method.

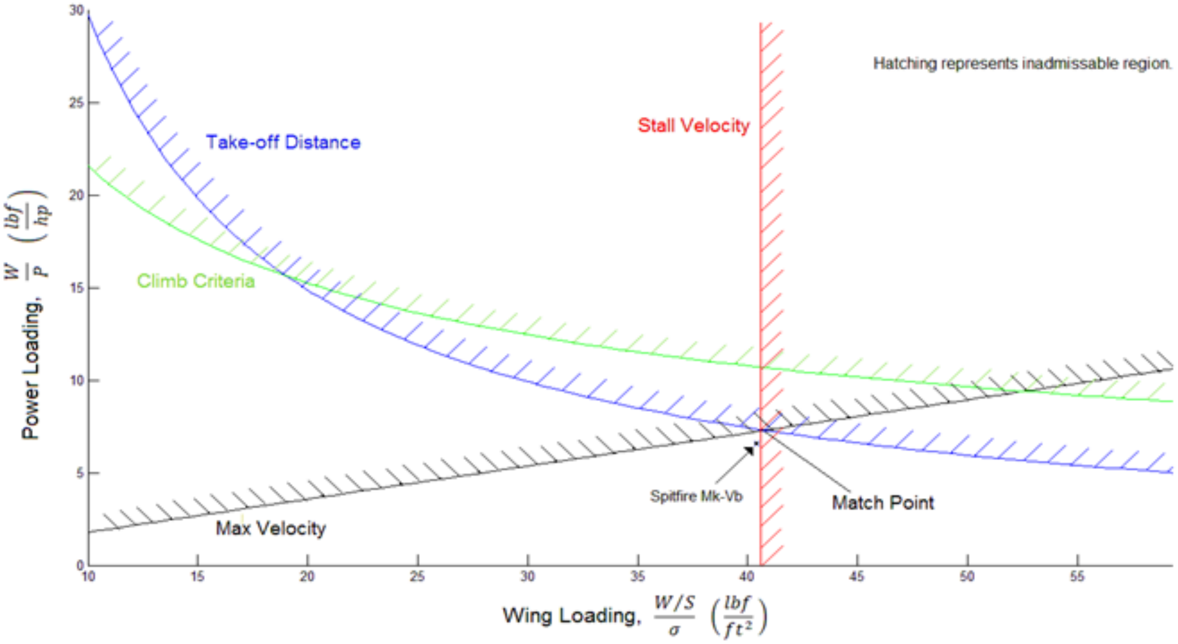

Figure 2. Visualized match point of the Supermarine Spitfire.

Summary and Conclusions

The biggest takeaway from this project has been the level of complexity involved in analyzing or designing an aircraft, even if this aircraft has been sitting in museums for over 50 years. The methodology employed by the group has allowed for not only a better understanding of the reverse engineering of an aircraft, but has also given insight into the conceptual design phase commonly employed in industry. Though working as a large group consisted of many challenges, the teamwork allowed for a truly cooperative learning experience which helped the growth of each individual member. The group was able to break up into the various disciplines involved in aircraft design and successfully reverse engineer the aircraft to show that the Supermarine Spitfire flew. Using the results from each of these disciplines, a basic conceptual design of the Spitfire was recreated using the parametric sizing method of Lawrence Loftin. This conceptual design simulation resulted in an accurate and realistic solution space for the sizing of an aircraft with the Spitfire's performance capabilities, and it has been shown that the Spitfire's sizing is within this acceptable space and very near the match point created. The combination of the reverse engineering and conceptual design of an aircraft has been both interesting and engaging, and has truly given an insight into the genius of the aircraft designers of the past.

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