ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

THESIS PRESENTED TO
ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
A MASTER’S DEGREE WITH THESIS IN AEROSPACE ENGINEERING
M. A. Sc.

BY
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AIRCRAFT CONCEPTUAL DESIGN STUDY OF THE CANARD AND THREE-SURFACE UNCONVENTIONAL CONFIGURATIONS FOR THE PURPOSES OF REDUCING ENVIRONMENTAL IMPACTS

MONTREAL, OCTOBER 3, 2014

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ACKNOWLEDGMENT

First, I would like to thank my thesis director, Mr. Julien Weiss, for his support and his understanding of the special nature of this master's research. This project has been made possible by the BMP scholarship program which provides an important financial support for graduate students to work in close collaboration with, and for a company.

My main acknowledgment goes to Johan Johnsson from Bombardier Aerospace who gave me the opportunity to work in the Advanced Design department. It has been a very formative experience to work in this department on the interesting and complex subject of aircraft conceptual design. It goes without saying that all this new knowledge will be helpful for my future. I also want to say a big thank you to my research supervisor, Mr. Graham Potter, and Mr. Sid Banerjee for their support and guidance. Among all other members of Advanced Design, I want to specifically thank Pat Piperni, Mark Rakowitz, Kenny Huynh and Jasveer Singh for their help which were all very helpful when I faced the more advanced technical aspects of aircraft design, more specifically concerning aerodynamics, MDO and stability and control.

Lastly, I would like thank everybody who supported me, mainly my family. I owe them a great part of my success. They have congratulated me for my accomplishments and have encouraged me from the beginning until the very end. Their ongoing support has helped me to continue working hard even when things advanced at a much slower rate than expected.

ÉTUDE SUR LE DESIGN CONCEPTUEL D'AVIONS À CONFIGURATION NON CONVENTIONNELLE DE TYPE CANARD ET TROIS-SURFACES DANS LE BUT DE RÉDUIRE LES IMPACTS ENVIRONNEMENTAUX

Olivier DESHARNAIS

RÉSUMÉ

Avec une constante augmentation de la demande pour le transport aérien et les prix actuellement élevés du pétrole, l'industrie aéronautique recherche activement de nouvelles techniques d'opération et de nouvelles technologies afin d'améliorer son efficacité et ainsi réduire ses impacts sur l'environnement. Les constructeurs d'avions explorent plusieurs options en vue de concevoir et construire de meilleurs avions. Une des options considérées est l'utilisation d'une configuration dite non-conventionnelle.

L'objectif de cette recherche est d'étudier deux configurations, canard et trois-surfaces, en les appliquant à un avion grande vitesse typique à propulsion par moteurs à réaction. En se basant sur les outils de design conceptuels pour avions conventionnels disponible à Bombardier Aéronautique, certains d'entre eux ont été modifiés et validés pour les deux configurations à l'étude. Ceci a inclus une estimation du poids du plan canard, une validation exhaustive d'un outil aérodynamique, AVL, et la modification d'un outil détaillé de dimensionnement de l'empennage. Le dernier outil s'est avéré nécessaire pour obtenir un degré de précision satisfaisant au niveau du dimensionnement du plan canard et du stabilisateur horizontal arrière, du balancement de l'avion, de la définition de l'enveloppe du centre de gravité et de la stabilité et contrôle.

Par la suite, un avion canard comparable à l'avion de la plate-forme de recherche de Bombardier a été conçu. Les solutions finales n'ont pas été obtenues à la suite d'une optimisation à cause de certaines limitations dans le procédé de design. Les résultats préliminaires indiquent une augmentation de 10% de la quantité de carburant brulé ce qui fait en sorte d'augmenter les impacts environnementaux. L'avantage théorique de ne pas générer de portance négative est clairement surpassée par la faible efficacité du système d'hypersustentation. L'incapacité d'obtenir un niveau de portance maximale similaire à celle des avions conventionnels explique en grande partie pourquoi la configuration canard ne possède pas de réels avantages pour ce type application.

Quant à la configuration trois-surfaces, même si aucune solution finale n'ait été obtenue dans la présente recherche, elle a été identifiée comme étant meilleure que la configuration canard selon l'information recueillie dans la revue de littérature. Effectivement, certaines études précédentes ont conclues qu'il y avait une petite amélioration de la consommation de carburant comparativement à la configuration conventionnelle dépendamment du type d'application. Cette configuration non-conventionnelle est connue comme permettant de réduire la traînée d'équilibrage et aussi de permettre un vol à trainée minimale pour toutes les

positions du centre de gravité. Pour cette raison, il est important de continuer le travail commencé dans ce projet de recherche afin de vérifier si un avion trois-surfaces grande vitesse à propulsion par moteur à réaction pourrait éventuellement s'avérer plus efficace.

Mots-clés: Design conceptuel d'avion, Configuration canard, Configuration trois-surfaces

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AIRCRAFT CONCEPTUAL DESIGN STUDY OF THE CANARD AND THREE-SURFACE UNCONVENTIONAL CONFIGURATIONS FOR THE PURPOSES OF REDUCING ENVIRONMENTAL IMPACTS

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ABSTRACT

With a constant increase in the demand for air transport and today's high fuel price, the aerospace industry is actively searching for new operation methods and technologies to improve efficiency and to reduce the impact it has on the environment. Aircraft manufacturers are exploring many different ways of designing and building better airplanes. One of the considered methods is the use of unconventional aircraft configurations.

The objective of this research is to study two configurations, the canard and three-surface, by applying them into a typical high-speed jet aircraft using the conceptual design tools for conventional aircraft available at Bombardier Aerospace (some of them have been modified and validated for the two configurations of interest). This included a weight estimation of the foreplane, an extensive validation of the aerodynamic tool, AVL, and a modification of a physics-based tail-sizing tool. The last tool was found necessary for an accurate foreplane/tailplane sizing, aircraft balancing, establishing the CG envelope and for the assessment of all stability and control requirements.

Then, a canard aircraft comparable to the Bombardier research platform aircraft was designed. Final solutions were not obtained from a complete optimization because of some limitations in the design process. The preliminary results show an increase of fuel burn of 10%, leading to an increase of the environmental impacts. The theoretical advantage of not generating any download lift is clearly overwhelmed by the poor effectiveness of the high-lift system. The incapacity to reach a level of high-lift performance close to the one of conventional high-speed aircrafts mostly explains why the canard configuration was found to have no true benefits in this application.

Even if no final solution of a three-surface aircraft was obtained in this research, this configuration was identified as being better than the canard case according to the information found in the literature. Some past studies concluded that there's a small improvement in fuel burn over the conventional configuration depending on the application. This unconventional configuration is recognized to have lower trim drag and the capability to fly at minimum drag for all CGs. For this reason, it's worth continuing the work started in this project to see if a three-surface high-speed jet aircraft could eventually be more efficient.

Keywords: Aircraft design, Canard configuration, Three-surface configuration

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LIST OF ABBREVIATIONS

AC	Aerodynamic center
AR	Aspect ratio
AVL	Athena Vortex Lattice, ref. (Drela and Youngren, 2012)
BOW	Basic operating weight (no payload, no fuel, with crew)
CFD	Computational fluid dynamics
CG	Center of gravity (generally referred to its location)
CO2	Carbon dioxide
DOC	Direct operating cost
L/D	Lift-to-drag ratio
MAC	Mean aerodynamic chord (ft)
MDO	Multidisciplinary design optimization
MLG	Main landing gear
MRC	Moment reference center
MTOW	Maximum takeoff weight (lbs)
MWE	Manufacturer weight empty (lbs)
NLG	Nose landing gear
Swet	Wetted area (ft^2)
TO	Takeoff
TR	Taper ratio
VLM	Vortex lattice method
ZFW	Zero-fuel weight (lbs)

LIST OF SYMBOLS AND UNITS

Symbols

α	Angle of attack (degrees)
ε	Downwash (degrees)
δ	Control surface deflection (degrees)
μ	Friction Coeffieicent (adimensionnal)
σ	Induced drag interference factor (adimensionnal)
Λ	Sweep angle (degrees)
η	Dynamic pressure ratio (adimensionnal)
AC	Aerodynamic center
Alpha	Angle of attack (degrees)
AoA	Angle of attack (degrees)
b	Span (ft)
CL	Lift coefficient (adimensionnal)
CLmax	Maximum lift coefficient (adimensionnal)
CD	Drag coefficient (adimensionnal)
CD0	Zero-lift drag coefficient (adimensionnal)
CDi	Induced drag coefficient (adimensionnal)
CM	Moment coefficient (about surface aerodynamic center or about the CG)
Cn	Normal lift coefficient
D	Drag (lbs)
e	Spanload efficiency factor or Oswald factor (adimensionnal)
Eta	Spanwise coordinate (adimensionnal)
i	Incidence angle (degrees)
Iyy	Longitudinal inertia ($slg \cdot ft^2$)
k	Factor or exponent value (adimensionnal)
L	Lift (lbs)
LM	Length of the moment arm (ft)
M	Moment (lbs·ft)

n_{ult} Ultimate load factor (adimensionnal, g's)

q Dynamic pressure (lbs/ft^2)

S Area (ft^2)

T Thrust (lbs)

W Weight (lbs)

x_0 Factor or exponent value (adimensionnal)

X Longitudinal location (ft)

Z Vertical location (ft)

Subscript symbols

α Gradient relative to the AoA

0 Value at zero AoA

ac Location of the AC or a moment relative to the local surface AC

c Canard

c/4 Quarter-chord

e Elevator

h Horizontal stabilizer / Tailplane

t Horizontal stabilizer / Tailplane

wb Wing-body

Units

Ft Foot

Kt Knot

Lbs Pound

m Meter

Nm Nautical mile

SHP Shaft horsepower

Slg Slug

Us gal. Us gallon

INTRODUCTION

Since the beginning of the modern high-speed air transport age with the advent of jet aircrafts in the late 1950's, a major improvement in terms of fuel-efficiency was achieved. According to the NASA Report Global Atmospheric Effects of Aviation (Albritton *et al*, 1997), fuel burn per seat was improved by 70% when comparing the 1995 Boeing 777-200 to the 1960 De Havilland Comet 4. Figure 0.1 presents the fuel efficiency of jet airliners relative to the Comet 4.

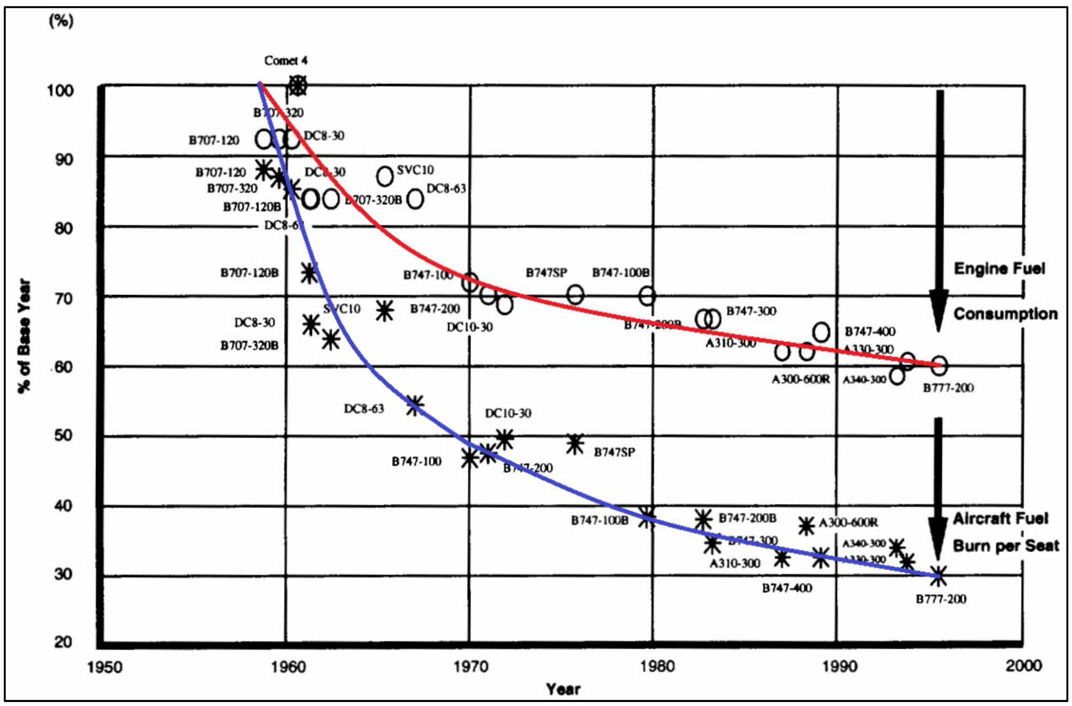

Figure 0.1 Fuel efficiency of jet airliners (adapted from (Albritton *et al*, 1997, p.45))

Those improvements are coming from more efficient technologies: about 57% comes from more efficient engines and 43% from lighter airframe generating less drag. Recent aircraft like the Airbus A380 and the Boeing 787 achieved an improvement of around 82% compared to the Comet 4 (International Air Transport Association, 2009). It has required significant progress to reach this level of efficiency. In the case of the two aforementioned airplanes, their main improvement is the design of a double-decker jumbo jet and the massive usage of lightweight advanced composite materials, respectively.

With today's high fuel price, an expected constant and important growth of the demand for air transport and a commitment from the aviation industry to reduce their environmental impacts, important research is done on different technologies that are improving fuel-efficiency. One of those, and probably the most radical, is to design an aircraft with an unconventional configuration. The conventional arrangement (e.g. cylindrical fuselage, wing and an aft-empennage) has essentially remained the only one used for commercial and business transport aircraft. This well-proven design has greatly evolved since its beginning up to a more mature stage. This is indicated by smaller efficiency improvement per year in the last few decades; it has become more difficult to further reduce fuel consumption. Other reasons explaining the continuity of this design philosophy in the last 60 years, i.e. the evolution of the conventional aircraft, are technologies readiness, relatively low fuel prices, and the high financial and technical risk associated to the development of a new unconventional aircraft. However, if a certain aircraft having an unconventional configuration proves to be better than his equivalent conventional design, aircraft manufacturers may develop such aircraft. Among all reasons that could justify a change of configuration of future aircrafts, the main ones are: lower operating cost, higher efficiency without largely reducing performance level (mainly the cruise speed), and more recently reduced environmental impacts. Emissions and noise are now an important concern for the aviation industry: climate effects and the global warming phenomena are better understood than ever before. Some organizations like the International Council on Clean Transportation ICCT are working to provide information for the public and environmental regulators to promote better efficiency in transport with less climate impacts. Air transport currently accounts for 2% of the global CO2 emissions, and 3% of the total greenhouse gas emissions, when non-CO2 effects are taken into account (International Air Transport Association, 2009). Over the next 35 years, despite a forecasted increase in demand, the aviation industry's ambitious objectives is to cap net emissions from 2020 through carbon neutral growth and, by 2050, achieve a 50% CO2 reduction compared to what they were in 2005 (Air Transport Action Group, 2011).

In the last few years, different unconventional concepts using current and future technologies have been proposed and studied. Some of these are the very-large blended-wing body aircraft (Liebeck, 2004), the strut-braced wing SUGAR concept from Boeing (Bradley and Droney, 2011) or the double-bubble fuselage D8 concept (Drela, 2011). All those studies are showing improvement in fuel burn compared to equivalent conventional aircraft. Fuel efficiency is certainly one of the most important criteria in aircraft design since CO2 emissions are directly proportional to fuel burn (Penner *et al*, 1999) and because of the drastic rise in fuel cost share of total operating cost in the last few years (from 13.6% in 2001 to 32.3% in 2008 (International Air Transport Association, 2010)).

Among all unconventional configurations, the canard and three-surface concepts are those studied in this project. The canard design, which places the horizontal stabilizer at a forward location, is the oldest aircraft configuration; in 1903, it was used by the Wright Brothers in the first powered heavier-than-air airplane, the Wright Flyer I. All Wright's canard airplanes were showing severe problem with stability and control (Culick and Jex, 1984). Shortly after, the aft-tail configuration rapidly became, and still remains, the standard configuration. Since that time, the canard configuration and later three-surface design, obtained by adding a foreplane to a conventional aircraft, are to this day, still subjects of interest. A debate on whether or not the canard and three-surface configurations offer the superiority versus the conventional arrangement always exists in the technical community.

This research project is about the conceptual design of a canard and a three-surface high-speed aircraft. It was done in collaboration with Bombardier Aerospace's Advanced Design Department. The final objective is to compare those aircrafts to an existing equivalent conventional version and to assess the potential fuel and cost benefits associated to those configurations. Practical considerations and a good level of details are of highest importance to ensure designing feasible aircrafts. Also, assuming the same level of technology and the same set of requirements as a conventional reference aircraft will allow the comparison to be fair between all configurations. Due to time constraints, the design was limited to a preliminary canard aircraft using the most-advanced tools currently ready at the time of writing this report. Fully optimized versions of a canard and three-surface aircraft were postponed as part of the future work.

This work can be divided into four main chapters, with the first being a literature review describing of both unconventional configurations. Next, a summary of the most important theoretical and practical studies done on this subject is presented. Existing aircrafts of those configurations are also covered with the presentation of three specific airplanes. Then, the Bombardier conceptual design process is briefly explained in Chapter 2. This section also identifies which part of this process has to be modified and validated for the two configurations under study. The modifications and validations are discussed in Chapter 3: Tool Development. Canard weight estimation, calculation and validation of aerodynamic data, and the modification of a tail sizing tool are all covered in this chapter. Development and validation of new design tools represents the largest and the most valuable work done in this research. Finally, a canard jet aircraft was designed using the updated Bombardier Advanced Design's conceptual design process. Results are then discussed and compared to the reference aircraft and to what was found in the literature review. A conclusion about the canard configuration is given although it remains based on preliminary results. Even if no real application was done for the three-surface configuration, some concluding comments mostly based on the literature review, are given. Finally, recommendations are made concerning future work to be done at Bombardier.

CHAPTER 1

LITERATURE REVIEW

This section gives a general description of the canard and three-surface configuration. Furthermore, their respective theoretical benefits and disadvantages will be explained, as well as some specific facts related to critical aspects of the design. Literature, (Raymer, 2012), (Torenbeek, 2013), (Gudmundsson, 2014), (Phillips, 2010), (Sterk and Torenbeek, 1987), was the main source of information for the two first sub-sections. Studies that have applied the canard and three-surface configuration into the development of different conceptual aircraft are also presented. Finally, details will be given concerning existing aircrafts that are using those configurations and that are the most similar to a jet aircraft. One goal of the literature review is to give an idea about what kind of results could be expected, and allow for a better comparison between this research project and past work.

1.1 The canard configuration

The canard configuration consists of moving the aft horizontal stabilizer forward of the main wing at the fuselage nose. At his new location, this surface is called a canard or a foreplane. It's important to not confuse this configuration with the tandem configuration that uses two wings of approximately the same size. In the canard configuration, the foreplane area is smaller than the main wing and it is mainly used for control purposes although it may carry a significant fraction of the total aircraft lift. For typical transport aircraft applications, the configuration uses a long-coupled canard, i.e. it has a long moment arm, more than 300% MAC, between wing AC and canard AC.

The key element of the canard configuration is that the foreplane surface is generating upward lift during all flight phases. It solves a main drawback found on conventional aircraft where the tailplane is almost always producing negative lift to balance the moment about the CG. This negative tail lift must be compensated by additional wing lift, causing the wing to operate at higher CL and also responsible for increasing drag. The stability behavior of a canard aircraft is the main reason explaining why all lifting surfaces are constantly uploaded. Since the foreplane is strongly destabilizing the aircraft, the CG has to be set at a very forward location relative to wing AC in order to make the aircraft stable, having the consequence of making all lifting surfaces generating upward lift. This CG location is also responsible for other important aspects of the canard configuration.

First, it leads to a high loading of the canard and causes it to operate at a higher local CL than the main wing for a typical configuration. A possible disadvantage caused by a highly-loaded canard is an increase of total drag, mainly because this lifting surface is generally less efficient for lift generation than the main wing. Therefore, in order to ensure an efficient canard surface, it would have to feature a high aspect ratio with a lift distribution that will minimize drag, i.e. high Oswald factor.

On the other hand, a canard aircraft is a more stall-proof design than the conventional configuration due to the fact that the highly-loaded foreplane stalls before the main wing. When the canard stalls, the aircraft nose drops, therefore it creates the nose-down attitude necessary for the recovery. This stall progression pattern allows limiting the maximum possible AoA, whereby the aircraft cannot be forced to exceed an AoA which could results in unsafe flying qualities. During design, particular attention must be given to this feature and also to the canard stalling behavior, like a smooth decrease of lift at stall AoA. This is because if the main wing is to stall first, recovery would be nearly impossible. The stall-proofing represents an advantage in flying qualities more than safety since a conventional aircraft is as safe as a canard one.

Another important aspect regarding the canard configuration is the aerodynamic interference between the canard and the main wing. Both lifting surfaces have an influence on the other one. Mainly, it consists of a significant downwash on the wing and a small upwash on the canard. This mutual interference points out a more complex sizing of the canard and the wing. The wing needs to be specifically designed to operate in the canard downwash to obtain a good level of performance regarding drag at cruise. On a conventional aircraft, the only interference effect is a significant downwash on the aft tail. Another possible form of interference is the one between the canard and the engines. It's preferable to have an arrangement that minimizes disturbances on the airflow going into the engine, especially in the case of turbofan engines.

The high canard loading and a downwash on the wing are two factors that are limiting the aircraft capability to achieve high CLmax. The foreplane must be designed for high CLmax. Since the usable maximum lift of the main wing will most likely be lower for this configuration due to the reduced inboard lift caused by the canard downwash, the integration and the usefulness of high-lift devices is questionable. Although a simple or no high-lift system at all on the main wing could save weight, the resulting low CLmax of this configuration is definitely considered as a drawback that needs to be taken care of in the design of a canard aircraft.

To obtain and maintain the forward CG necessary for stability, it requires balancing the aircraft in a very different way. Compared to a conventional aircraft, the main wing moves aft and the payload is situated at a location forward of the wing. This unconventional balancing brings the aircraft CG more aft than a conventional aircraft in terms of absolute location for a constant fuselage length. It then shortens the vertical stabilizer moment arm, thus requiring a larger area to achieve the same level of lateral stability and control. Fuel storage and management is also an important concern for a canard aircraft. As for most aircraft, fuel is normally kept close to the zero-fuel CG. This is to minimize the travel of the CG when fuel is loaded or burned. Because the main wing is located at a very aft location, having the total amount of fuel inside of it is not the best solution for this type of aircraft, especially in the case of an aft-swept wing. Some methods to bring fuel CG closer to aircraft CG are: forward auxiliary fuel tanks or a modified wing planform with leading edge extension at wing root. Unsurprisingly, the integration of the main landing gear will be much more unconventional due to this forward CG location. In the case of a low-wing canard aircraft, the design of a wing box integrating the main landing gear, and all or some of the fuel tanks represents a technical challenge in the detailed design of a canard aircraft.

A summary of the previously described advantages and disadvantages is given in Table 1.1.

Table 1.1 Summary of the canard configuration advantages and disadvantages

Advantages / Potential improvements	Disadvantages / Potential problems
➢ No negative lift / Wing area reduction – Lower drag ➢ Canard stalls first / Stall-proof design	➢ High canard loading / Low aircraft CLmax if canard CLmax is low – Higher drag – High foreplane weight ➢ CG travel and forward location / Balancing problem (fuel, payload, etc.) ➢ Forward CG / Integration of main landing gear and fuel tanks (low-wing aircraft) ➢ Important interference effects / Difficult design of wing and canard – Higher drag ➢ Large reduction in vertical stabilizer moment arm / lower lateral stability – Bigger vertical stabilizer (increase wetted area, more weight, more drag) ➢ Canard tip vortices / Significant challenge for engine integration ➢ Large foreplane / Structural integration of canard into the forward fuselage – Operational challenges on ground ➢ Foreplane is highly destabilizing / May require active stability and control

1.2 The three-surface configuration

The three-surface configuration simply consists of adding a third plane forward of the main wing to a conventional aircraft. The addition of a third lifting surface extends the number of design possibilities. For example, the canard can be fixed or variable incidence with or without elevator/flaps, etc. It can also be a free-floating canard depending on the function to be accomplished by the canard, whether it is lift generation for control or for drag minimization. The same kind of variation can be applied to the aft tail, although it's more likely to keep its conventional role.

The three-surface configuration has the same benefit as the pure two-surface canard aircraft: generating upward lift on the foreplane and the main wing. This allows reducing the required negative lift on the horizontal tail. It can be argued that the presence of the canard may lead to a reduction in wing area even though the canard/wing interference is still present. The stall-proof design is less true for three-surface aircraft because the canard and the main wing can be designed to partially or completely stall at the same time if the aft tail remains effective for recovery.

Similarly, it is possible to say that most of the design challenges presented by the canard configuration are reduced since the three-surface is more comparable to the conventional aircraft (smaller canard, less destabilization, CG closer to main wing, etc.). However, with the large flexibility in the design, the complexity of such aircraft may have a significant impact on operating cost, reliability and as well as more difficulty in the certification, which is applicable to most unconventional aircraft configurations. A promising concept applicable to medium and large aircraft is the one using a variable incidence mechanism on the canard and on the tailplane. With this system, multiple trim settings for the canard and the tailplane exist. It allows always having the best possible lift distribution between all three surfaces for all CG locations. Such a three-surface concept may achieve lower drag mostly by reducing the part of drag associated to trim, called the trim drag. This represents a potential advantage over any two-surface configuration for which (trim) drag is usually minimal only at one single CG location.

Globally, the three-surface configuration is a sort of compromise between the conventional and the two-surface canard; it may be able to combine the best of both configurations. That is why this configuration is more advantageous than the canard configuration when comparing Table 1.1 and Table 1.2. In addition, the three-surface has about the same number of disadvantages but they are reduced compared to what they were for the canard configuration.

Table 1.2 Summary of the three-surface configuration advantages and disadvantages

Advantages / Potential improvements	Disadvantages / Potential problems
➢ Three lifting surfaces available for lift and control / Greater design flexibility – Large CG travel could be achieved if needed ➢ Two surfaces for trimming / Possibility to design the aircraft to minimize drag for all CG locations (trim drag reduction) ➢ Less negative lift on the aft tail / Wing area reduction – Less drag	➢ Three surfaces available for lift and control / More complex aircraft – Higher cost ➢ Medium-high canard loading / Higher drag ➢ Small interference effects / Difficult design of wing and canard – Higher drag ➢ Small interference effects / Difficult design of wing and canard – Higher drag ➢ Small reduction in vertical stabilizer moment arm / lower lateral stability – Bigger vertical stabilizer (increase wetted area, more weight, more drag) ➢ Canard tip vortices / Challenge for engine integration ➢ Small foreplane / Structural integration of canard into the forward fuselage – Operational challenges on ground

1.3 Past studies

Although the idea of the foreplane is a very old concept, some of the most valuable source of information was found in papers written in the 80’s, a decade where many good studies about this subject were conducted by multiples sources including NASA, researchers from university, and some aerospace companies.

Since the configurations under study, as well as the conventional one, are multiplane aircraft that experience interference between each lifting surface, it is important to recall two old aerodynamic theories: the Prandtl biplane theory (Prandtl, 1924) and the Munk’s stagger theorem (Munk, 1923). Prandtl examined the induced drag of two wings, one over the other, and derived a simple equation, eq. (1.1), to compute the total induced drag from the self-induced drag of both wings in isolation with the increase associated to the mutual interference. D_i represents the induced drag, L is for lift, q is the dynamic pressure, and b is span. Subscript letters w and c are used to identified values of wing and canard respectively. σ is a factor obtained from a chart given by Prandlt and based on the span ratio and vertical separation (gap).

$$\mathrm{D}_i = \frac{1}{\pi q}\left(\frac{L_w^2}{b_w^2} + 2\sigma\frac{L_w}{b_w}\frac{L_c}{b_c} + \frac{L_c^2}{b_c^2}\right) \tag{1.1}$$

The middle term inside the parenthesis represents the part of the induced drag associated to the interference between both surfaces. Munk stated that the induced drag of multiple lifting surfaces remains the same when any plane is moved in the streamwise direction if the lift distribution is kept constant on all surfaces.

Even if the two theories were developed during the biplane era (1915 – 1930), they are still in use. Kroo has revised and applied those theories to compute the minimum induced drag of canard configuration (Kroo, 1982). A revision was necessary because those theories are assuming elliptical lift distribution on each lifting surface, which is not valid in the case of the canard configuration. Kroo assumed an elliptical lift distribution on the foreplane and analytically computed the required wing lift distribution to achieve minimum total induced drag. Referring to Munk's theorem, he also stated that the minimum induced drag occurred when the total lift distribution is elliptical in the case of a zero-gap canard/wing configuration. The Prandtl original biplane formula was adapted for this optimized canard configuration; a new interference factor, σ_*, was added to account for the non-elliptical loading of the wing.

$$\mathrm{D}_i = \frac{1}{\pi q}\left(\frac{L_w^2}{b_w^2} + 2\sigma\frac{L_w}{b_w}\frac{L_c}{b_c} + \sigma_*\frac{L_c^2}{b_c^2}\right) \tag{1.2}$$

Applying equation (1.2) with the corresponding chart for σ and σ_* given in Kroo's paper to different span ratio and lift share ratio indicates that:

- The original Prandtl equation, with σ_* equal to one, largely over predicts the induced drag compared to the minimum value obtained using Kroo's equation;
- For a span ratio below 0.5, induced drag is minimal when the wing carries the highest fraction of total lift. The short span canard generates a lot of induced drag;
- For certain cases with zero and small vertical gap, interference effects can be beneficial: only a little increase of total vortex drag is observed compared to the induced drag with zero lift on the canard. This conclusion is different than the one from the original Prandtl for which, vortex drag are much higher for zero and small vertical gap.

Later, Kroo and McGeer made a comprehensive comparison between the canard and the conventional configuration by considering a simple lifting system of two surfaces with a fixed moment arm (McGeer and Kroo, 1983). They varied multiple parameters of this system like the span ratio, lift ratio, area ratio and they examined the performance assuming a constant level of static stability. Even though the study is theoretical, practical considerations are given on the feasibility of both configurations. For a canard aircraft, a small foreplane is better for CLmax but worse for minimum induced drag; a high aspect ratio on the canard is required to minimize drag. In most cases, the canard configuration is inferior and more sensitive to change from the design CL than the conventional configuration. Kroo and McGeer concluded that the canard configuration has a higher level of drag for the same weight and stall speed. From references (Kroo, 1995) and (Kroo, 1984), the same kinds of conclusions were found regarding the canard performance against the conventional. The canard system is more optimal when designed as an unstable aircraft (negative static margin); in this case, the canard aircraft could achieve performance close to the conventional configuration. The three-surface configuration was also studied in those papers. It says that the three-surface system is not experiencing the penalties associated with the canard system. However, no real performance improvements were found when compared to the conventional system.

P. Douglas Arbuckle and Steven M. Sliwa from the NASA Langley Research Center have worked on a practical application of the canard configuration (Arbuckle and Sliwa, 1985). They designed and optimized three configurations: canard, tandem and conventional. All targeted as a commercial aircraft of 200 passengers for the same mission, range of 3000 nm at Mach 0.80, with the same level of performance. The level of fidelity of their study is quite good – multiple effects were considered, like trim drag, weight, stability, trimmability at low-speed and take-off rotation. The comparison demonstrated that the canard aircraft is capable of achieving 2% lower operating cost. Final planform views are shown in Figure 1.1.

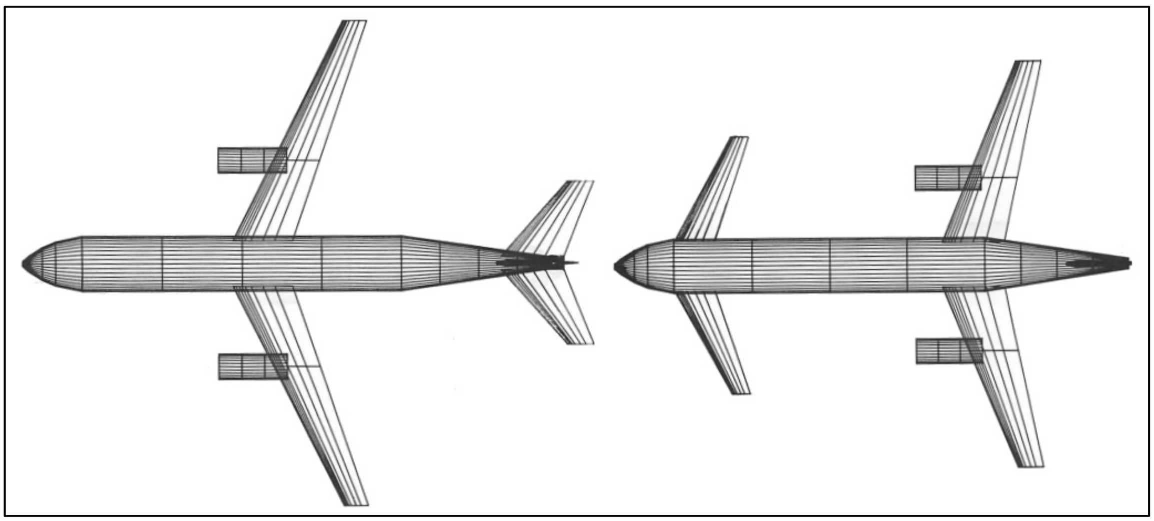

Figure 1.1 NASA Transport aircraft study, Conventional and canard planform view (taken from (Arbuckle and Sliwa, 1985, p. 19-20))

This result was made possible due to the relief of an important design limitations found on a canard aircraft. Canard CLmax was assumed to be equal to a very high value of 3.15, and no weight penalty was considered for the foreplane high-lift devices. Also, the main landing gear was free to move and no weight penalty was considered for fuselage strengthening. The maximum attainable lift coefficient problem is clearly identified as the most critical aspect in the design of a transport canard aircraft; the design is highly sensitive to this parameter. To make possible such high level of CLmax on the canard, it would require a complex flap system specially designed with the capability for active pitch control. In this NASA's study, it is stated that such system for a transport aircraft has never been designed or demonstrated.

However, a comparable system has been used on the Tupolev TU-144. This supersonic transport aircraft, similar the Concorde, had a retractable foreplane. The highly cambered canard was equipped with fixed leading edge slat and extensible trailing edge double-slotted flaps. It is important to say that the addition of the foreplane was only for the purpose of generating lift and nose-up pitching moment to improve field performance; there is no active control surface on the foreplane and the wing elevons have remained the control surfaces used for trim and pitch control. The CLmax of the TU-144's canard surface is said to be as high as three according to reference (Flight International, 1973). Figure 1.2 is showing a close view of the deployed canard with flaps extended.

Figure 1.2 "Retractable foreplane of the Tupolev TU-144" (cropped image)
by Leonid Kruzhkov is licensed under CC BY-NC-ND 2.0
(taken from (Kruzhkov, 2007))

Economically, the canard configuration is not superior to the conventional aft-tailed, since it would require more development work to only be slightly better in terms of performance. The only apparent complaint of Arbuckle and Sliwa's study is the lack of information on how the aircraft balancing was done (fuel storage, CG travel during mission, empty CG, etc.) and on the vertical stabilizer sizing.

It was found in technical papers and in books that making the gap and stagger as large as possible increases the aerodynamic efficiency. It minimizes the interference effect between the wing and canard allowing for lower induced drag and reducing the canard lift needed for trim due to a longer moment arm. Experimental results from Feistel, Corsiglia and Levin, 1981, (Feistel, Corsiglia and Levin, 1981), showed that a high canard has better lift characteristics, higher lift slope and CLmax, than a zero-gap or negative gap canard. Also, in the case of a zero-gap canard, the required lift distribution on the wing for minimum drag might be difficult to obtain in reality due to non-smooth airfoil-camber and twist distribution. However, for long-coupled canard aircraft, the effect of gap on aerodynamic performance is small, so this solution can still be considered acceptable if other constraints have to be met. For the canard configuration, span ratio, lift ratio and aspect-ratio ratio are the parameters having the largest impact.

Kendall has compared the three-surface configuration to the canard and conventional in references Kendall, 1980 and 1984. Based on an empirical analysis, he came to the conclusion that a three-surface airplane can attain minimum induced drag over a practical range of CG without compromising longitudinal trim and stability. The condition needed for minimum induced drag is to have equal and opposite trim loads on the canard and aft tail. A two-surface aircraft can only achieve its minimum induced drag at one CG location. The canard configuration has a higher level of drag than the conventional and three-surface configurations. Also, it is impossible to reach the minimum induced drag on a trimmed canard aircraft and be inherently stable. Kendall’s main conclusion is that the three-surface configuration may be better than the conventional design only for some specific applications designed for higher than normal trim capability, possibly required for a bigger CG envelope.

Rokhsaz and Selberg have conceptually designed general aviation aircraft with 6 and 12 seats using the conventional, canard and three-surface configuration, ref. (Selberg and Rokhsaz, 1986), (Rokhsaz and Selberg, 1986) and (Rokhsaz and Selberg, 1989). Assuming a constant total area for canard and/or tail and keeping the wing constant for all aircraft designs, they came to the conclusion that the conventional configuration has the highest lift-to-drag ratio and canard configuration has the lowest. The three-surface concept falls between the two other configurations studied. The only case showing different results is when the aspect ratio of the canard and/or tail was set to be twice that of the wing. In this case, the canard configuration has the highest lift-to-drag ratio followed by the conventional, and finally the three-surface. Similar results were found in references (Selberg and Cronin, 1985), (Keith and Selberg, 1983) and (Rokhsaz and Selberg, 1985). Another important fact about those studies is that the difference in aerodynamic performance between these configurations is small and for some cases it can be almost equal. It indicates that the choice of one configuration has to be made based on other considerations than only the lift-to-drag ratio.

Ostowari and Naik, 1988, performed an experimental investigation on a typical business jet, based on a Learjet wind-tunnel model. All three possible configurations were tested. Data was expressed relative to total planform area to make a fair comparison. The conclusion is in agreement with theoretical studies: the conventional configuration has the minimum drag coefficient at normal cruise CL. The three-surface has better drag characteristics at high lift but not at cruise. Canard has the highest (untrimmed) maximum lift, but remains the worst configuration in terms of drag at cruise. It's important to mention that these results are for untrimmed data. Considering a trimmed condition at a given CG with a positive static margin would have some impact on the numbers, especially for the canard configuration.

A practical application study of the three-surface configuration with a very good degree of fidelity was done by Nunes, 1995. He designed a regional three-surface aircraft of 50 passengers at a cruise Mach number of 0.80. The range was varied from 1000 to 3000 nm. Design included single-objective optimization for minimum MTOW and DOC. The three-surface configuration optimized for minimum DOC made it possible for a reduction of MTOW in the order of 2% to 4% compared to the equivalent conventional version. The DOC benefit for those optimized aircrafts was of 0.5% for the 1000 nm mission and was of 3.5% for the longest mission. Fuel savings were in the order of 5%. Very similar results were obtained for the MTOW optimization study.

Another application of the three-surface configuration to a large transport aircraft was realized by Wichmann, Strohmeyer and Streit, 2000. This conference paper presents the work of the DLR Project: "Three-Surface Aircraft" done at the German Aerospace Center. In this advanced study, two options were analyzed: addition of a canard to a reference aircraft, an Airbus 340-200 (retrofit case) and by resizing the tail and moving the wing (design case). Compared to the baseline conventional configured aircraft, final optimized results indicated an increase in aerodynamic performance: Mach-lift-to-drag ratio (Mach·L/D) increased by 1% and 2.3% for the first and second option, respectively. For the retrofit case, a consequence of adding a canard was to reduce the static margin of about 15-20% MAC. The design case was set to have a static margin of 10% MAC. Then, the reference conventional aircraft was redesigned with the same static margin as the three-surface design case. Both aircraft showed very similar Mach-lift-to-drag ratio. An important conclusion is that to achieve the potential benefit of the three-surface configuration, a free-floating canard has to be used. This type of foreplane does not influence the static stability since its "free" to rotate; it aligns itself with the local flow to produce a constant lift due to a constant local AoA.

One last study that is worth mentioning is Middel,1992. Although no final numbers were given about a reference conventional aircraft and a three-surface one, he developed a computer assisted toolbox for aerodynamic design of multi-surface aircraft. He also described the conceptual design procedure required for the three-surface configuration. His analysis suggested that the three-surface aircraft will find only limited application unless the usual prerequisite of positive static margin can be relieved. In other words, the three-surface configuration might achieve lower drag levels than the conventional one depending on the level of stability of the aircraft – including negative stability. It is also stated that the complexity of the necessary system to maintain optimal lift between canard and tail for drag minimization at all CG locations remains a questionable aspect in the design of such aircraft.

1.4 Existing canard and three-surface aircraft

The usage of a foreplane is more popular on military aircrafts. For supersonic airplanes, canard is mostly used for better manoeuvrability coming from the favorable interference between foreplane and wing at high AoA. For example, the Eurofighter Typhoon, a highly agile fighter jet currently in production, and the North American XB-70, a strategic bomber project dating from the 1960's, are both supersonic airplanes using a delta wing and a canard. Note that the XB-70 was a true canard aircraft since the foreplane was fixed, so used also at high-speed compared to the aforementioned Tupolev TU-144. In the general aviation and business aircraft market, only a few canard and three-surface aircraft have been designed and homebuilt or commercially produced over the last century: the Rutan VariEze, the Beechcraft Starship and the Piaggio P180 Avanti. These three aircrafts are the most comparable one to the actual reference aircraft used in this research.

1.4.1 Homebuilt general aviation canard aircraft

In this market segment, the VariEze is certainly the most famous canard aircraft. It was designed by Burt Rutan, an aerospace engineer, during the 70's. It's a single-engine pusher high-performance homebuilt aircraft. Shortly after its official unveiling at Oshkosh air show in 1976, it became a big success. The canard configuration allows the natural stall limiting feature, the most important innovation of this aircraft.

Figure 1.3 Rutan VariEze "Patrouille Reva" by Peter Gronemann is licensed under CC BY-NC-ND 2.0 (taken from (Gronemann, 2014))

As seen in Figure 1.3, this aircraft uses a high-aspect ratio rectangular canard to reduce drag. The wing is swept to increase stagger and to increase the moment arm of the large winglets used for lateral stability and control. The leading edge of the wing extends at the root to store the fuel at this location close to the aircraft CG. The fuselage has small cross-section due to the inline seating configuration. It doesn't have any high-lift systems. The main characteristics are given in ANNEX I.

The VariEze is entirely made of composite and is known to be light, fast and efficient, which explains why it is classified as a high-performance aircraft. The Delaminator, a modified VariEze made and piloted by Klaus Savier, won the Fuel Venture 400 of 2009, (Paur, 2009). This competition determines the most fuel-efficient general aviation aircraft. Although this victory cannot only be attributed to the canard configuration, it represents a good example of how efficient this type of aircraft can be. Since Rutan has stopped selling VariEze plans, multiple companies start using the exact same canard configuration (Cozy, Eracer and Velocity). The Velocity aircraft company, founded in 1984, sells different aircrafts as kit airplanes with all of them using the same canard design as the Rutan VariEze. Recently, they have designed a twin-engine version on which a single vertical stabilizer located on the aft-fuselage was used.

Even today, the VariEze remains one of the most unconventional and successful aircraft in this market. It well represents how brilliant and original the aircrafts designed by Burt Rutan were.

1.4.2 Beechcraft Starship

In the early 80's, the US aircraft manufacturer Beechcraft wanted to develop an advanced business aircraft to replace their older popular twin-turboprop, the King Air. They had the intention to compete with executive jets but at a much higher level of efficiency. The canard configuration was chosen mainly for its benefit of generating only upward lift. Since for this type of aircraft cabin noise is an important design criterion, the canard-pusher arrangement allows having the engine and props far aft which helps to lower noise level in the cabin. Burt Rutan, the expert of canard configuration at the time, was deeply involved in the design of the Starship; as he was consultant for Beechcraft. In addition, Rutan's company, Scaled Composites, built the 85% scale proof-of-concept prototype used for flight testing before going into production. As seen in Figure 1.4, the final layout is very similar to the Rutan VariEze except that engines were mounted on the wing.

Figure 1.4 "Beechcraft Starship at Oshkosh 2011" by Ken Mist is licensed under CC BY-NC-ND 2.0 (taken from (Mist, 2011))

Fuel is stored in the wing leading edge extension (two tanks on each side) and the wing has a special multi-spar structure to accommodate the retractable main landing gear, fuel tanks and engines. Another very important difference is the presence of a high-lift system. It consists of fowler flaps on the main wing and a variable sweep canard. The use of variable geometry on the canard was done to achieve better efficiency at high-speed and maintain adequate control and trim at all phases of flight. The canard not only changes sweep angle, the incidence angle increases and the dihedral angle decreases as the canard is unswept from 30° to –5°. This high-lift system is patented, (Rutan, 1987). As noted in the specifications given in ANNEX I, the difference in stall speed between clean and flaps-down configuration is only 5 knots for this aircraft; which demonstrates the low performance of this high-lift system.

During development, weight was increased due to some modifications needed for certification. Performance and fuel efficiency were not as good as initially planned. Some original specifications have been found in ref (Beechcraft, 2003) and they are significantly different than the one of the production aircraft.

With the high acquisition cost relative to other similar-sized business jet aircrafts and a low acceptance from the market, only 50 units were sold plus three prototypes needed for certification. At the beginning of the 2000’s, Beechcraft took the business decision to stop supporting the small fleet that was in service which marked the death of the Starship, considering most aircrafts were bought back for scrapping. Even though the Starship program was a financial failure, technically, it was a revolutionary design, not only due to the canard configuration but also for its high level of technology for this time (from ref. (Weems, 2009)):

- first certificated canard aircraft,
- first certificated pusher,
- first certificated all composite business aircraft,
- first certificated all glass cockpit.

1.4.3 Piaggio P180 Avanti

This aircraft is a three-surface pusher twin-turboprop executive aircraft. The Avanti was designed by Piaggio Aero Industries, an Italian aircraft manufacturer, in the 80’s and certified in 1990. Learjet had participated in the development of this aircraft. It’s very similar to the Starship in terms of range, seat capacity and cabin size. This European patented aircraft (European Patent 0084686, ref. (Mazzoni, 1987)) is still in production despite a slow start of sales and a change of ownership at the end of the 90’s. Other main characteristics are the high-aspect ratio wing with natural laminar flow, the low drag variable cross-section fuselage and the unconventional flap system necessary for the thee-surface configuration. Figure 1.5 is showing this aircraft in flight.

Figure 1.5 "Piaggio P180 Avanti" by Haz[a_a] is licensed under CC BY-NC-ND 2.0 (taken from ref. (Haz[a_a], 2010))

High-lift devices consist of inboard/outboard flaps on the main wing along with a third set of flaps located on the canard. They move sequentially to minimize change in pitching moment. The use of a fixed-incidence canard equipped with flaps to counter balance the nose-down moment due to main wing flaps extension appears to be a good and efficient design for this unconventional aircraft configuration. Flight controls are exactly the same as a conventional aircraft; the elevator on the tail remains the only control surface for pitch. Trim is achieved through the use of variable incidence horizontal tailplane. Specifications and performance are presented in the ANNEX I.

When comparing the Piaggio Avanti to the Beechcraft Starship using specifications given in Table-A I-2, it is clear that the Italian aircraft is superior as it is much lighter and has less engine power. The Piaggio is 19% lighter and has a flat-rated power 29% less than the

Beechcraft. It also flies faster, 17% more, and at a higher level of efficiency. In fact, it's the fastest turboprop aircraft currently on the market, and it's also one of the most fuel-efficient business aircraft.

A paper from Sacco and Lanari (Piagigo Aero Industries), 2005, gives important information about the design of this aircraft. The main reason why Piaggio choose the three-surface configuration over conventional configuration is to position the wing behind the cabin. Also, the aft location of the wing made it possible to mount it at mid-fuselage for structural synergism and improved aerodynamics (clean fuselage-wing intersection, no fairing, reduced frontal and wetted area). This unconventional wing location also allows improving passenger comfort due to a larger cabin room and lower noise level inside the airplane. The only problem of moving the wing aft is the CG location for different loading conditions. Since fuel and payload are far from each other, a large CG travel is expected. In the case of the Piaggio, it certainly wasn't a major issue since all fuel was kept at the wing location (inside the wing box and fuselage); no wing leading edge extension was necessary to achieve proper balancing of the aircraft as opposed to the Starship.

The efficiency improvement related to this aircraft compared to an equivalent conventional configuration was given in by Sacco and Lanari as drag savings.

Table 1.3 Drag savings breakdown for the Piaggio P180 Avanti (taken from ref. (Sacco and Lanari, 2005))

Forward wing	+ 7%
Main wing reduction	– 6%
Mid-wing and fuselage shape	– 3%
Trim drag	– 2%
Laminar flow	– 8%
Total drag reduction	– 12%

The net result of adding a foreplane is a small increase in drag (1%), but allows for trim drag reduction and for a mid-wing location which helps to reduce drag. Another key element of this aircraft is the laminar flow technology used on wing and canard. This technology, also applicable to conventional aircraft, has allowed an important drag reduction of 8% which represents more than the savings made possible by using the three-surface configuration. The Piaggio P180 Avanti is the best example of how great it is to apply the three-surface concept and other technologies into a business aircraft. Even though the configuration is unconventional, which leads to a distinctive appearance, this aircraft uses mostly conventional systems, like flight control, materials, structure is made at 90% of aluminium, and it has a great efficiency combined with good performance. With the important increase of fuel price in the last few years, it's not surprising to see that this aircraft is getting more popular than at its beginning. Piaggio has launched an updated version in 2014, the Avanti EVO; which has a better efficiency, reduced fuel burn, greater range and higher rate of climb, ref. (George, 2014).

CHAPTER 2

OVERVIEW OF AIRCRAFT CONCEPTUAL DESIGN PROCESS

Conceptual aircraft design involves many different disciplines that all need to be coupled together. It makes this engineering subject a complex task. Conceptual design generally dictates if the next design stage of aircraft development is started or not. The chances of success in meeting the requirements while achieving an attractive aircraft at a competitive sale price largely depends on design decisions taken at this early stage. Later, any modification becomes more and more difficult and expensive to do. The more details that are included, and the more advanced and accurate the computation methods are, the more trustworthy the final conceptual design will be. This safeguards against designing a paper aircraft that would turn out to be significantly different once the concept is developed into a real (detailed) aircraft and analysed with higher fidelity calculation methods. When stating conclusions about any conceptual aircraft, it’s important to keep in mind the level of complexity used in the process and to be aware of all hypotheses assumed; what would happen to the design if one or more assumptions are false? On top of that, design optimization, commonly known as Multidisciplinary Design Optimization (MDO), is affecting the final result depending on the objectives considered.

This project makes use of the process followed in the Advanced Design department at Bombardier Aerospace. It is considered to have a high level of confidence because it has been validated for most of Bombardier’s commercial and business aircrafts. The conceptual design process consists of multiple design tools developed over the years by the Advanced Design department. Each of them calculates specific aircraft characteristics and has its own limitations. Those tools can be used independently (manual operation) or together in an automated simulation environment (automated operation). The integration of those multiple separated design tools into a single design process, called a workflow, allows to rapidly produce an aircraft solution. Also, it is possible to explore the design space by varying one or more input values by manual iteration or by using an optimizer (MDO). The general design sequence followed in this project is given in Figure 2.1.

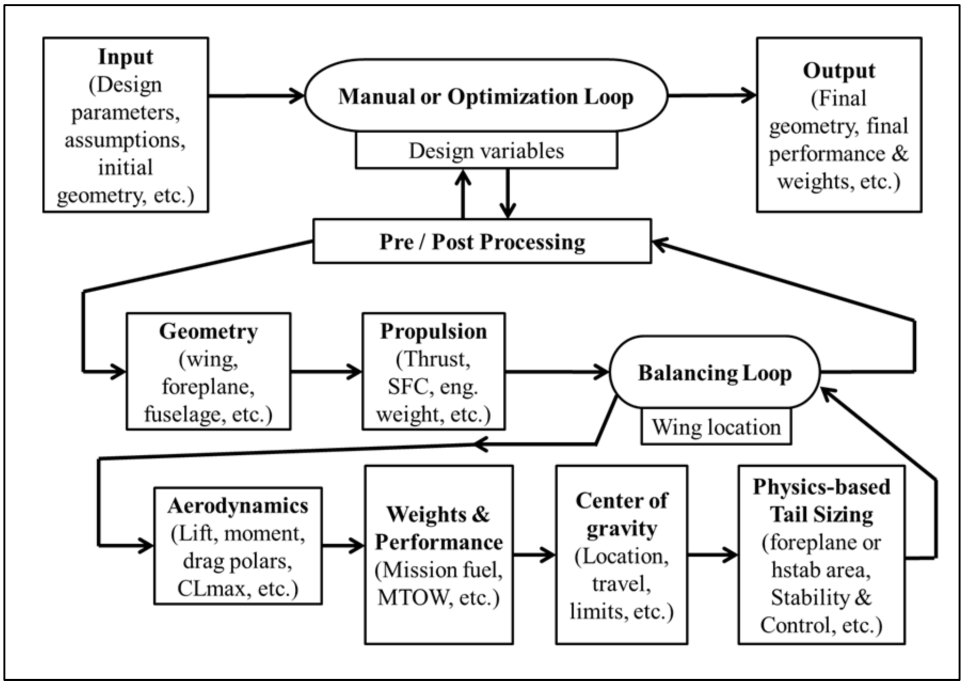

Figure 2.1 General design sequence (Workflow)

The process presented above starts with a set of inputs which includes the initial geometry and engine data, assumed values and constraints, calculation settings, and any other not-computed input data needed by tools. Then, this set of data is fed to a component that can change it, whether manually or automatically by an optimization algorithm. Values that are changed are called the design variables. An optimizer is used to systematically vary a number of design variables (wing area and AR, engine thrust, etc.) until a solution is found which offers a minimum/maximum value of the chosen design objective (e.g. minimize MTOW), while satisfying a number of design constraints (stall speed, TO field length, etc.).

The pre-process component consists of computing and updating the modified input data to obtain all the final common input data used by all tools. All other components represent the individuals design tools. The first one, Geometry, is another pre-processing step specifically for the geometry; detailed geometry is computed and defined, including wetted areas and airfoils. The Propulsion component simply computes the engine size, weigh, thrust and fuel flow. The new engine is based on an existing one and it is sized with an engine scaling factor (relative to maximum thrust).

The next components are included in the balancing loop because they required the final CG location and tail size to produce valid output data, explaining why an iteration process is used. Note that the first time the balancing loop is executed; it uses some assumed input data, like an initial tail size for example. The next component is Aerodynamics which computes drag polars for differents Mach number, CLmax, and all aerodynamic data for low and high speed and for each flap settings. Weights and Performance is used for the estimation of the aircraft fuel and weight, and the computation of all performance characteristics like the TO and landing field length. The CG component computes the final aircraft CG location for different loading conditions. The Physics-based tail-sizing component then determines the proper foreplane or tailplane using the aerodynamic, weights and CG data. After a couple of iterations (normally between three and five), foreplane or tailplane area and CG location have stabilized as well as all the output data of each tool in the balancing loop. At the end, a final post-processing of the output data is done. Then, design variables can be changed multiple times manually or by the optimizer depending on final results and constraints.

Starting from design tools applicable to conventional aircraft, made available by Bombardier Aerospace, some of those have been modified and validated for the two configurations under study. The update of the conceptual design process basically requires adding a foreplane and all its effects on aircraft weight, lift and drag. As identified in the literature review, sizing of the canard is more difficult than a tailplane for which the traditional volume coefficient method can be used with confidence. This simple sizing technique is using a constant coefficient, V_h, to determine the tailplane size, S_h, as presented by the equation below. MAC is the mean aerodynamic chord of the wing and LM_h is the length of the tail moment arm.

$$V_h = \frac{LM_h \cdot S_h}{MAC \cdot S_w} \tag{2.1}$$

For the foreplane, it was decided to not use the traditional volume coefficient method; a physics-based tail sizing was developed and implemented in the balancing loop. The aerodynamic data necessary for this tool is computed using Vortex Lattice aerodynamic computational software that has been validated using public wind-tunnel data and high-fidelity CFD-data produced by Bombardier. A weight estimation algorithm for the canard is also determined. Those modifications represent the most important one done to the original workflow. These tools are described in the next chapter. The complete update of the workflow has consisted to:

1. Add options for canard and three-surface configuration (in Input and Pre/post processing);
2. Add all the variables for the geometry of the foreplane (in Geometry);
3. Implement canard weight estimation (in Weights & Performance);
4. Implement low-speed aerodynamic tool (in Aerodynamics);
5. Implement physics-based tail-sizing tool (in Physics-based Tail Sizing);
6. Revise the aircraft balancing loop;
7. Implement all assumptions where necessary;
8. Create new links in the workflow for the canard (balancing tool, CD0 calculation tool, etc.);
9. Setup a basic optimization (MDO).

Individual tools were used in the phase 1 design, Section 4.2.1, and later the updated workflow was used in the second design phase, Section 4.2.2.

CHAPTER 3

TOOL DEVELOPMENT

3.1 Canard weight estimation

Even if a foreplane is geometrically similar to a horizontal tailplane, its structure needs to be stronger because it is operating at much higher surface loading. For this reason, a canard weight estimation algorithm was developed. Also, for a canard configuration, it may be good to choose an unswept foreplane, therefore a pre-validation of some weight estimations algorithm was done on most Bombardier aircrafts. A calibrated version of the Raymer horizontal tail formula (Raymer, 2012, p. 589), shown below, was found to be good for most tested aircraft including the Q400 turboprop aircraft which has a low-sweep horizontal tail. Calibration was done by changing some of the X_n factors compared to their original Raymer's values in order to minimize the prediction error based on Bombardier aircraft.

$$W_{\text{Hstab-Raymer}} = x_0 \cdot k_h \cdot \left(1 + \frac{Fuse_{width}}{b_h}\right)^{x_1} \cdot MTOW^{x_2} \cdot n_{ult}^{x_3} \cdot S_h^{x_4} \cdot LM_h^{x_5} \cdot k_y^{x_6} \cdot \left(\cos \Lambda_{h\,c/4}\right)^{x_7} \cdot AR_h^{x_8} \cdot \left(1 + \frac{S_e}{S_h}\right)^{x_9} \tag{3.1}$$

In the equation (3.1), W is the weight of the horizontal stabilizer, k_h is a factor for all-moving tail, n_{ult} is the ultimate load factor, S_h is the tail area, LM is the length of the tail moment arm, $\Lambda_{c/4}$ is the quarter-chord sweep angle, k_y is the aircraft pitch radius of gyration, AR is the aspect ratio and Se is the exposed area of the horizontal tail. Again, subscript h is used to refer to tail. The good correlation of the final horizontal stabilizer weight algorithm is demonstrated by Figure 3.1.

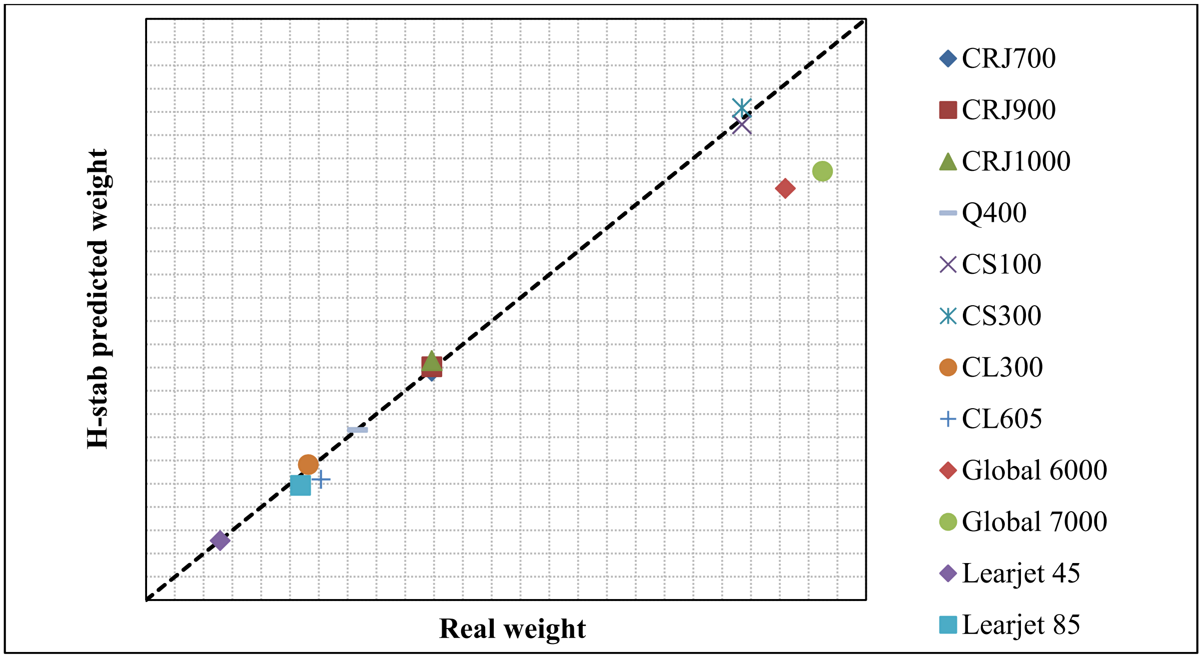

Figure 3.1 Predicted horizontal tail weight vs. real weight for some Bombardier aircrafts

Finally, to take into account the high surface loading on the canard, a mix between a wing weight algorithm and the Raymer formula was taken to estimate canard weight.

$$W_{\text{Canard}} = W_{\text{Canard as Hstab-Raymer}} + x_0 \cdot \left(W_{\text{Canard as Wing}} - W_{\text{Canard as Hstab-Raymer}}\right) \tag{3.2}$$

The factor x_0 in the equation (3.2) was set equal to 0.75 because canard weight will be closer to the estimation based on the wing weight algorithm. Even if this value was not validated, the final formula using this factor is considered to be acceptable to estimate the canard weight in the case of a high-speed jet aircraft.

3.2 Aerodynamic tool modification and validation

The tool used for this project is AVL, Athena Vortex Lattice. It is an aerodynamic computational software developed by Mark Drela and Harold Youngren, 2012. It is based on the Vortex Lattice Method (VLM), a potential flow theory (insviscid and irrotationnal flow). For this reason, it doesn't take into account any viscous effects. Compressibility effects are included with the application of a pressure correction, the Prandlt-Glauert transformation.

Thickness effects are also neglected since lifting surfaces are represented infinitely thin lattices of discrete horseshoe vortices, making this tool suitable for thin airfoils at small AoAs.

AVL is already known to work well for the conventional configuration; it has been previously validated using aerodynamic data of some Bombardier aircrafts. Thin lifting surfaces, small 3D interference between bodies and surfaces and a negligible contribution of the fuselage to lift and moment are the main reasons explaining the good performance of this computational tool. None of the limitations described in AVL's documentation are violated when used for a conventional aircraft. However, for canard and three-surface configurations, the VLM has to be validated. The information on this subject in the literature was found to be very limited. The canard strongly affects the wing flow (significant downwash in the wake of the canard) and it needed to be ensured that AVL reproduces this behavior, which is found on both studied configurations. Because of this lack of knowledge, and because accurate aerodynamic data is of paramount importance in aircraft conceptual design, a major validation exercise was done. AVL is also used to compute all longitudinal aerodynamic characteristics required for longitudinal stability and control calculations. The aerodynamic data is also used in the foreplane sizing process, described in Section 3.3.

The work consisted of modelling an aircraft in AVL, followed by running the code for multiple AoAs, extracting computed data, and post-processing the results. To compare experimental and AVL results, two approaches were applied: absolute and increment. The absolute method is simply to compare experimental and AVL values while the increment is for capturing the effects of a single parameter. One of the increment studies is to take a three-surface configuration and subtract a conventional configuration to obtain the effects of adding a canard (small increase in lift and large increase in moment). This second method can sometime give better results as it can cancel some of the discrepancy due to the fuselage for example. The fuselage was modeled in AVL by a non-lifting flat plate that generates a small amount of moment. Furthermore, it was verified that the number of AVL-panels was high enough to obtain accurate results that were independent of the number of panels used.

3.2.1 AVL modification and validation part I

The first part of the validation uses wind-tunnel data found in public technical literature. AVL was checked for lift, moment and static margin. Induced drag and lift distribution was verified in the second part of this validation. The four best papers found for this validation are identified as: Prague (Patek and Smrcek, 1999), NASA Langley (Owens, Coe Jr. and Perkins, 1990), Texas A&M (Ostowari and Naik, 1988), and Rutan VariEze (Holmes, Obara and Yip, 1984) and (Yip, 1985).

This first test case is an experiment done at the Aeronautical Research and Test Institute, Prague, Czech Republic (VZLU) in the 1.8 m low-speed wind-tunnel. The model is very simple and it was tested for all three different aircraft configurations: conventional, canard and three-surface. Table 3.1 gives the most important details of this test case. The AVL model is shown in Figure 3.2.

Table 3.1 General information of Prague case

Tested conditions	Reynolds number for wing M.A.C.: 335000 Assumed free transition	**Canard sizes and positions**	Single size 3 vertical locations 3 horizontal locations for a total of 9 positions
Tested configurations	Conventional Canard Three-surface	**Missing Information**	Nothing
Wing sizes and positions	Single size 2 vertical positions	**Results for valid comparison**	CL vs. alpha CM vs. alpha
Tail sizes and positions	Single size 4 vertical positions		

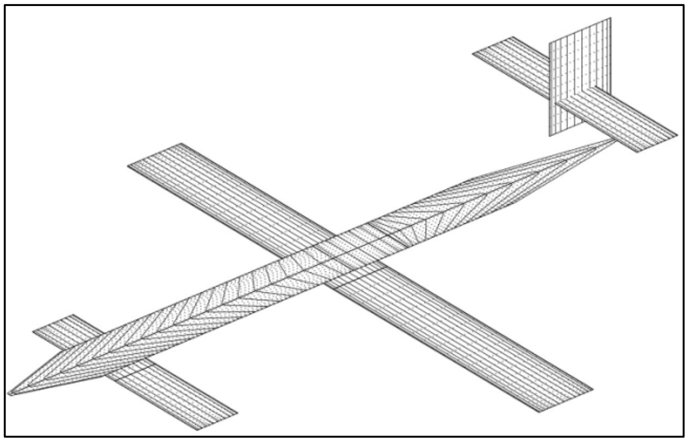

Figure 3.2 AVL model of the Prague case (Shown in three-surface configuration)

When comparing AVL results to experimental, presented in Figure 3.3 and Figure 3.4, lift is well predicted but not the moment. An important discrepancy exists for CM_0 and CMα which makes the static margin prediction wrong. Since airfoils are symmetrical, AVL predicts zero lift and moment at zero AoA, but the experimental data shows a positive CM_0. It's considered to come from significant thickness effects (mainly from the fuselage and the relatively thick wing (15%)) and probably from viscosity effects due to the low Reynolds number for this experiment. For those reasons, this test case was not considered an acceptable validation case for AVL.

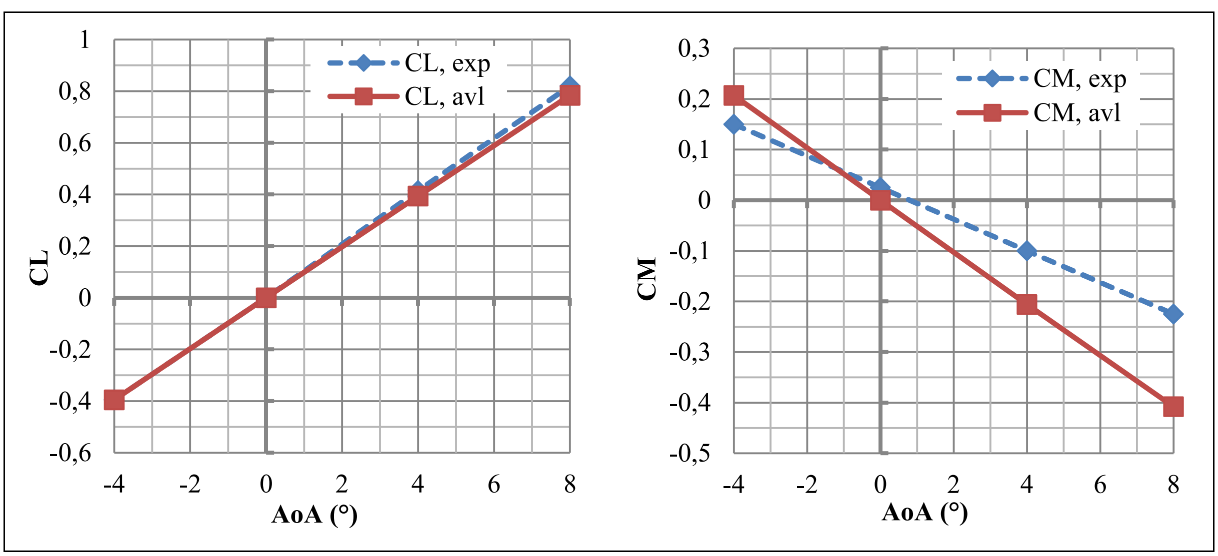

Figure 3.3 Prague – Conventional configuration results

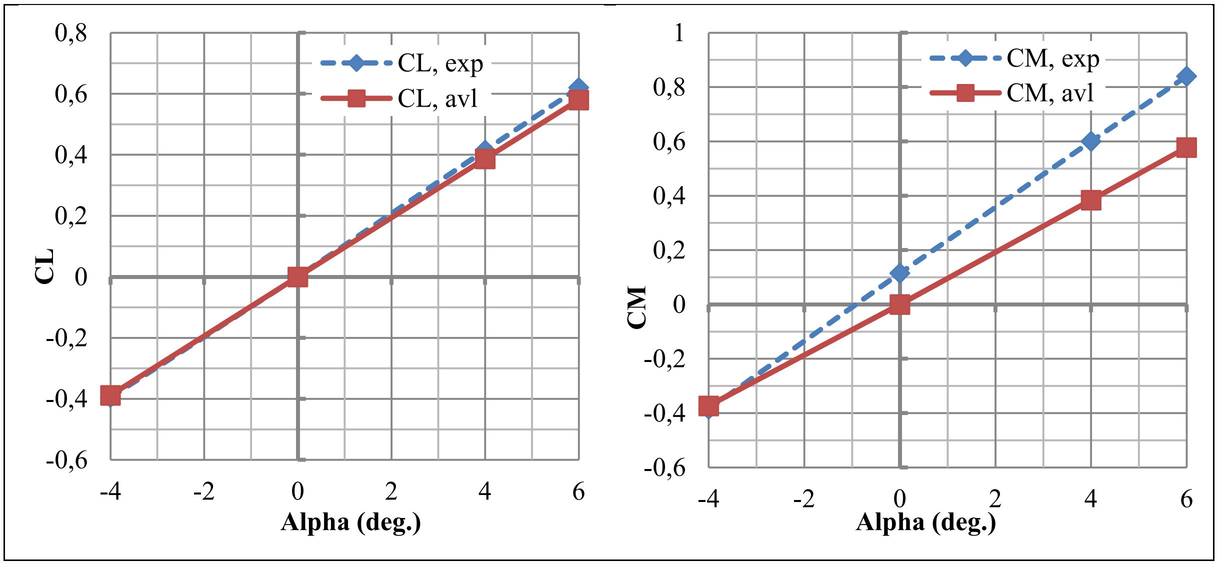

Figure 3.4 Prague – Canard configuration results

The second test case was done at NASA Langley's 12 foot low-speed wind tunnel. The 17.5% scale model is a three-surface, forward-swept wing, aft mounted, twin-pusher propeller. Table 3.2, Figure 3.5 and Figure 3.6 give the most important details of this test case.

Table 3.2 General information of NASA Langley case

Tested conditions	Reynolds number for wing MAC: 400000 Assumed free-transition	**Canard sizes and positions**	3 sizes 1 vertical location 1 horizontal location
Tested configurations	Wing-body Conventional Three-surface	**Missing Information**	Exact wing planform Wing chord inconsistency Pylon & nacelle incidence Canard geometry for the 2 largest sizes
Wing sizes and positions	Single size 2 horizontal positions		
Tail sizes and positions	Single size 2 vertical positions		
		Results for valid comparison	CL vs. alpha CM vs. alpha

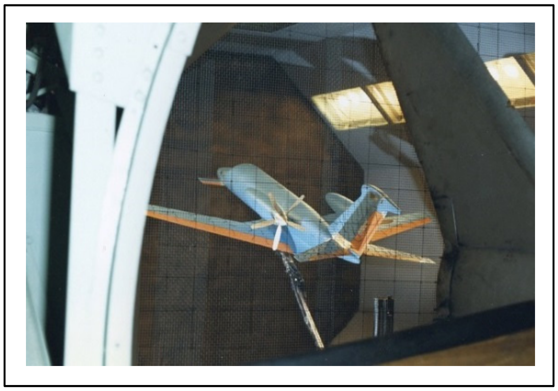

Figure 3.5 NASA Langley wind-tunnel model (taken from (NASA Langley Research Center, 1989))

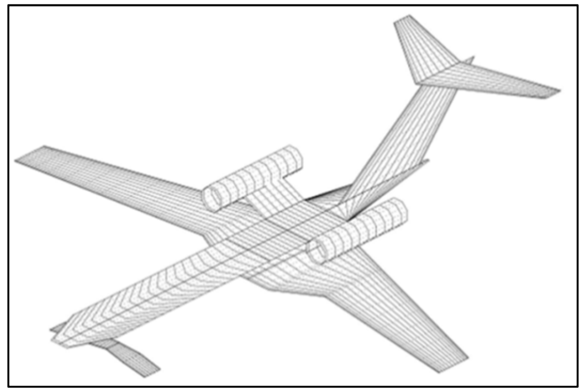

Figure 3.6 AVL model of the NASA Langley case (Shown in three-surface configuration)

An accurate AVL model of this aircraft was not possible due to the complex geometry and also because important information was not given in the paper (e.g. the exact definition of the wing planform). Results for the wing-body are presented in Figure 3.7. They show a small difference for lift and a significant discrepancy in moment. The absolute analysis of the conventional low-tail configuration didn't give better results for the moment. The static margin prediction was off by more than 10% MAC. The uncertainty in MRC location and wing planform, the presence of large nacelle just above the wing and the relatively low Reynolds number may explain the bad moment prediction and the small lift over-prediction of AVL.

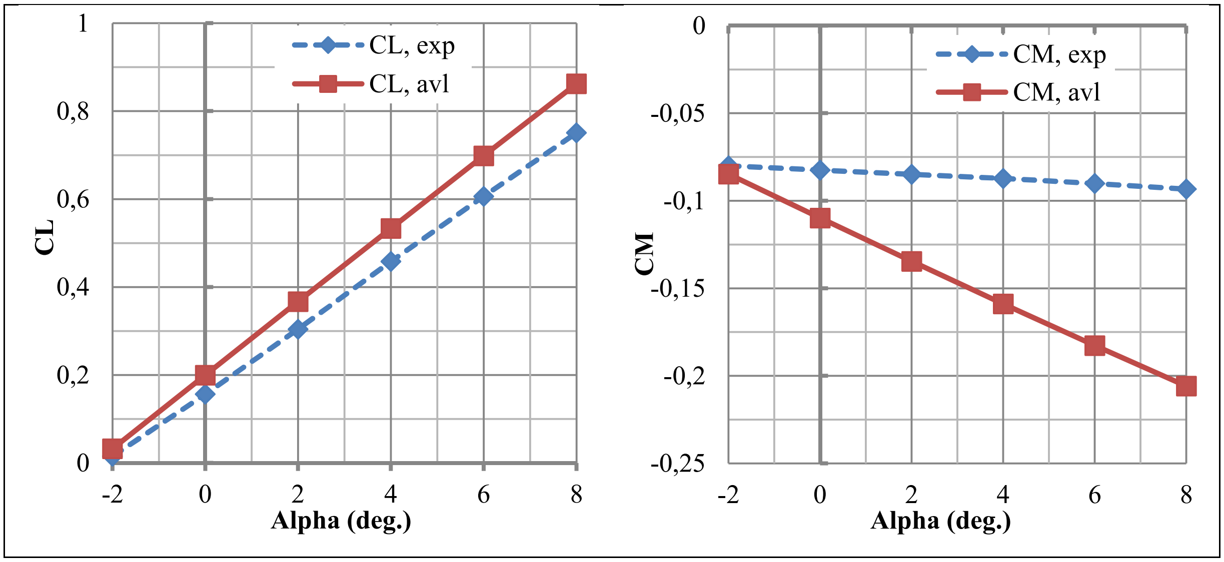

Figure 3.7 NASA Langley – Wing-body results

The increment study of the effect of adding a canard and a horizontal tail (three-surface minus wing-body, same MRC) gave better results. Note that some of those errors may also come from the poor quality of experimental plots. At least, the comparison of curves from a qualitative point of view indicates that AVL is capturing the increase in lift and the decrease in moment curve slope reasonably well. The trends in slopes are reproduced by AVL but the accuracy is barely acceptable. The best agreement is for the T-tail, Figure 3.8, while for the low-tail; there is a large discrepancy in CL_0 and CM_0. This is probably due to a stronger downwash-zero at the aft tail in the wind-tunnel than in AVL. It may be caused by the interference of the wing, pylon and nacelle. The low-tail horizontal stabilizer is vertically much closer to those structures than the T-tail which means that it operates in a more disturbed flow (wake of pylon and wing). Other increment studies with the two larger canard sizes and the low-tail gave slightly worse results. The curves were all similar to those shown in Figure 3.9.

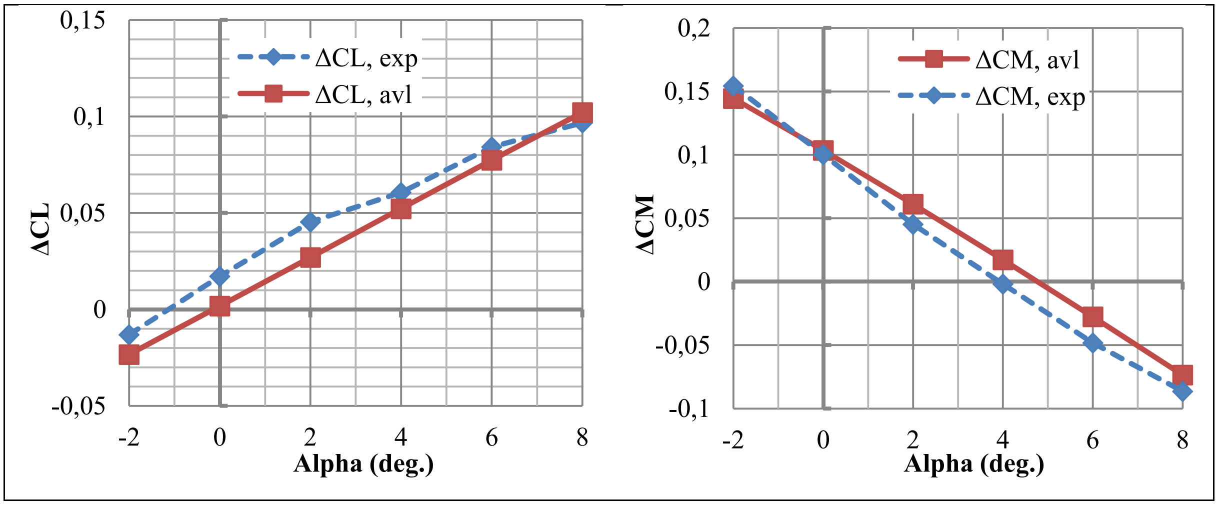

Figure 3.8 NASA Langley – Effect of adding the small canard
and the horizontal tail (T-tail)

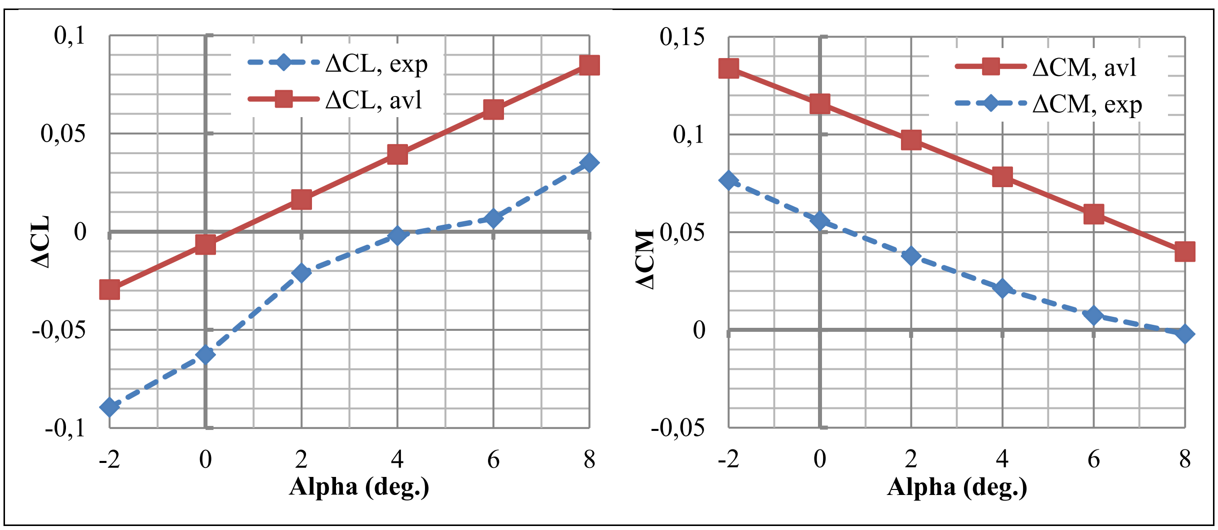

Figure 3.9 NASA Langley – Effect of adding the small canard
and the horizontal tail (low-tail)

The major problems with this test case are the poor quality of experimental plots, the uncertainty with the wing planform geometry and the low Reynolds number. This has reduced confidence in AVL’s ability to better match this experimental data.

The third test case is an experiment of a typical business jet 15% model provided by Gates Learjet Corporation. Testing was done at Texas A&M University low-speed wind-tunnel.

The quality of results is considered to be very good, since Reynolds was above 1 million, the model had thin airfoils and no engine or pylon. Table 3.3 lists the most important details of this specific test case. AVL model is presented in Figure 3.10.

Table 3.3 Texas paper General information

Tested conditions	Reynolds number for wing MAC: 1300000 Assumed free transition	**Wing sizes and positions**	Single size 2 horizontal positions
Tested configurations	Conventional Canard Three-surface	**Canard sizes and positions**	2 sizes (5% and 8% of area wing area) 1 vertical location 2 horizontal positions 3 incidence angles
Fuselage sizes	2 sizes Fuselage plug inserted between canard / wing	**Missing information**	H-stab moment arm Wing incidence
Tail sizes and positions	Single size 2 vertical positions 2 horizontal positions 1 incidence angle	**Results for valid comparison**	CL vs. alpha CM vs. CL

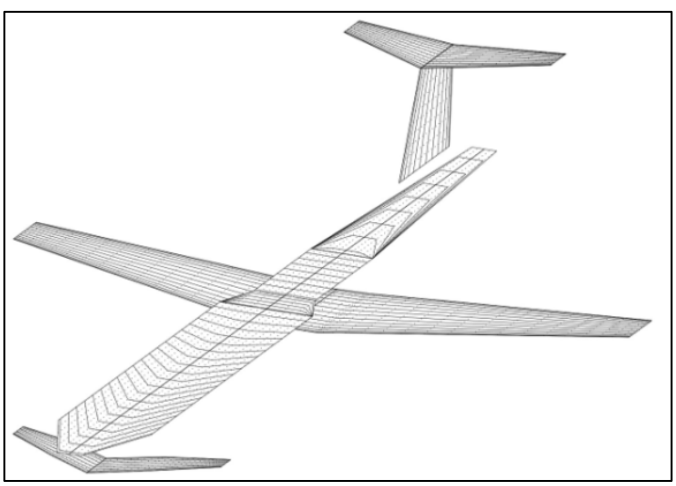

Figure 3.10 AVL model of the Texas case

Unfortunately, missing information led to an approximate AVL model, based on two assumed values for the aft tail moment arm and the wing incidence angle. A large discrepancy in lift and moment prediction for the conventional case is shown by the dotted line in Figure 3.11. It is considered to come from wrong assumptions made during the modeling of this aircraft in AVL. For this reason, it was decided to change the wing incidence and the aft tail moment arm to match the experimental data of the conventional configuration (calibration case). The required wing incidence angle was 1.6° and the horizontal stabilizer moment was reduced from 1.2 to 1.05 m. No change was done to the incidence angle of the aft horizontal stabilizer. This has led to the final AVL model which gives results identified with the solid line in Figure 3.11.

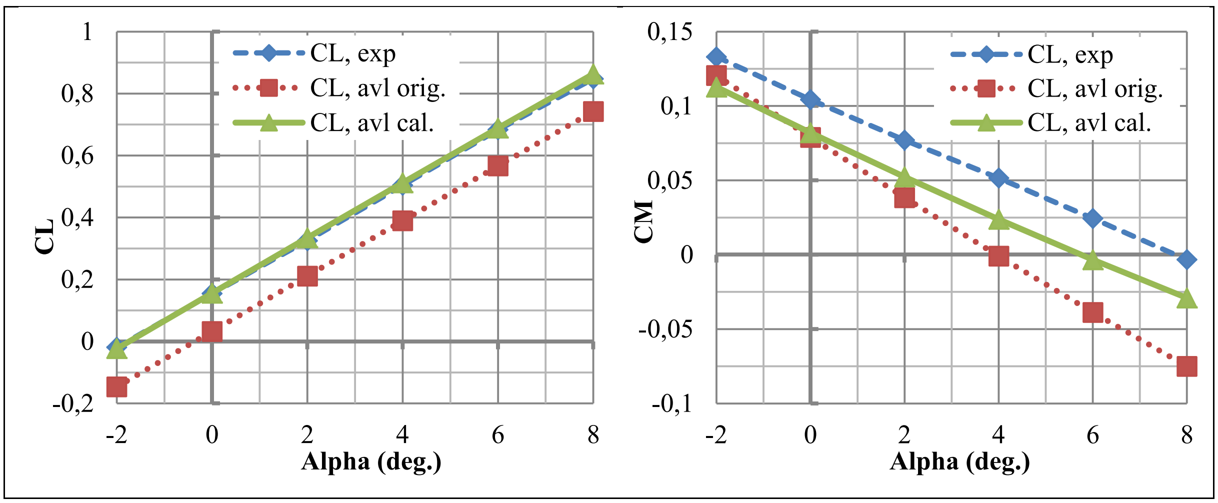

Figure 3.11 Texas – Conventional configuration results with and without calibration

The canard configuration gave good results, except for CM_0, and it uses the given canard geometry, including the given moment arm. All curves of Figure 3.12 are parallel and fully linear showing a good agreement and quality of the experimental results. The discrepancy with CM_0 may come from a difference in downwash at zero AoA due to the inability of AVL to reproduce any thickness or large 3D effects that may be present in the flow around fuselage and wing. Another reason for this difference may be the modification of the wing incidence and/or the tail moment arm. By changing those design parameters, it's affecting the amount of downwash on the aft tail at zero AoA, thus impacting the CM_0 value.

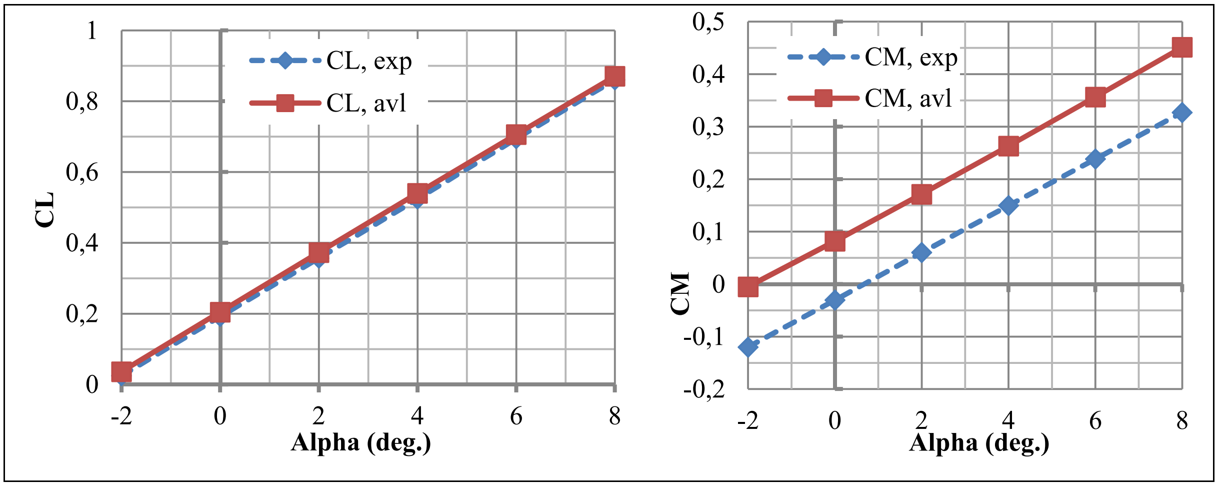

Figure 3.12 Texas – Canard configuration results

Most of the results for all tested configurations were as good the one presented in Figure 3.12 except for CM_0; the discrepancy remains present. Static margin predictions were also satisfactory, within an absolute error of 4% MAC. Incremental results were also calculated for different effects, like the effect of adding a canard, increasing canard area, moment arm, etc. The results were acceptable, although a significant difference was found in CL_0 and CM_0 which indicates a problem of AVL to not well predict flow conditions at zero AoA.

A main trend was observed for all cases using a foreplane: there was a small over-prediction of lift and increase in pitch-up moment due to canard that was too large. Since the beginning of this work, achieving a good canard lift prediction was identified as critical to obtain good overall results, especially for static margin. Furthermore, since the fuselage width over canard span ratio is a lot bigger than the one of the main wing, the fuselage-canard interference is probably more important and not well captured by AVL. To correct this problem, canard modeling was modified. Two calibration methods were tested based on the two different canard sizes tested in this experiment. The most accurate method found was to partially remove some lifting area of the foreplane, more specifically into the area covered by the fuselage. The quarter-chord sweep is also maintained at the same angle.

This technique allows reducing canard lift by changing the carry-over lift while keeping the same exposed area. Then, a calibration factor in percentage of removed area was determined by best matching lift and moment slope. All results were found to be improved when using the same calibrated canard for all cases. Based on results obtained with this paper, AVL proves to be good for prediction of lift and moment slope, but values at zero AoA remain a problem. At this point, because of those discrepancies at zero AoA and because the validation of drag and lift distribution was not done, the validation work was continued.

The last paper used in this validation exercise is about a full-scale wind-tunnel investigation of a general aviation canard aircraft, the Rutan VariEze, which has already been presented in Section 1.4.1. The experiment was done at NASA Langley's 30-by-60 Foot Tunnel. The quality seems to be very good, and the level of details of presented results is high. Table 3.4 lists the most important details of this test case.

Table 3.4 General information of Rutan VariEze case

Tested conditions	3 Reynolds Numbers: 0.6, 1.6 and 2.25 mil. Free/Fixed transition With and without leading edge droop	**Canard sizes and positions**	Single size 2 vertical locations 3 incidence angles 2 different airfoils
Tested configurations	Wing-body &Canard (+ measurement of lift and moment for the canard only)	**Missing information**	Inboard section of wing Wing tip airfoil
Fuselage sizes	Single size	**Results for valid comparison**	CL vs. alpha CM vs. CL CL vs. CD CL trim vs. CD trim Lift distribution
Wing sizes and positions	Single size Leading edge droop on / off		

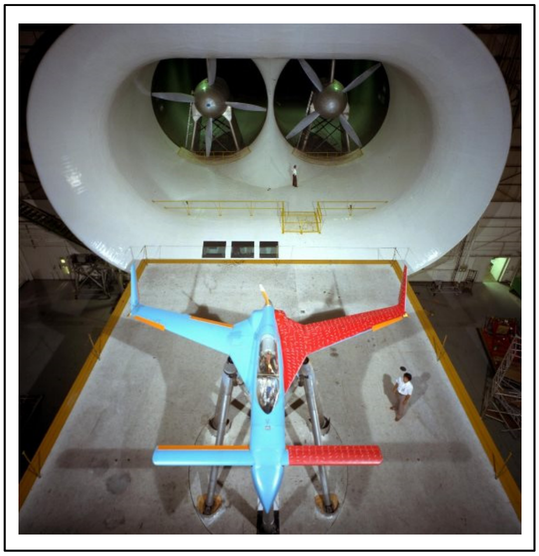

Figure 3.13 Rutan VariEze in the NASA Langley wind-tunnel (taken from ref. (NASA Langley Research Center, 1981))

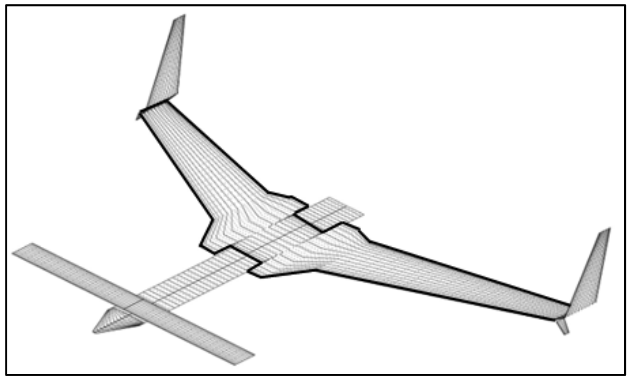

Figure 3.14 AVL model of the Rutan VariEze case

Due to the large crank at the leading edge and trailing edge of the wing root, AVL modeling of the wing was modified slightly from the real planform to avoid over predicting lift. Final modeling is presented in Figure 3.14 and the full-scale model in wind-tunnel is presented in Figure 3.13.

Figure 3.15 shows results for the wing-body. A significant difference exists at zero AoA. Experimental results were found to rapidly become non-linear compared to previous papers. An important change in lift and moment slope was occurring at an AoA of 4°. This can be directly observed on the experimental curves of the wing-body and the canard configuration, Figure 3.15 and Figure 3.16. In the paper, it is explained that this non-linearity was caused by the development of a spanwise flow due to wing sweep. The spanwise flow, starting at an AoA of 4°, is reducing the wing lift which increases the moment slope. For this reason, the studied linear AoA range was limited from -2° to 4°. In this range, AVL captures lift and moment slopes reasonably well.

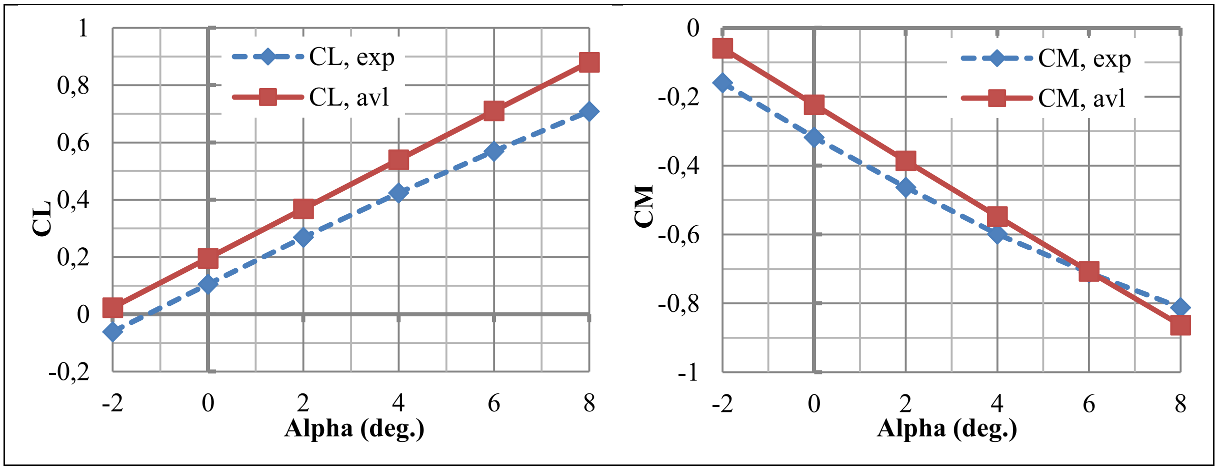

Figure 3.15 Rutan VariEze – Wing-body results

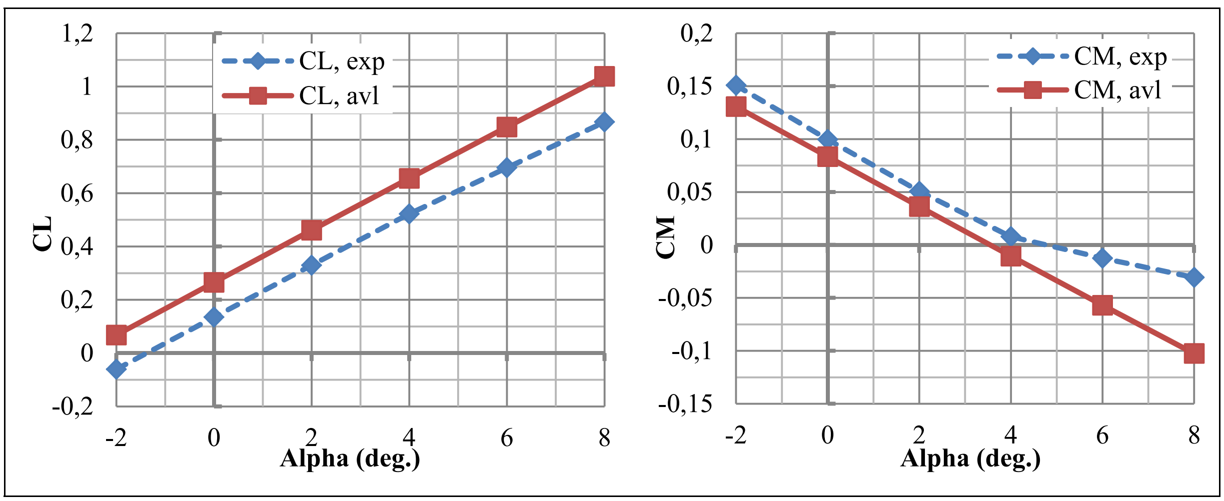

Figure 3.16 Rutan VariEze – Canard configuration results

Wing-body lift distribution was significantly different especially at the wing tip as observed on Figure 3.17. It may be due to an incorrect geometry (twist distribution) and to some 3D/thickness effect not reproduce by AVL due to the presence of the large winglet. At an AoA of 1.5 deg. the large upper winglet was negatively loaded, while in AVL was positively loaded (with the given incidence of 0 deg.). To better match the experimental lift distribution, it was decided to apply a symmetrical airfoil at wing tip (missing information) and the upper winglet incidence was reduced to -10 deg. (equivalent to a toe-out angle of 10 deg.). After these modifications, wing-body lift distribution showed good correlation with the experimental data.

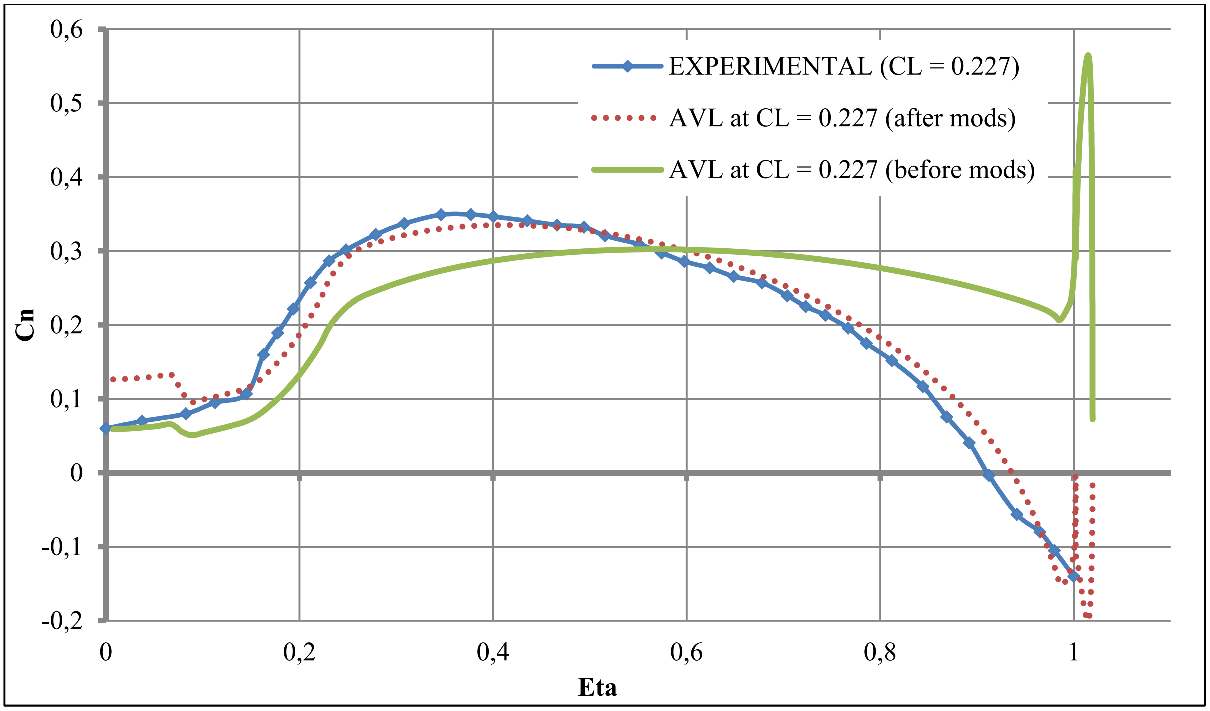

Figure 3.17 Rutan VariEze – Wing-body spanloads

When comparing spanload with the canard on and the modified wing-body, Figure 3.18, results were found to be acceptable for the wing but not for the canard. AVL largely over predicts canard lift. This result may come from the special airfoil used on the canard. Also, a problem with the experimental data was observed: when integrating canard spanload to obtain the total canard CL, it was significantly different from the value obtained directly from the CL-alpha experimental plot for the given AoA.

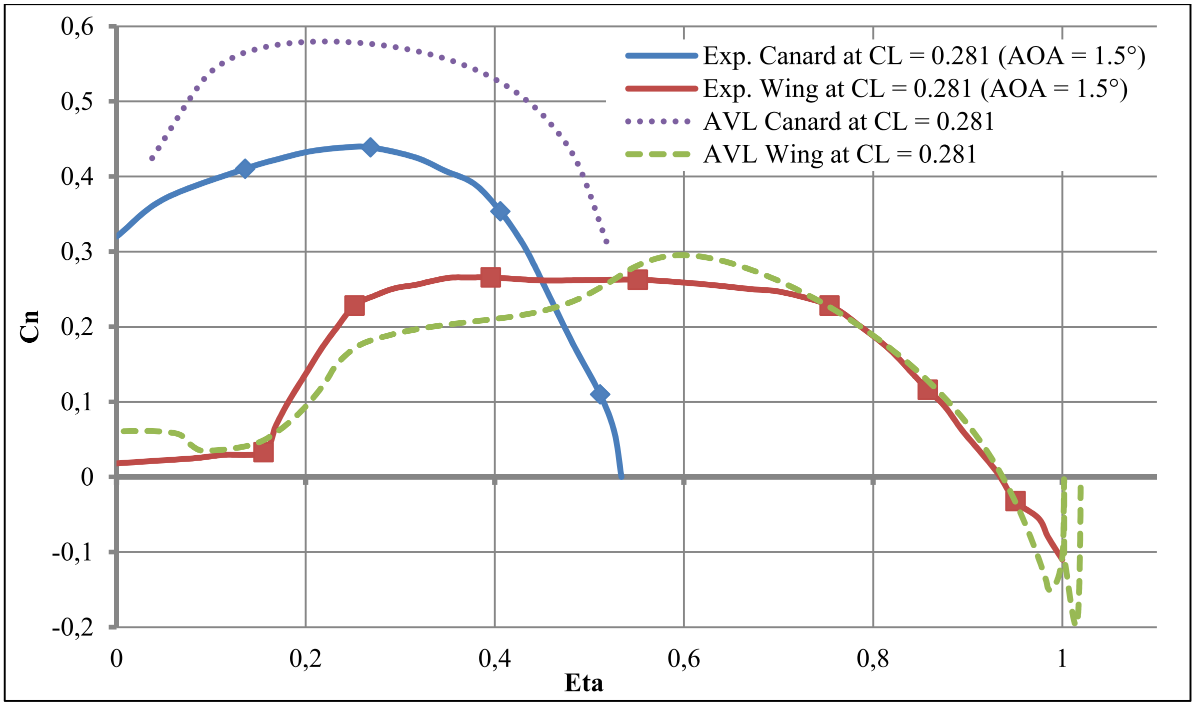

Figure 3.18 Rutan VariEze – Canard configuration spanloads

Even though some accurate drag polars were given in the NASA report, they weren't used for validation because of the initial poor results with the lift distribution. Finally, due to the thick and highly cambered canard airfoil, the considerable modifications required for matching the experimental lift distribution of the wing-body, the significant and early non-linearity in the experimental data and a large discrepancy with CL_0, the confidence in this test case is greatly reduced. However, it can be said that AVL may not be that accurate when the canard is large (25% of wing area and 50% of wing span), when a large winglet is used. In this situation, interference effects and 3D effects of canard on the wing are stronger.

Among all four papers tested, the Texas validation test case gave the best results, most likely due to the Reynolds number being above one million and having a clean-configured model. AVL was generally able to accurately predict lift and moment slopes. Values at zero AoA still need to be verified since those results were not acceptable. This validation work proved to be difficult to do without having good, accurate, complete and reliable experimental data. Most scientific papers don't have this level of quality and details. In most cases, uncertainties in geometry and/or experimental results were introduced due to missing information and poor quality of experimental plots. In some cases, the tested aircraft had some special characteristics other than just the canard. Therefore, to be able to complete this validation exercise, another experimental source with a complete, accurate and detailed dataset was needed. This, in turn, would allow to confirm the level of accuracy of AVL regarding lift distribution and drag, re-verify canard calibration modeling and to investigate the problem with CM_0.

3.2.2 AVL modification and validation part II

Due to the fact that no better experimental data was found, it was decided to generate aerodynamic data for a simple canard aircraft using high-fidelity analysis as a replacement of real wind-tunnel testing. The analysis used was a Navier-Stokes CFD simulation completed by Bombardier's Advanced Aerodynamic Department. The simulation parameters and geometry were set to be suitable for AVL: thin lifting surface, high Reynolds number and low AoA (flow separation has to be minimal). The aircraft used is based on the Bombardier research platform aircraft transformed into a simple canard configuration. To maintain a typical foreplane moment arm, a forward fuselage plug was added instead of moving the wing aft; to avoid having to redesign the belly fairing and also not to bring the engine too close to wing. Even if this model is not an optimized canard aircraft, it remains perfectly acceptable for validation purposes. The 3D model used and the AVL model are presented in Figure 3.19.

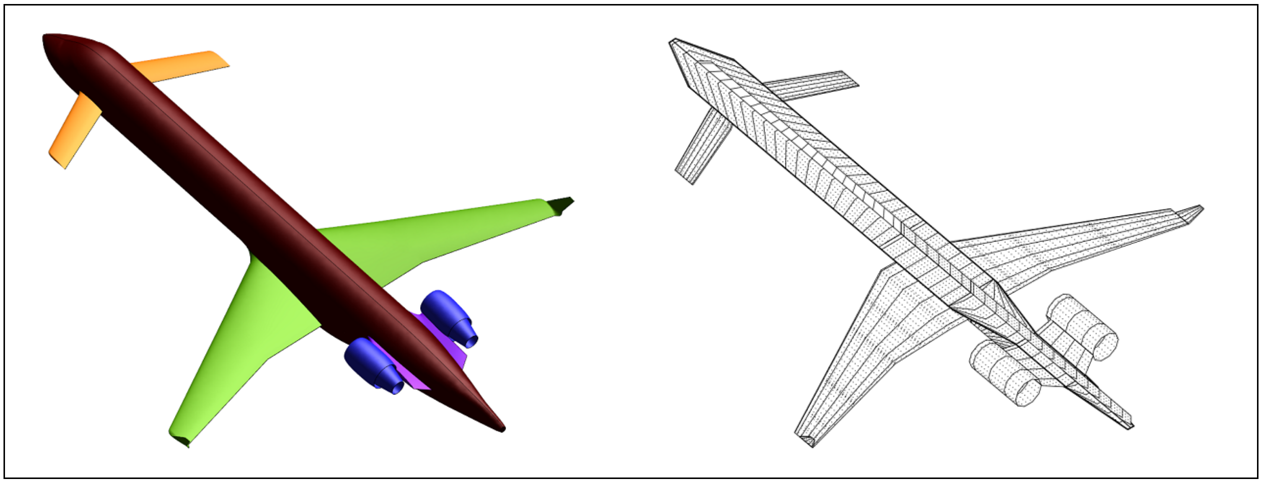

Figure 3.19 Canard research platform aircraft – 3D CFD Model and AVL model

A wide variety of cases were analyzed by Bombardier's Advanced Aerodynamic department to allow studying more complex aerodynamic characteristics, like the canard elevator effectiveness and the effect of changing the foreplane incidence angle. All cases used the mid-fuselage canard except the last one, which was done with a high-canard. For each of the eight cases, a brief description and the type of comparison analysis done between CFD and AVL can be found in ANNEX II.

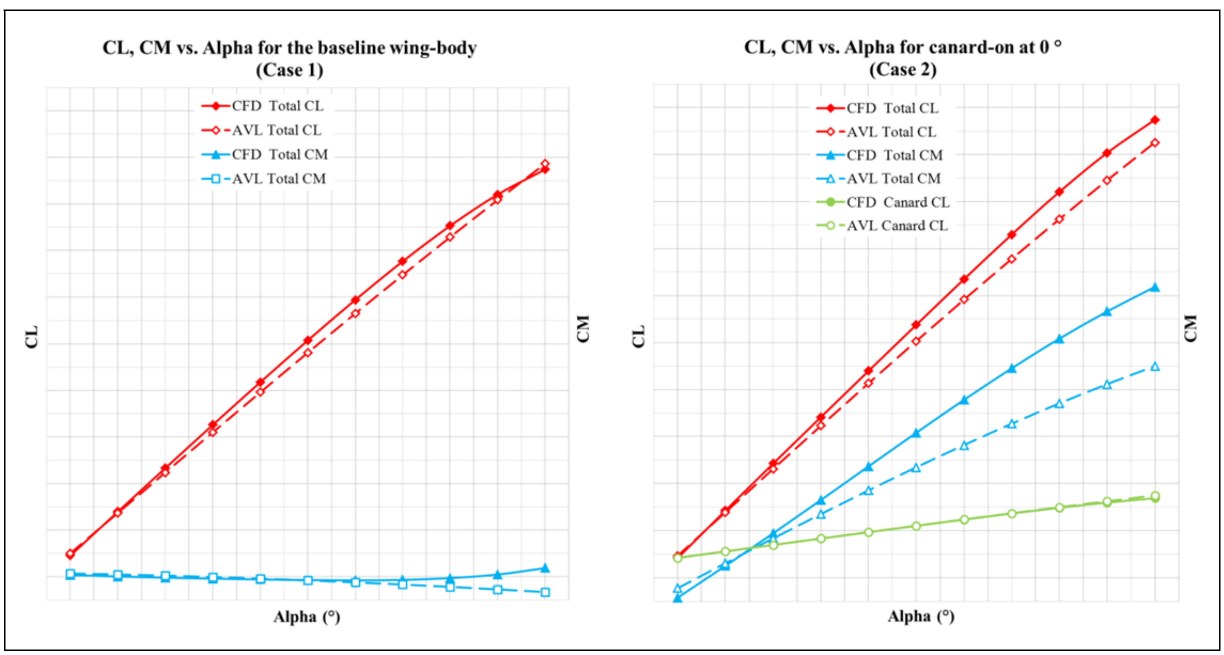

Figure 3.20 Canard research platform aircraft – Wing-body and canard configuration results

AVL predictions for the wing-body were acceptable as demonstrated by the results shown on the left of Figure 3.20. However, there was a small non-negligible difference in CL_0 and $CL\alpha$. Because this small discrepancy was present for most cases, all lift distribution comparisons were also done at equal total CL. As shown on the right of Figure 3.20, the first canard case gives similar results for total lift. An adjustment of the canard calibration factor was done to improve foreplane lift prediction. The calibration method used was previously described at the end of the Texas validation case in the previous section. The largest discrepancy is in the moment: AVL moment predictions are well below CFD data. A more detailed analysis of the results revealed that the stronger CFD moment was caused by the interference between fuselage and canard. Adding a foreplane at a mid-fuselage location affects the fuselage pressure distribution at the nose. Since the fuselage is considered as a flat plate in AVL, this interference effect is not present in AVL – vertical movement of the canard had almost no effect on fuselage moment. According to CFD results, there is a significant increase of fuselage moment slope with the canard located at mid-fuselage and a small increase when the canard is high. At this point, different canard modeling techniques were tested to see if moment predictions could be made acceptable without applying any manual correction to the results. Those different modelings were obtained by changing the canard planform inside the fuselage and keeping constant the exposed planform. But, no better solution was found because the moment discrepancy was important. The results needed to be corrected to obtain a satisfactory match with the CFD data. All cases having the canard located at mid-fuselage exhibit this strong interference leading to bad results for moment and static margins. A common correction dataset was computed by taking the mean difference between CFD and AVL results. Those correction values were then applied to all AVL's results. However, it was observed that varying canard area, moment arm, incidence angle or deflecting the elevator changes the magnitude of the canard-fuselage interference, requiring different corrections to obtain a good match in moment slope. In the end, a common correction and a specific correction for some cases, like the one with elevator deflected, was found to make AVL's results satisfactory. This, in turn, makes AVL not universal, and only applicable for similar canard/fuselage geometries.

Using CFD data from two cases, canard at zero and four degrees incidence angle, the canard effectiveness and the upwash gradient were calculated using the general equation of lift, equation (3.3).

$$CL = CL_{\alpha} \cdot \left(\alpha \cdot \left(1 - \varepsilon_{d,\alpha}\right) + i_c \right) + CL_0 \qquad (3.3)$$

$$CL_0 \text{ includes the effect of } \varepsilon_{d,0}$$

In the equation above, CL is the lift coefficient, α is the AoA, ε_d is the downwash angle and ic is the canard incidence angle. Subscripts α and 0 indicates gradient relative to AoA and values at zero AoA respectively. The same procedure was applied to AVL. Final results, presented in Table 3.5, were compared. Although AVL's individual characteristics like the effectiveness and the upwash gradient are not so good, the total effectiveness and CL0 are well predicted due to the recalibrated canard modelling in AVL.

Table 3.5 Canard research platform aircraft – Lift characteristics

Characteristic	**CFD**	**AVL**	**Error**
Canard effectiveness (CL_{α})	0.009	0.010	11.6%
Canard upwash gradient ($\varepsilon_{d,\alpha}$)	-0.482	-0.334	-30.7 %
Total canard effectiveness ($CL_{\alpha} \cdot (1 - \varepsilon_{d,\alpha})$)	0.014	0.014	0.5%
Canard CL_0	0.040	0.040	0.0%

Figure 3.21 and Figure 3.22 present lift distributions for the wing-body alone and the baseline canard; there is a good agreement between CFD data and AVL when comparing at same total CL.

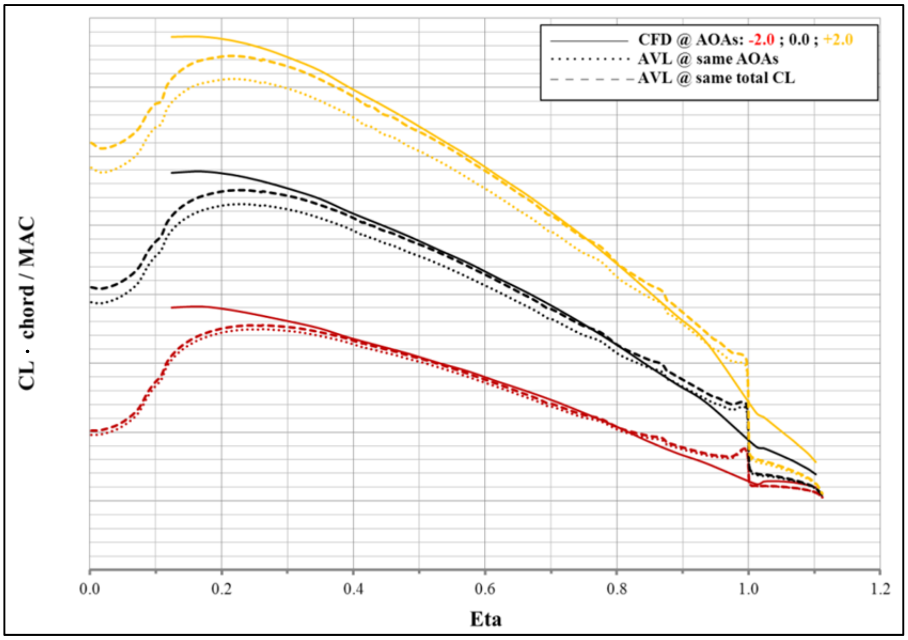

Figure 3.21 Canard research platform aircraft – Wing and foreplane lift distribution for the baseline wing-body case

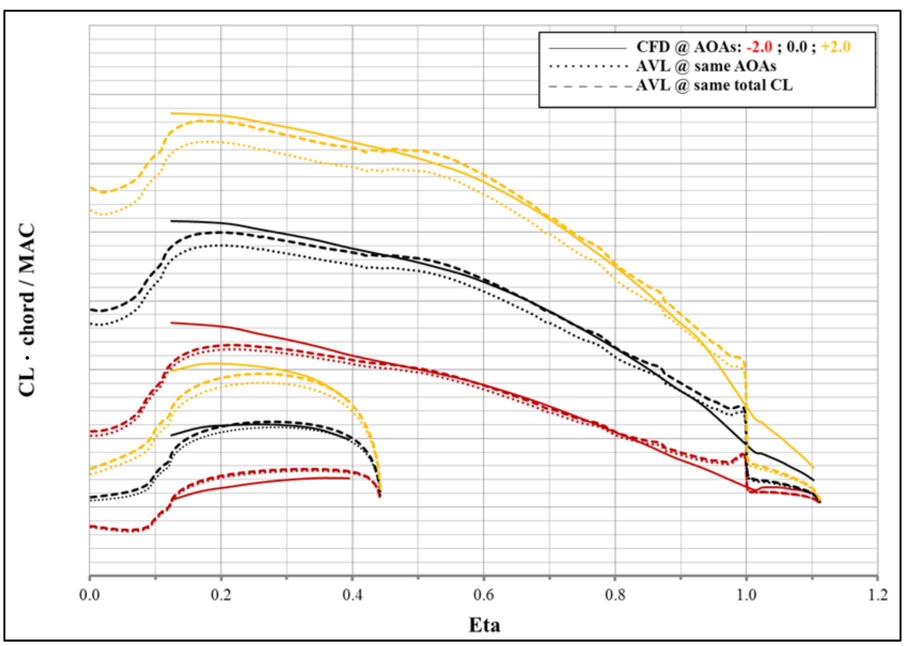

Figure 3.22 Canard research platform aircraft – Wing and foreplane lift distribution for the baseline canard case

The two locations where AVL has difficulty correctly predicting spanloads are at the wing tip and at the wing root: two regions where the flow is disturbed by the presence of the winglet and fuselage, respectively. As identified with the Rutan VariEze validation case, the presence of a winglet causes AVL to over predict lift at the wingtip. All other CFD cases confirmed that AVL is reasonably accurate in the computation of spanloads at low AoA. These good results indicate a good reproduction of the interference effects between canard and wing. This conclusion also applies to cases where the effect of canard downwash on wing is stronger, like the case with the elevator deflected presented in Figure 3.23.

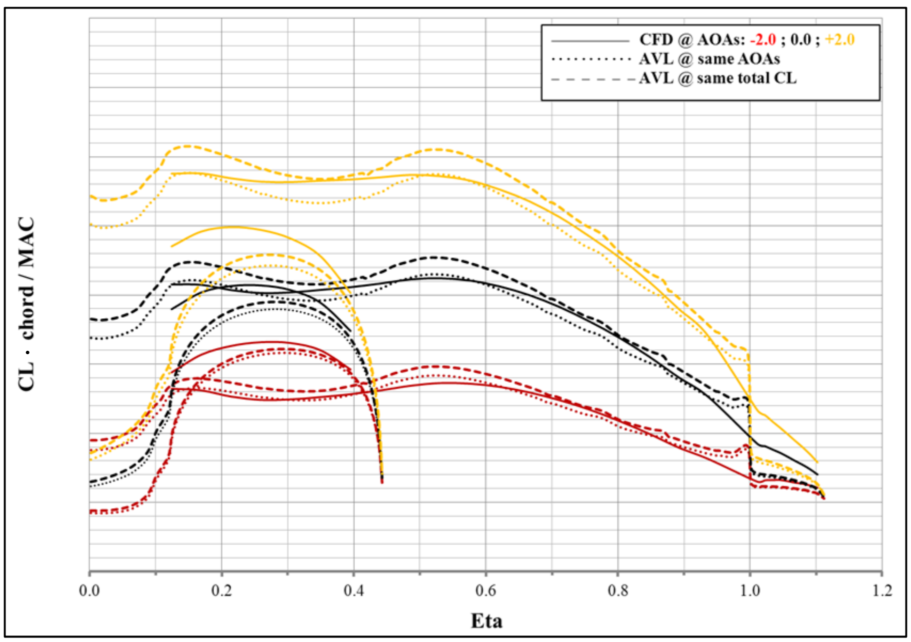

Figure 3.23 Canard research platform aircraft – Wing and foreplane lift distribution for the canard case with elevator deflected

AVL also has some problem with the lift prediction at the canard root when the elevator is deflected. The end-plate effect of the fuselage is not well reproduced in AVL due to the flat plate fuselage modeling. The lower predicted lift obviously affected the accuracy of the elevator effectiveness, which was found to be under predicted by 14%. This difference and the ones concerning the canard upwash gradient and the canard effectiveness will affect the calculated trimmed flight conditions obtained using the trim equations. However, no corrections were applied on those values because it was found that those small discrepancies have little impact on final trimmed results.

The next aerodynamic characteristic to be validated in AVL is the induced drag or more precisely the Oswald factor. Since AVL outputs CDi values for each surfaces defined in the model, *e* can easily be computed using the classical drag formula (3.4).

$$CD = CD_0 + CD_i = CD_0 + \frac{1}{\pi \cdot e \cdot AR} CL^2 \qquad (3.4)$$

For CFD, only the total drag coefficient is computed. Therefore, the Oswald factor was calculated based on the CL^2-CD slope (equal to $1/(\pi \cdot e \cdot AR)$) for the range of normal operating lift coefficient.

Table 3.6 Canard research platform aircraft – Oswald factors results

Case	***e*, CFD – e, CFD case 1**	***e*, AVL – e, CFD**
Case 1 – Baseline wing-body	XX.X% (ref. value)	0.6%
Case 2 – Baseline canard	-6.1%	-0.1%
Case 3 – Canard with increased incidence angle	-11.8%	0.6%
Case 4 – Closed-coupled canard	-8.4%	1.3%
Case 5 – Canard with elevator deflected	-13.7%	0.0%
Case 6 – Larger canard	-6.8%	-0.4%
Case 7 – Larger canard with reduced AR	-9.7%	2.5%
Case 8 – Canard located on top of fuselage	-4.1%	0.8%

Table 3.6 is presenting the span efficiency factor for all cases. The results are very good, as it was expected, as lift spanloads were all well predicted by AVL. In addition, AVL proved to be good in computing the CD0 increment due to a change in canard incidence angle or elevator deflection. Two methods were used to compare the CFD drag polar to the AVL one based on the standard drag formulation by using the computed AVL's Oswald factor and using the AVL's output CDi value. Both methods were found to be accurate in the normal CL range. Only a small gap in CD0 remains present between both methods. CD0 is not part of this validation because during the design phase, it will be computed using another tool. Figure 3.24 presents drag polars for the baseline canard.

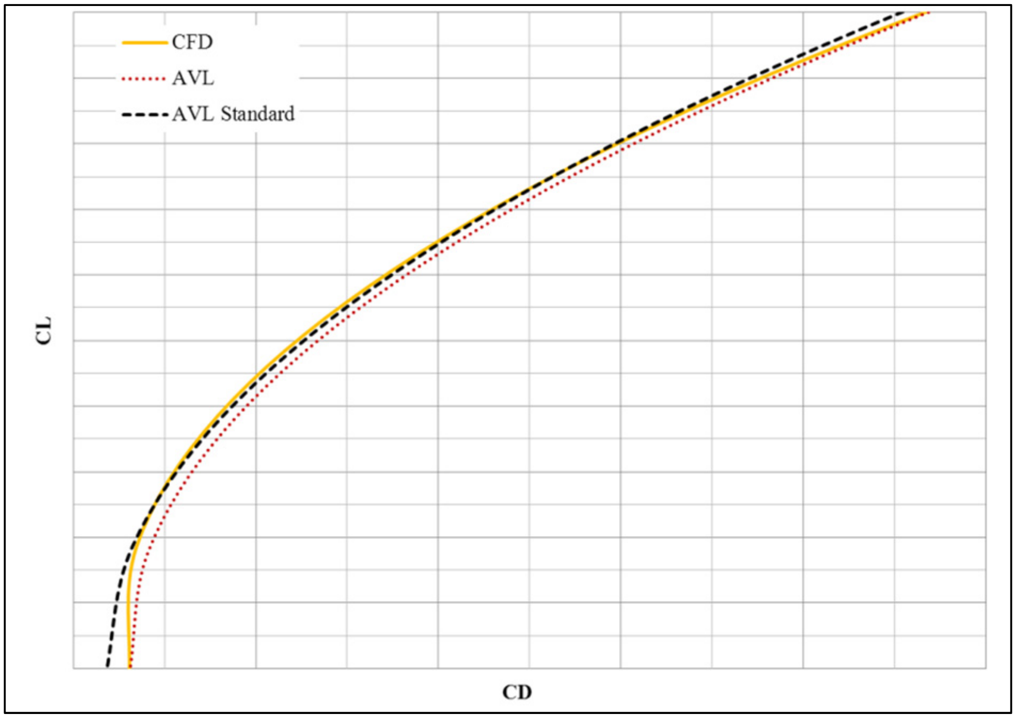

Figure 3.24 Canard research platform aircraft – Drag polars for the baseline canard

At higher CL, AVL is able to partially capture the decrease in Oswald factor, but its drag polar doesn't perfectly match the CFD one. At higher AoA, other viscous effects, like local flow separation, are not simulated with the VLM, leading to a lower drag prediction.

In summary, according to the more detailed validation work done in this second part, AVL is good for lift and spanload prediction, as well as for the calculation of the Oswald factor. Although small discrepancies with some aerodynamic characteristics exist, the most serious problem of AVL is in the prediction of the moment when a significant fuselage-canard interference effect exists. When the canard is mounted at a mid or high fuselage location, is causes a certain change in the fuselage moment. Due to the fact that AVL only uses infinitely thin surfaces, the aerodynamic connection between canard and fuselage is not present. For this reason, AVL moment results need to be corrected to obtain an acceptable agreement with CFD data, including a good prediction of the static margin.

All the validation work presented in this section is strictly related to a clean aircraft (no deflection of high-lift devices). Generally, to make a complete analysis of the low-speed performance and stability and control, a full and accurate set of aerodynamics data is required for each flaps setting. AVL was already known to be unreliable when any high-lift device is deflected, especially for large deflection. For this reason, all the increases in the wing-body lift and moment were taken from wind-tunnel values of the Bombardier research platform aircraft. AVL was only used to calculate the change in wing-body lift and moment associated to the foreplane downwash effect. This method does not allow changing the wing planform or the high-lift system of the main wing as the geometry has to remain similar to the one on which the wind-tunnel increment values are based. This is considered as a limitation in the design of a canard or three-surface aircraft using VLM.

3.3 Physics-based tailplane and canard sizing

The physics-based tail sizing tool replaced the original volume coefficient method for sizing of tailplane and foreplane. This replacement was needed because canard and three-surface configurations are significantly different from conventional aircraft in terms of pitch control, neutral point location, lift share ratio and CG location. Additionally, even if the Starship and Avanti could be used as reference in the tail-sizing process, it's preferable to only use them for basic comparison because a high-speed jet aircraft is different from a turboprop business aircraft.

Longitudinal stability and control of a conventional aircraft is primarily achieved by using an aft-tail. On a canard configuration, the foreplane is the main surface on which lift can be varied by deflecting the elevator to control the aircraft. However, since it's forward to the CG, it causes destabilization. The wing becomes the lifting surface that stabilizes the aircraft due to its location aft of CG. On a three-surface aircraft, the canard and/or the tailplane can be used for control depending on the particular design. For this configuration as well, the canard reduces stability, while the horizontal tail increases it. The wing also generally increases stability slightly depending on the CG location. Since the control surfaces are increasing weight and wetted area, they have to be sized as small as possible as only the required area to allow a sufficient level of stability and control for all possible maneuvers.

The work done consisted of modifying and improving an existing physics-based tail sizing tool developed for conventional aircraft. The main modification was to implement the foreplane into the aerodynamic formulae: lift, moment and the interference effect between the canard and wing. This tool computes the required foreplane or tailplane area for each defined critical case using known aircraft characteristics:

- Weights, longitudinal inertia, Iyy, and wing area;
- Aerodynamic coefficients for each flap setting (including CLmax);
- Most forward and most aft longitudinal CG locations;
- Engine location and maximum thrust;
- Landing gear position;
- Wing, canard, horizontal tail aerodynamic center locations (all assumed constant);
- Flight conditions for critical stability and control:
    - Weight, vertical CG location and speed (absolute value or relative to aircraft stall speed) or AoA;
    - Flaps and thrust setting;
    - Elevator deflection and incidence angle (canard and tailplane);
    - Required angular acceleration (for take-off rotation) and margin (for static margin and manoeuvre margin);
    - Foreplane and tailplane effectiveness reduction factor.

The most critical flight conditions in terms of longitudinal stability and control in general, are derived from the requirements defined in regulations for aircraft certification. The subpart B of the Federal Aviation Regulations for transport aircraft, FAR 25, (Federal Aviation Administration, 2014), describes the minimum acceptable characteristics for performance, controllability, manoeuvrability and stability for normal and emergency operating conditions. The most common cases for a transport aircraft can be classified into:

- Flight conditions for control and trim:
    - Normal & mistrim take-off rotation,

- Take-off trim & landing trim with icing conditions,
- Go-around trim,
- Stall capability & recovery.
- Flight conditions for static stability:
  - Static & manoeuvre margin.

The aforementioned cases must be properly defined to ensure they represent the critical scenarios for tail sizing of the given aircraft. They have to be verified for the entire flight envelope: weights, speeds, thrust setting and CG limits. Most of the time, a single combination of those flight parameters requires a larger tail area than any other one. For the majority of the cases, it happens to be at low-speed at maximum weight, when the aircraft operates close to its CLmax. Note that other parameters are affecting the tail sizing process including local tailplane/foreplane/wing CLmax and the incidence angle limits for canard and/or tailplane if applicable. A safety margins for local stalling of a surface must be taken into account to ensure good characteristics at stall.

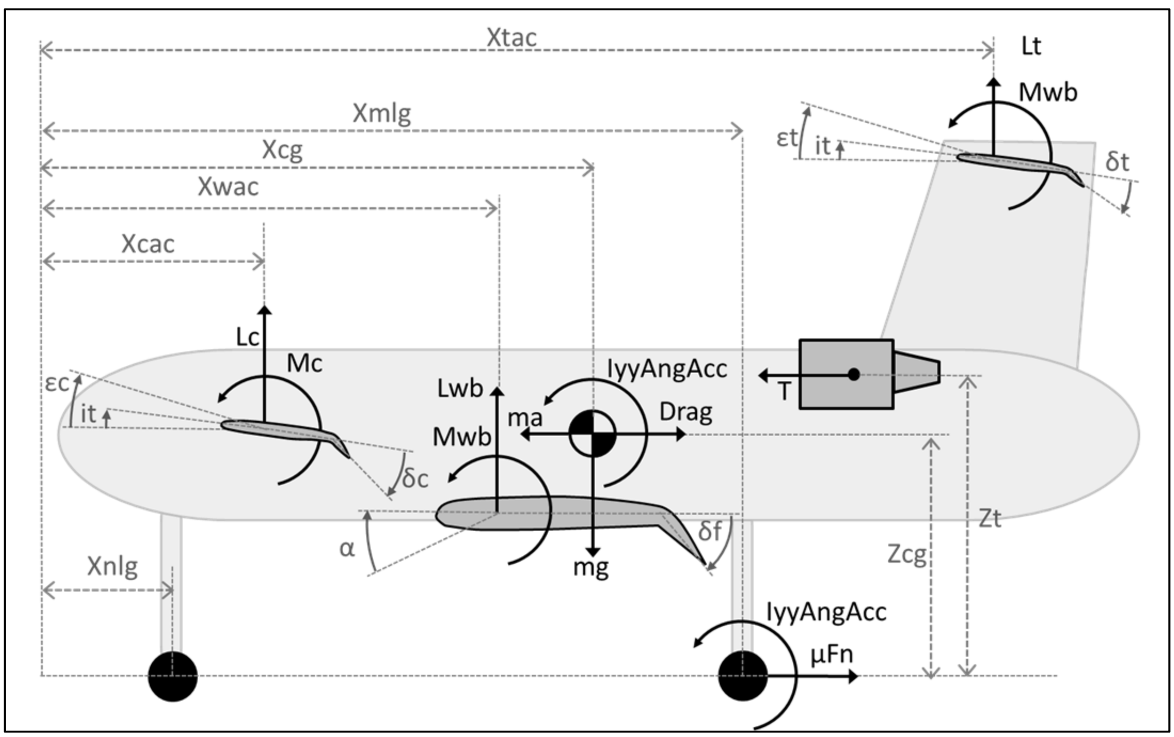

Figure 3.25 Longitudinal forces and moments for a three-surface aircraft

The modification of aerodynamic lift and moment equations was done based on the forces and moments defined in Figure 3.25. They use the standard definition of the downwash on the canard and horizontal tail, elevators effectiveness and the change in incidence angle. The drag force is considered to be applied to the CG, so it does not contribute to moment. These aerodynamic equations are presented below; lift equation (3.5) and moment equation (3.6). In those equations, CL is the lift coefficient, CM is the moment relative to the CG if the subscript ac is not used, S is the surface area, i is the surface incidence angle, δ is the elevator deflection, ε is the downwash angle and η is the ratio of dynamic pressure. Subscripts α and 0 are for gradient relative to AoA and values at zero AoA. Subscripts wb, t and c are used for the wing-body, tail and canard respectively. The subscript ac is used when the moment is relative to the surface aerodynamic center. The symbol X represents a longitudinal location (CG, wing-body aerodynamic center, etc.) and MAC is the mean aerodynamic chord; the reference length used for all moment coefficient.

$$\begin{aligned}
CL_{aircraft} &= CL_{wb} + CL_t + CL_c \\
CL_{wb} &= CL_{0,wb} + CL_{\alpha,wb} \cdot \alpha + \frac{d\,CL_{wb}}{d\,i_c} \cdot i_c + \frac{d\,CL_{wb}}{d\,\delta_c} \cdot \delta_c \\
CL_t &= \left\{ CL_{0,t} + CL_{\alpha,t} \cdot \left(\alpha \cdot \left(1 - \varepsilon_{\alpha,t}\right) - \varepsilon_{0,t} + i_t \right) + \frac{d\,CL_t}{d\,\delta_t} \cdot \delta_t \right\} \cdot \eta_t \cdot \frac{S_t}{S_w} \\
CL_c &= \left\{ CL_{0,c} + CL_{\alpha,c} \cdot \left(\alpha \cdot \left(1 - \varepsilon_{\alpha,c}\right) - \varepsilon_{0,c} + i_c \right) + \frac{d\,CL_c}{d\,\delta_c} \cdot \delta_c \right\} \cdot \eta_c \cdot \frac{S_c}{S_w}
\end{aligned} \tag{3.5}$$

$$\begin{aligned}
CM_{aircraft} &= CM_{wb} + CM_t + CM_c \\
CM_{wb} &= CM_{0,wbac} + CM_{\alpha,wbac} \cdot \alpha + \frac{d\,CM_{wbac}}{d\,i_c} \cdot i_c + \frac{d\,CM_{wbac}}{d\delta_c} \cdot \delta_c + CL_{wb} \cdot \left(\frac{X_{CG} - X_{wbac}}{MAC} \right) \\
CM_t &= \left\{ CM_{0,tac} + CM_{\alpha,tac} \cdot \left(\alpha \cdot \left(1 - \varepsilon_{\alpha,t}\right) - \varepsilon_{0,t} + i_t \right) + \frac{dCM_{tac}}{d\,\delta_t} \cdot \delta_t + CL_t \cdot \left(\frac{X_{CG} - X_{tac}}{MAC} \right) \right\} \cdot \eta_t \cdot \frac{S_t}{S_w} \\
CM_c &= \left\{ CM_{0,cac} + CM_{\alpha,cac} \cdot \left(\alpha \cdot \left(1 - \varepsilon_{\alpha,c}\right) - \varepsilon_{0,c} + i_c \right) + \frac{dCM_{cac}}{d\,\delta_c} \cdot \delta_c + CL_c \cdot \left(\frac{X_{CG} - X_{cac}}{MAC} \right) \right\} \cdot \eta_c \cdot \frac{S_c}{S_w}
\end{aligned} \tag{3.6}$$

The effect of the canard downwash is considered to already be included in the wing-body lift and moment slopes. Which is why, if a canard is used, all the wing-body aerodynamic characteristics must be obtained with the foreplane on at zero incidence and zero elevator deflection. The effect of changing the canard incidence angle (ic) and the foreplane elevator (δc) on the wing-body aerodynamic characteristics is represented by the four derivatives terms: *dCLwbac/dic*, *dCLwbac/dδc*, *dCMwbac/dic*, *dCMwbac/dδc*.

The tail-sizing tool starts with the computation of total aircraft CL if weight and speed are known, and AoA becomes one unknown to determine. If AoA is the input value, total aircraft CL become the unknown. The summation of forces in Y and the summation of moments about CG or about main landing gear pivot for take-off rotation are the two equations that must be solved to obtain all other unknown values. They include aerodynamic lift and moment, thrust, longitudinal and angular acceleration, drag (for TO rotation only) and aircraft weight as described in Figure 3.25. Although, the summation of forces in X can be considered, it's not a useful equation for this tool as it can only be used to determine the longitudinal acceleration of the aircraft (ma) which has no impact on the tail size. Others equations are the ones for the stability including both the static and maneuver margin. For each critical flight conditions, the trim & stability equations have been solved for the different sets of two unknowns: AoA or total aircraft CL and tail size or tail incidence angle or CG location. Afterwards, the final solved equations were implemented in the main script. The normal procedure of this physics-based tail sizing tool consists of computing the AoA or CL and the tail size for a range of CG locations for each defined critical flight conditions and to present results in the form of a plot of foreplane/tailplane area vs. CG, called a scissor plot. Even if this tool was previously validated for some Bombardier aircrafts, some minor details have affected the results for a conventional aircraft; therefore a re-validation for the Bombardier research platform aircraft using wind-tunnel aerodynamic coefficients was done. The results were as good as before. Figure 3.26 presents the scissor plot.

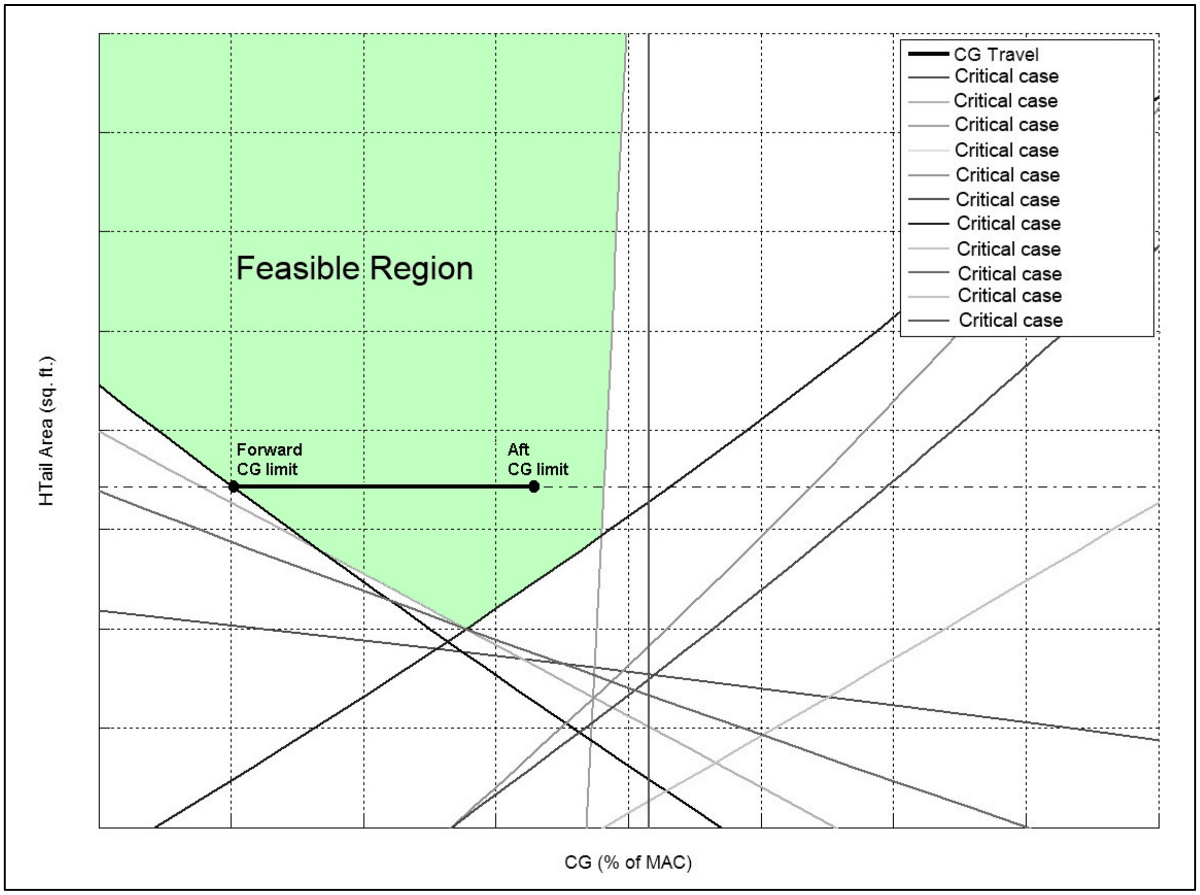

Figure 3.26 Tail size scissor plot of the Bombardier research platform aircraft

The last step of this tool is to determine the feasible tail area region and to compute the required area. As previously explained the final area is determined by taking the smallest area inside the feasible region that respects the aft and forward CG limits. As seen in the scissor plot of Figure 3.26, the minimum tailplane size is determined by the forward CG limit. It must be mentioned that the accuracy of the input data is highly important. Aerodynamic data is the most difficult one to accurately predict and it has the largest impact on the different boundary lines of the scissor plot. This applies to any configurations and mainly explains why AVL was validated extensively, although the prediction of aerodynamic data with high-lift devices remains to be improved.

For a three-surface aircraft, foreplane and tailplane have to be sized. A sizing of both surfaces at the same time could be possible by having a third equation based on a lift share ratio of the foreplane upload relative to the tailplane download. A more simple approach was adopted: sizing the canard or horizontal tail based on a fixed size tailplane or foreplane respectively. This way, the physics-based tail sizing doesn't require any other modification for application to three-surface configuration. This sizing technique is inspired by the one used during the design of the Piaggio Avanti P180, described in ref. (Sacco and Lanari, 2005), which follows these steps: choose a wing area, choose a foreplane area, size the horizontal tail for adequate stability and control, check design for feasibility (stall speed, CG travel, etc.) and efficiency (drag at cruise). Although this sizing technique will give feasible aircraft design, it could require several iterations before obtaining an optimal design indicating that the optimization of a three-surface aircraft will be more complex and take longer to complete.

Finally, even if the tool wasn't validated for a real canard or three-surface aircraft, it is considered to be acceptable as a preliminary design tool since it is based on a physical formulation of the aerodynamics contribution of the foreplane on total aircraft lift and moment, as well as his interference effect on wing. If the aerodynamic data is accurate, this tool is expected to give reasonable results.

3.4 Future tools and study

Other tools could be developed to enhance the robustness and extend the flexibility of the design process. It would allow some limitations to be removed and some assumed parameters to be replaced by computed values.

The first limitation that should be removed is the calculation of the aerodynamic characteristics with high-lift devices deflected. Currently the wing-planform and the type of flap system cannot be changed. A tool capable of computing all aerodynamic data with flaps deflected and valid for varying wing and flap geometry would be ideal. A 3D panel method might be a good choice to compute low-speed aerodynamic data at this conceptual level. Such tools may also be found to be better than AVL, since thickness effects are included in the analysis. If results could be used without applying any other corrections, it would make such tools a lot more universal than AVL. The canard-fuselage interference effect would certainly be more accurately captured using a 3D panel method analysis where the fuselage is modeled as a true 3D body.

Another tool that would be useful is one that would be able to compute the canard CLmax with and without elevator deflection. A semi-empirical calculation tool was already developed by Bombardier, but it is only applicable to typical wings. A canard is different from a normal wing which explains why the actual tool was only used to get a rough estimation of the foreplane CLmax. Also, a study of the effect of the canard downwash on the wing CLmax would be helpful. This downwash is lowering the inboard wing lift which will delay flow separation at this location. Most probably, flow separation will occur near the wing tip, a region lightly influenced by the downwash. Depending on the new stall AoA of the wing under foreplane downwash compared to the wing not influenced by a foreplane, wing CLmax might be reduced because of lower inboard wing lift if stall AoA remains about the same. A significant flow separation at the wing tip can also be critical for roll effectiveness.

Other studies that could be pursued include: spanload optimization study using AVL for both configurations, detailed analysis of trim and cruise drag at transonic Mach number for both configurations, an improved tail-sizing procedure for the three-surface configuration (a simultaneous sizing of the foreplane and tailplane to minimize drag) and finally CG envelope analysis and off-CG performance for all configurations including the conventional one.

CHAPTER 4

APPLICATION OF THE UNCONVENTIONAL AIRCRAFT CONFIGURATIONS

4.1 Presentation of the Bombardier research platform aircraft

The Bombardier research platform aircraft is a typical medium-haul turbofan-powered conventionally configured airplane. The exact configuration of this aircraft consists of a low-aft-swept wing with two aft-fuselage mounted engines and a T-tail empennage. The general characteristics are given in Table 4.1.

Table 4.1 General specifications of the Bombardier research platform aircraft

MTOW	77000 lbs	**Range**	2000 nm
BOW	44000 lbs	**Cruise Mach number**	0.78
Payload	16000 lbs	**Landing field length**	5100 ft.
Wing area	740 ft^2	**TO field length**	6100 ft.
Wing AR	7.4	**Thrust per engine**	13000 lbs
Wing loading	104.1 lbs/ft^2	**Thrust-to-weight ratio**	0.34 : 1

The aircraft is considered as a reference in terms of mission, performance requirements and the level of technology. The first configuration to be designed is the canard configuration, presented in Section 4.2. Then, application of the more complex three-surface concept is discussed in Section 4.3.

4.2 Canard configuration

Application of the canard configuration was done in a two-phase approach. The first one represents a low-level manual redesign of the reference aircraft into a canard one using the basic design tools in manual operation. The second phase was done using the workflow and all updated design tools. In both phases, the reference aircraft represents the baseline starting point from which the new canard designs were obtained.

4.2.1 Canard design phase 1

The phase 1 canard aircraft was designed to get an initial idea of what would be the impacts of simply replacing the tailplane by a foreplane. The main interest for this first design stage is to assess the consequences on MTOW, on vertical stabilizer size, on aircraft static margin and on the aircraft balancing. Another goal was to get familiar with Bombardier's design tools. The design process consists of:

1- Choosing a canard area;
2- Computing static margin and trimmed flight conditions using simple calculation based on empirical equations;
3- Balance the aircraft by relocating the wing to obtain a minimum static margin of 5% MAC;
4- Resize the vertical stabilizer;
5- Relocate the main landing gear;
6- Iterate on wing location for steps 2-3-4-5 until convergence;
7- Assuming same CLmax and same drag polars, evaluate aircraft performance for the new MTOW.

It was decided to choose a canard size having approximately the same exposed area as the aft horizontal stabilizer of the reference aircraft with higher AR and TR. Using the weight estimation previously presented, equation (3.2), the weight of this lifting surface was found to be 130% heavier than the horizontal tail of the Bombardier research platform aircraft. The overall impact of the foreplane and the new vertical stabilizer size (25% bigger) on MTOW is an increase of 1500 lbs. This had a small negative impact on performance. Due to the large destabilizing effect of the canard, the wing was moved aft by more than 10 ft. to obtain the 5% static margin at the aft CG.

At this location, the wing trailing edge at root is ending just after the beginning of the nacelle. As seen in Figure 4.1, the CG travel due to fuel is very large, 20% MAC, compared to the travel before moving the wing aft, 5% MAC, which is typical of a conventional aircraft. Note that the absolute locations of curves is not exact and that this figure is intended only to show the relative CG travel caused by moving the wing aft. Also, the travel associated to the loading of the payload for the canard aircraft is larger since it is located at a more forward location than before moving the wing.

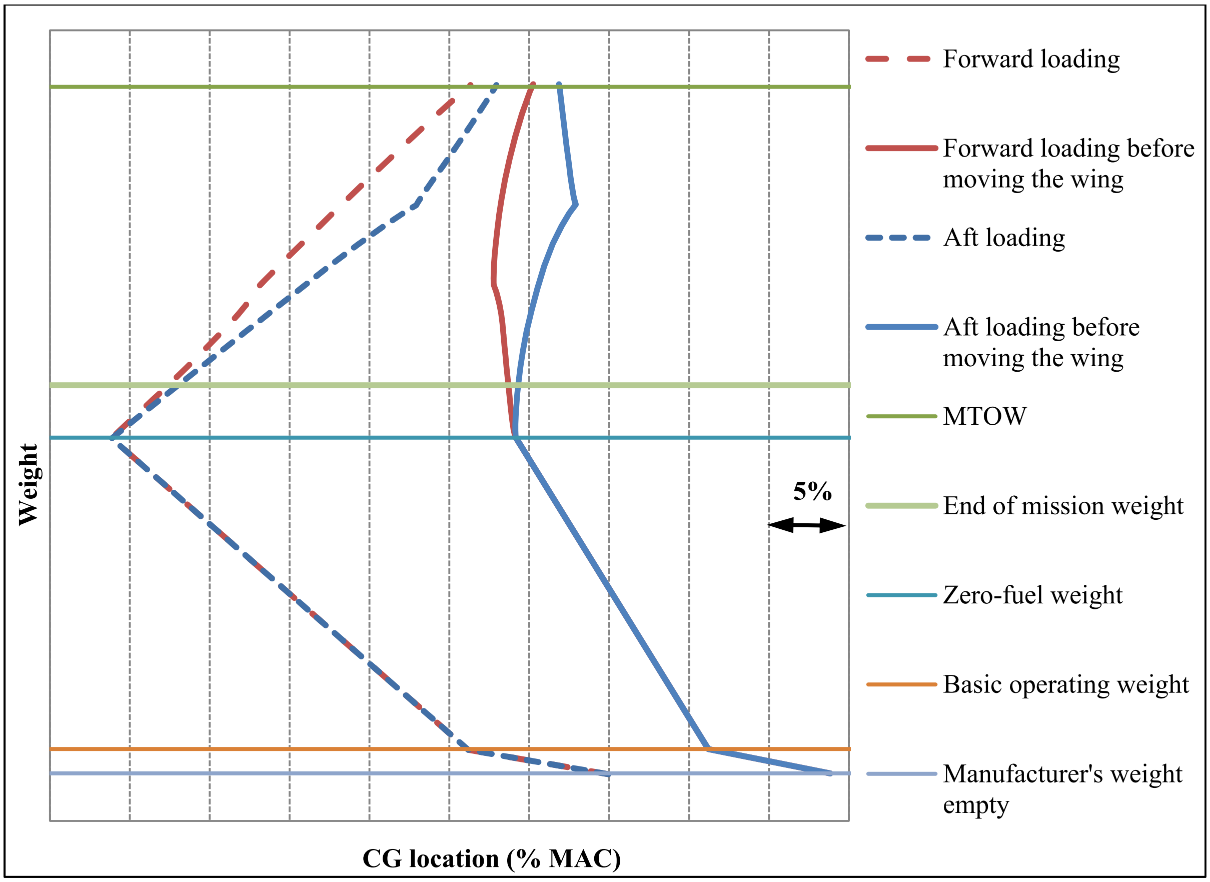

Figure 4.1 Loading diagram of the canard phase I

A problem with the weight-CG loading curve would happen if fewer passengers are carried. The final loaded CG would become more aft, thus reducing the static margin which is not acceptable. This is just the consequence of having the payload far-forward and the fuel far-aft from the loaded aircraft CG. Fuel and payload should be closer to accommodate all possible loading conditions including the zero payload ferry flight therefore the design has to be changed. At cruise condition, the estimated lift load division between the canard and the wing is about 25% / 75%. The foreplane loading and local CL are similar to the reference aircraft's values of the main wing which validates the first hypothesis of considering the canard as a wing for weight estimation. Furthermore, the foreplane CL is higher than the main wing which is typical for a stable canard configuration. Even if the wing loading has decreased, the same weight estimation equation was used because it's assumed that the wing's root bending moment will not decrease that much since the foreplane downwash contributes to unload the inboard section of the wing. Since phase I results are for the cruise condition, it's obvious that at low-speed, a very high foreplane CL will be required to obtain the same aircraft CLmax as the reference aircraft. The location of the MLG was computed to be at -30% to maintain the same weight sharing ratio between the nose and main landing gear at MTOW.

Finally, the work done in this first phase allowed to clearly identify the issue of CG travel and the severe weight penalty associated to a highly loaded foreplane. Also, cruise flight condition was found to be in agreement with the literature (foreplane CL is higher than main wing CL). The next design phase will include a detailed low-speed analysis coupled with physics-based foreplane sizing and a solution to the CG problem will also be proposed.

4.2.2 Canard design phase 2

In the second design phase, the updated workflow was used for the design. This second iteration is much more detailed and more representative of what a real canard aircraft would be, meeting the same requirements and performance as the reference aircraft. The main physical concern which is not taken into account is the integration of the main landing gear inside the wing box hence, the wing tanks are considered uncut, some space of the center fuel tank will be needed for storing of the main landing gear. More details will later be given in this section.

Before presenting any results, it's important to list all assumptions considered for this phase:

- Minimum static margin of 5% MAC;
- Main landing gear and wing are free to move (balancing);

- Keep exact same wing planform and high-lift systems as the reference aircraft except that wing area and wing fuel tanks can change;
- Canard is assumed to be ice-protected (no decrement in effectiveness);
- Canard CLmax is set to be equal to 1.4;
- Configuration is assumed to have the same Oswald factor as the reference aircraft;
- Assumed an auxiliary fuselage tank located underneath the floor and forward to main wing (approximately 20-25% of total fuel capacity);
- Assumed an added fuel system weight for the auxiliary fuselage fuel tank;
- No high-lift devices on the foreplane, only an elevator;
- Foreplane has variable incidence for trimmability;
- Foreplane is located on top of fuselage, close to the cockpit;
- Vertical stabilizer is resized using the same volume coefficient as the reference aircraft assuming a conventional empennage (not T-tail, no endplate effect);
- Wing weight is calculated using the same equation as the reference aircraft (foreplane effects on wing's lift distribution are not considered, weight reduction due to removal of wing high-lift system is also not considered);
- Fuselage size is kept the same, no extension;
- Engines/pylons are kept at their same locations, (engine size can vary);
- Foreplane basic geometry is kept similar to one used for the AVL validation part II (TR: 0.70, AR: 6.50, sweep: same as the main wing).

It was decided to put the foreplane on top of fuselage rather than at a lower location in order to minimize the interference effect with the wing and also with the fuselage and NLG. Although the detailed integration of the foreplane at this location was not analyzed, it's considered to be a feasible design that may simply require relocating the entry door and/or extending the fuselage. The variable-incidence mechanism used on the canard will also have to be considered. This system will need to be much stronger than the one used on a tailplane due to the high foreplane loading.

The canard CLmax of 1.4 was obtained by doing a rough estimation based on the initial canard planform using a typical bombardier transonic airfoil. This value is considered as the maximum clean canard CL that can safely be used. It includes a margin for gust and any form of foreplane contamination. The canard has ice protection to prevent having to decrease the canard CLmax even more. This design parameter has to be the highest possible.

The fuselage tank was necessary to bring fuel forward in order to reduce the CG travel during the mission. The balancing was setup to allow different loading conditions like zero payload flight, most-forward CG loading and most-aft CG. The required conditions were to balance the aircraft at OWE to obtain the required minimum static margin. The total allowable CG travel was set to 20% MAC and the CG envelope was kept rectangular (forward-heavy and aft-heavy limits).

Calculations of drag for the canard configuration were done using the classical formulation. They were simply computed using the common tool applicable to conventional aircrafts and by considering the same Oswald factor as the reference aircraft. This means that the canard over wing lift ratio and the foreplane geometry is not taken into account. The drag polar resulting from this method can be said to give similar drag levels as the reference aircraft except that it is scaled for the increase in wing area and for the new total aircraft wetted surface (CD0). The literature review revealed that generally the induced drag of a canard aircraft is higher than having all the lift carried by the main wing unless the foreplane AR is higher than wing's AR. Because foreplane's AR is lower than wing's AR, it is acceptable to use this simple drag calculation method. Results for the current canard design are still valid even when considering this simplification. A verification using the minimum induced drag equation (eq. (1.2)) developed by Kroo, ref. (Kroo, 1982)), was done and is presented in ANNEX III. Compared to the classical drag calculation method, induced drag was found to be 16% to 24% higher depending on the location of CG. Those results show the non-negligible variation of drag that exists between the aft and forward CG. An ideal drag computation for a canard aircraft would take into account the effect of the different trimmed flight conditions during the mission (CGs, canard and wing lift) and the complete geometry (gap, span ratio, canard moment arm, etc.). From those preliminary results and what can be found in the literature, it does not likely seems that the drag of an optimized canard aircraft would ever reach the level of efficiency of the reference aircraft, which is already considered as quite high.

Early in this design phase, it was identified that large flap deflection on the main wing was simply not possible and not necessary for a canard aircraft. For this reason, an aircraft with a small flaps deflection and another one with zero deflection were designed to investigate the benefit of incorporating a high-lift system on the main wing. It is important to specify that the flapless solution uses the same wing weight prediction; although a weight reduction should normally be considered. This quite conservative assumption was considered mainly because it is still uncertain if the wing needs flaps or not; Phase II solutions do not consider any weight reduction due to modification and/or removal of this heavy system compared to the reference aircraft.

The optimizer was used in the workflow to help search for feasible solutions. Due to the addition of the physics-based tail-sizing tool and the more detailed balancing loop, the number of inputs to manage has increased, thus making it more difficult to obtain a feasible design by manual iteration. The detail of this basic optimization is given in Table 4.2.

Table 4.2 Optimization parameter used for canard design phase II

Design variables	Wing area: –30% … +30% of reference aircraft's wing area
	Engine scaling factor: –30% … +30% of reference aircraft's engine
	Aircraft CLmax in landing configuration (1.0 to 3.0)
	Canard maximum incidence angle (5° to 12°)
Constraints	Approach speed <= reference aircraft's value
	TO field length <= reference aircraft's values
	Canard CLmax <= 1.4
Objective	Minimize MTOW

Note that the chosen landing performance criteria is the approach speed instead of the usual landing field length. It is important to recall that the performance and weights are calculated based on the design mission. The usual iteration process on MTOW, necessary because this value is an input and an output, is done and the required quantity of fuel (block fuel + reserve) is determined.

For simplicity and because of other technical details, not all critical flight condition cases were considered in the physics-based tail sizing tool used to size the foreplane. The seven cases used are listed below:

- TO rotation,
- Landing and TO trim,
- Static and manoeuvre margin,
- Stall capability,
- Nose-wheel reaction.

Results of both solutions are presented in Table 4.3.

Table 4.3 Results of the canard design phase II

	Low flap deflection solution	**Flapless solution**
MTOW	+10500 lbs (+13.6%)	+10182 lbs (+13.2%)
BOW	+8620 lbs (+19.8%)	+8515 (+19.6%)
Block fuel	+ 10.4%	+ 9.1%
Flap deflection (TO, Landing)	10° / 15°	0° / 0°
Wing area	1069 ft^2 (+45%)	1094 ft^2 (+48%)
Canard area	298 ft^2	262 ft^2
Wing loading based on total area (Wing+canard)	64.0 lbs / ft^2	64.3 lbs / ft^2
Wing longitudinal location	+ 15.2 ft	+ 12.0 ft
Aircraft Swet	+ 23 %	+ 23 %
Aircraft CLmax	– 23%	– 24%
CG limits	– 93% , – 73%	– 75% , – 55%
Engine Scaling factor	1.23	1.23
Thrust-to-weight ratio	0.37 : 1 (+9%)	0.37 : 1 (+9%)

The canard aircraft is considerably heavier than the reference aircraft. The increase mostly comes from the heavy foreplane, the larger wing, the fuselage auxiliary fuel tank, the more powerful engines and the bigger vertical stabilizer. Also, due to the much larger wing area, an increase of almost 50%, absolute drag has increased although the canard aircraft is cruising at lower CL values. The increase in wing area was necessary to respect two important constraints: the canard CLmax and the approach speed. The main effect of the low canard CLmax is an important reduction, close to 25%, in aircraft CLmax compared to the reference aircraft. More powerful engines were needed to achieve the same TO field length.

To balance the aircraft for the required CG, the wing was translated aft by approximately 12-15 feet which brings it very close to the engines. At this aft location, the wing structure can be used to shield the engine inlet noise from the ground. It represents a possible advantage of the canard configuration. A canard configuration was chosen by the DLR German Aerospace Center for the design of a low noise aircraft, due to the noise limiting effect of this configuration. The particular arrangement of this aircraft is shown in Figure 4.2, a CFD analysis showing the pressure distribution, tip vortices and local supersonic flow regions for cruise flight condition. The forward-swept wing with large leading and trailing edge extension along with two vertical stabilizers located on each side of the over-the-wing engines allows maximizing the noise shielding effect. This wing-engines-vertical stabilizers configuration is mainly made possible by the use of the canard configuration.

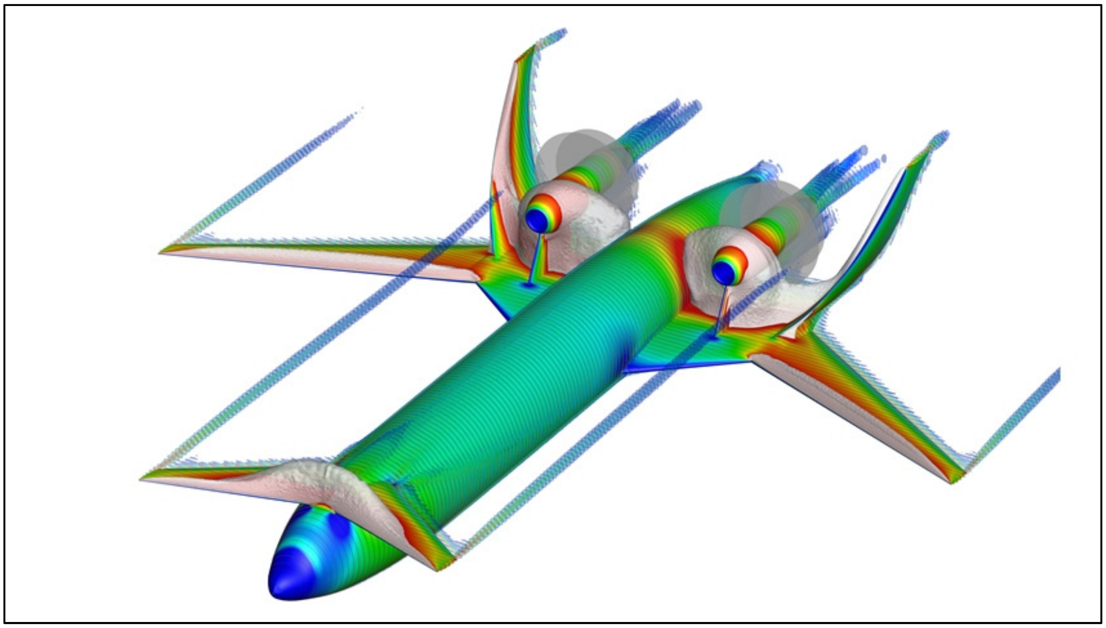

Figure 4.2 "DLR Low Noise Aircraft" by DLR German Aerospace Center is licensed under CC BY 3.0 (taken from ref. (DLR German Aerospace Center, 2014))

By analysing the different location of the CG for different loading conditions, it can be concluded that the CG problem was almost solved. For both solutions, the most-forward loading curve remains inside the allowable limits. CG travel during the mission is about 16% if a most-forward CG fuel depletion is used. When a more optimal depletion of the wing and auxiliary tank is done, the travel is reduced to 9% which is more than half of the value of 20% that was obtained in the phase 1 design. It is obvious that the fuselage fuel tank must always be filled and used the latest possible to maintain a CG at the most forward possible location. The only issue arises with low and zero payload loading conditions. In those cases, the CG can go too far aft if all fuel tanks are filled. Although a certain amount of fuel can always be stored while maintaining the CG inside the limits, an issue still exists with the aft CG of those solutions. It would certainly be possible by doing small changes in the balancing setup and by redesigning the wing fuel tanks for a more forward CG to achieve a canard design that would meet all possible loading conditions.

Other CG related results are the foreplane sizing scissor plots. The one for the low flap deflection is shown in Figure 4.3.

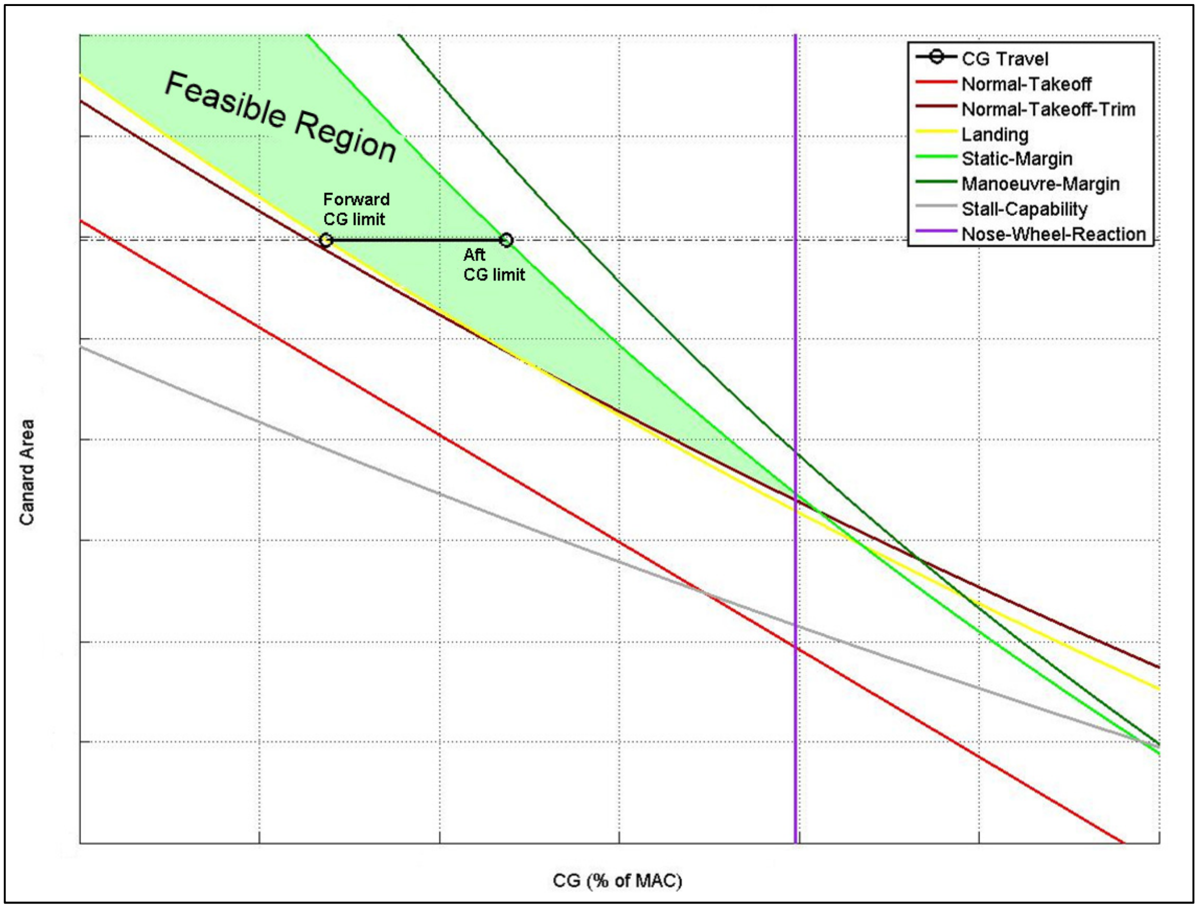

Figure 4.3 Foreplane size scissor plot of the canard phase II –
Low flap deflection solution

By comparing this scissor plot to the Bombardier research platform aircraft scissor plot, Figure 3.26, it's obvious that the canard configuration has a much smaller feasible region. The main difference is in the shape of this feasible region. The narrow region of the canard configuration is a lot more restrictive in terms of design. As opposed to the conventional configuration, the aft and forward CG limits are both moving forward as the canard area increases, indicating the importance of properly balancing the aircraft and sizing the wing/foreplane. This is why also it is important to have accurate aerodynamic data. The critical case for the forward CG is the landing trim case due to the increase in pitch-down moment generated by the flap deflection of 15°. All trim cases were found to be very sensitive to the amount of flap deflection used. The canard CLmax is the main driving parameter for those trim cases. The aft CG is limited by the minimum static margin of 5%. It indicates that the CG envelope cannot be expanded more aft for lower weights because the aircraft would simply be too unstable. On a conventional aircraft it is sometimes possible to push back the aft CG limit for a lower weight when the aft-CG limiting case is a control/trim case that is dependent on weight.

For the flapless solution, the main differences, compared to the low flap deflection solution, are the smaller canard area and CG limits that are 20% closer to the main wing, requiring less aft translation of the main wing to achieve the right balancing. The canard over wing area ratio for the flapless solution is lower, 23.9% vs. 27.9%. Also, the forward CG limiting case has become the TO trim. For this case, the canard maximum lift is required to trim the aircraft at forward CG with the engines at maximum thrust which creates a nose-down pitching-moment. This critical flight condition is followed closely by the landing trim case which has become less critical since the main wing moment is not affected by the flaps. The other important difference is the AoA for trim cases. For the flapless solution, AoAs are higher because there's no increase in CL_0 due to flap deflection. In the case of the low flap deflection solution, AoAs values are very similar to the reference aircraft. Trimmed flight conditions were also compared. The wing and the foreplane of the flapless solution are operating at a slightly higher CL than the low flap deflection solution. A small difference was also observed with the lift share ratio (67/33 vs. 70/30 for flapless). Eventually, a complete analysis of the drag will be used to replace the assumption made for the drag calculation and will be useful to determine which solution has the lowest total drag at cruise. Finally, both solutions are very similar and a more advanced analysis will need to done to identify which one is better and/or infeasible.

4.2.3 Brief comparison with other literature results and the Beechcraft Starship

The results obtained during phase I and II are in agreement with the ones found in literature; the canard configuration is not better than the conventional configuration. Even if this conclusion is normally related to the trimmed lift-to-drag ratio which was not fully considered, other factors like the high foreplane weight and the low CLmax has led to an aircraft which does not perform any better than the conventional reference aircraft. In the NASA research, ref. (Arbuckle and Sliwa, 1985), the canard configuration had similar performance and efficiency as their own conventional reference aircraft, but the NASA researchers assumed a very high foreplane CLmax similar to the wing CLmax with high-lift devices deflected. In the current study, the foreplane CLmax was set to a value of 1.4 which is much lower than a typical wing equipped with high-lift devices. This parameter has a significant impact on the final design. It would be interesting to increase the foreplane CLmax value and evaluate the different effects on the design as done in the NASA study.

When comparing the phase 2 solutions to the Beechcraft Starship, the main resemblance is about the aircraft CLmax. It was already said that the Starship has a low-performance high-lift system. The same thing can be said about the phase 2 designs for which the integration of a high-lift system on the main wing has a small impact on final results. In fact, the aircraft CLmax of both solutions and the Starship are all very similar.

This again brings question of whether using a flap system or not on the wing for a canard configuration. Phase II results demonstrated that there's no real benefit of using flaps. So, if the foreplane CLmax cannot be increased, the installation of flaps on the main wing will mostly yield no real advantage. In the case of the Beechcraft Starship, the variable-sweep foreplane allows varying the maximum lift that can be generated by the canard. At low-speed, the canard unsweeps to increase its CLmax and exposed area to produce more lift. At the same time, fowler flaps are deflected to increase wing lift and probably also in order to maintain an adequate margin for main wing stall. Instead of using this mechanism, a slat system could be used on the foreplane. Such a system would be good for increasing the canard CLmax without impacting the stability of the aircraft, and it would be a feasible design for a variable incidence foreplane.

It is important to say that in the case of the flapless solution, the wing may operate at a CL too close to the clean wing CLmax, bringing the danger of stalling the main wing before the foreplane. For this reason, a high-lift system might be necessary on the main wing. In the end, only an advanced low-speed analysis will be able to answer if the stall behavior is acceptable or not and whether or not flaps are required on the main wing.

4.3 Three-surface configuration

Even if this configuration was identified as being better than the canard one and more easily applicable to a jet aircraft, no solution was obtained during this project. It was found in the literature that the three-surface configuration can be slightly better than the conventional one for some applications. Due to the fact that the possible benefits are small, every detail in the design of such aircraft will need to be properly considered. The advantage of the three-surface configuration is mainly to reduce trim drag and to achieve minimum drag for all CG locations.

As trim drag and CG locations were not taken well into account in the analysis, at the end of this project, no attempt of designing a three-surface aircraft was made. Before starting the design of a three-surface aircraft, a tool that computes the trimmed high-speed cruise drag of a three-surface aircraft is required. Note, that all the work done for the canard configuration will be applied for this configuration.

CONCLUSION

The main objective of this master's project was to conceptually design a transport jet aircraft similar to the Bombardier research platform aircraft while trying to improve fuel efficiency, thus reducing environmental impacts. Research consisted of studying two unconventional aircraft configurations, the canard and the three-surface configuration, in order to determine if there is any benefit compared to the conventional reference aircraft. Furthermore, practical considerations in the design of such aircraft were included to ensure obtaining a feasible aircraft.

The methodology was first to perform a literature review on those two configurations, including existing aircrafts. Since this research was done in collaboration with Bombardier Aerospace, their conceptual design tools were used as a starting point. Some tools were modified and validated for application to the canard and three-surface configurations. This part of the project, which has accounted for most of the work done, included the development of a new foreplane weight prediction equation, the modification and validation of the aerodynamic tool, AVL, and finally a complete revision of an existing physics-based tail-sizing design tool. Some of the design tools were first used manually to design the phase I canard aircraft. This represented a first crude approximation mainly used to identify and experiment some of the critical aspects related to the design of this unconventional aircraft. The next design phase was done using the Bombardier workflow which was previously adapted for the canard configuration. All the new and updated tools were integrated. Although the level of detail was good, mainly because the low-speed stability and control was well represented, some assumptions and restrictions have limited the number of design possibilities. The most important ones are:

- Foreplane CLmax is assumed as a constant input value rather than computed from the geometry (assumption);
- The main landing gear and the wing are free to move longitudinally (assumption);
- Cruise drag is calculated using the classical method with the same Oswald factor as the reference aircraft (assumption, verified to be conservative);

- Changes in wing planform are not allowed (restriction).

Due to the fact that low-speed performance has a large impact on the design of a canard aircraft, two solutions were obtained, one using flaps on the main wing and the other without. Both solutions were using a variable incidence of a simple foreplane with an elevator for pitch control and assumed a same canard CLmax. Both canard aircraft were very similar showing that there is no benefit of using flaps on the main wing. The most probable reason to justify the use of a high-lift system on the wing is if the canard CLmax can be increased for the take-off/landing configuration compared to clean. This is how the Beechcraft Starship was designed, a business aircraft which uses a variable-sweep canard with a wing equipped with fowler flaps. Analysing this aircraft reveals that the performance of its high-lift system remains low. This is the major drawback of the canard configuration as demonstrated. Typically, jet aircrafts are achieving high CLmax in the landing configuration which helps to reduce the wing size to a minimum area while not landing at very-high speed. From results obtained in phase II, it is possible to state that the canard configuration:

- Has very low high-lift capability (CLmax has been reduced by almost 25%, wing area has increased by close to 50% to meet the same approach speed as the conventional aircraft);
- Is heavier (foreplane is heavy due to high loading, larger main wing area, MTOW + 13%);
- Has large CG travel due to fuel and payload being too far from the aircraft CG (was solved by using an auxiliary fuel tank forward to the main wing, close to the fully loaded aircraft CG location).

The canard configuration has led to a large reduction in the fuel efficiency and has required significantly more powerful engines to respect the take-off field length constraint. Fuel burn was increased by 10% compared to the reference aircraft. The results were in agreement with the main conclusions found in the literature as the canard configuration is not better than the conventional configuration when applied for a practical design, and has major drawbacks, like low CLmax and difficulty to limit the CG travel. One way to achieve a better design would be to increase the foreplane CLmax. Even if the phase II solutions were not obtained by doing a complete optimization and are considered to be preliminary, it is possible to conclude, in all likelihood, that no canard aircraft will be better than the Bombardier research platform aircraft.

For the other unconventional configuration under study, the three-surface configuration, it appears that it is a better configuration according to the literature review. Most theoretical studies concluded that this configuration is aerodynamically better than the canard one, but the conventional configuration which remains the best of all three. However some conceptual design studies that have applied the three-surface concept into business and regional aircrafts have shown some improvement over the conventional configuration. The main advantages of this configuration are to reduce trim drag and to be able to fly at minimum drag for all CG locations. In this project, no three-surface aircraft was designed since the workflow and some design tools were not fully ready for this type of configuration. The application of the three-surface configuration using a design procedure capable of capturing all the details related to this particular type of aircraft may, hopefully, result in a more-efficient aircraft. It would be interesting to know how much fuel could be saved and if it is really worth choosing this more-complex configuration over the conventional one.

RECOMMENDATIONS

This section is intended to give guidelines concerning the future of this research to be continued by the Advanced Design department of Bombardier Aerospace.

In the short term, the work on the canard configuration has to be continued before starting to work on the application of the three-surface configuration. It is important to develop new tools and continue to update the existing ones. Doing so will allow increasing the design space that can be explored, thus a better and more-optimal canard aircraft could probably be designed using the workflow with a complete and more-detailed optimization. Then, conclusions about the canard will be more definitive. Also, the change from canard to three-surface configuration should not require much additional work. The following paragraph gives more detailed information about the main tasks to be done. Note that some information on this subject was already given in Section 3.4.

Since the foreplane CLmax was a main limiting factor in the design of a canard aircraft and will most likely be one for the three-surface configuration, a detailed study about the different methods to maximize this parameter should be done. Concerning the workflow and the design tools, the limitation on the modification of the wing planform has to be removed. For this, a tool capable of computing the low-speed aerodynamics with high-lift devices deflected is mandatory. Another important point to be updated is the drag calculation. Instead of considering the classical drag formula where all the lift is considered to be carried by the main wing, a method which takes into account the true lift distribution between canard, wing and tailplane for trimmed flight condition based on the actual CG locations during the missions would be much more appropriate. Also, a way to minimize drag should be implemented. AVL was found to be good to predict the Oswald factor, so it could be used to optimize spanload and, in the case of a three-surface, used to find the ideal foreplane/tailplane trim forces. Two other more-advanced aspects should ideally be captured with sufficient accuracy in the design procedure. The first aspect is the transonic effects on drag and stability at cruise speed while the other aspect is the behavior of the aircraft at stall.

For this, the canard CLmax and the wing CLmax operating in the foreplane downwash have to be known. As these two aspects can be difficult to evaluate using empirical and/or low-fidelity physics tool, a validation using a high-fidelity analysis should be done on a satisfactory optimized solution of a canard aircraft at low and high speed. It would allow confirming the feasibility and the performance of the given solution.

In the long term, different kinds of designs based on those two unconventional configurations should be considered. Some of these design possibilities are:

- Low-canard, high-wing,
- Non-trapezoidal wing planform and forward-swept wing,
- Forward-swept foreplane,
- Engines under the wing,
- Free-floating canard,
- Different vertical stabilizer configuration.

It's important to mention that the concept of forward-swept wing, used on the DLR Low Noise Aircraft of Figure 4.2, might be well suited for any configuration using a foreplane since this type of planform has higher wing's local CL inboard than an aft-swept wing. Therefore, using a foreplane with a forward-swept wing will present a more uniform wing spanload and may be beneficial to prevent the usual wingtip stall associated with a back-swept wing. In addition, designing the foreplane with forward sweep would allow increasing its moment arm, thus reducing the required area for this surface.

As a final recommendation, emphasis should be put on the development of a three-surface aircraft simply because this concept might be able to take the best out of the canard and conventional configuration without some of their respective drawbacks.

ANNEX I

SPECIFICATIONS OF RUTAN VARIEZE, BEECHCRAFT STARSHIP 2000A AND PIAGGIO P180 AVANTI II

Table-A I-1 Specifications of the Rutan VariEze

		Rutan VariEze	
Weights	MTOW	1050	lb
	MEW	580	lb
	Usable Fuel capacity	24	Us gal.
Dimensions	Crew + Passenger	1 + 1	
	Wing / foreplane area	53.6 / 13.0	ft^2
	Wing / foreplane span	22.2 / 12.5	ft
	Wing loading	19.6	lbs / ft^2
	Overall length	14.2	ft
Engines	Number of engine	1	
	Engine power	100	SHP
	Power-to-weight ratio	0.095 : 1	
Performance	Cruise speed (max/econ)	170 / 143	kt
	Stall speed (clean/flaps ext.)	48 / 48	kt
	Range (max/ typ.)	738 / 608	nm
	TO / Landing run	900	ft

Table-A I-2 Specifications of the Beechcraft Starship 2000A and the Piaggio P180 Avanti II

		Beechcraft Starship 2000A	**Piaggio P180 Avanti II**	
Weights	MTOW	14900	12100	lbs
	Empty weight	10120	7800	lbs
	Max payload	2480	2000	lbs
	Usable Fuel capacity	565	422	Us gal.
Dimensions	Crew + Max passenger	1 or 2 + 8	1 or 2 + 8	
	Cabin volume	362	375	ft^3
	Wing area	280.9	172.2	ft^2
	Foreplane area	61.0	23.6	ft^2
	Tailplane area	0.0	41.2	ft^2
	Wing span (AR)	54.4 (10.5)	46.0 (12.3)	ft
	Foreplane span (AR)	22.0 (7.9)	11.0 (5.1)	ft
	Tailplane span (AR)	0.0 (0.0)	14.0 (4.8)	ft
	Wing loading	53.0	70.3	lbs / ft^2
	Overall length / height	46.1 / 12.9	47.3 / 13.1	ft
Engines	Number of engines	2	2	
	Flat-rated power per engine	1200	850	SHP
	Power-to-weight ratio	0.16 : 1	0.14 : 1	
Performance	Cruise speed (max/econ)	334 / 279	390 / 298	ktas
	Maximum operating speed	0.60	0.70	Mach
	Stall speed (clean/landing)	97 / 92	112 / 97	kt
	Range with reserve (max/typ.)	1576 / 1514	1456 / 1507	nm
	Max rate of climb	2750	2950	ft / min
	TO field length	3854	3235	ft
	Landing field length	2390	3500	ft

Sources:

Rutan VariEze: Jane's All the World's Aircraft 1982-1983

Beechcraft Starship 2000A: Jane's All the World's Aircraft 1994-1995 and from Beechcraft, 2003-2.

Piaggio P180 Avanti II: Jane's All the World's Aircraft 2008-2009

ANNEX II

DESCRIPTION OF THE EIGHT AVL VALIDATION CASES

Table-A II-1 Description of the AVL validation cases

Case	Description and type of analysis
1	**Baseline wing-body** - Absolute analysis only
2	**Baseline canard** - Absolute analysis - Increment analysis with case 1 (effect of adding a canard)
3	**Baseline canard with increased incidence angle** - Absolute analysis - Increment analysis with case 1 (effect of adding a canard with a higher incidence angle) - Increment analysis with case 2 (effect of increasing canard incidence angle)
4	**Baseline canard closed-coupled** - Absolute analysis - Increment analysis with case 1 (effect of adding a closed-coupled canard) - Increment analysis with case 2 (effect of reducing canard moment arm)
5	**Baseline canard with elevator deflected 10° down** - Absolute analysis - Increment analysis with case 1 (effect of adding a canard with deflected elevator) - Increment analysis with case 2 (effect of deflecting the elevator on the canard)
6	**Larger canard** - Absolute analysis - Increment analysis with case 1 (effect of adding a large canard) - Increment analysis with case 2 (effect of increasing canard area)
7	**Bigger canard with reduced aspect ratio** - Absolute analysis - Increment analysis with case 1 (effect of adding a large canard with reduced span) - Increment analysis with case 6 (effect of decreasing aspect ratio)
8	**Baseline canard located on top of fuselage** - Absolute analysis - Increment analysis with case 1 (effect of adding a high-canard) - Increment analysis with case 2 (effect of moving the canard from mid-fuselage to high-fuselage)

ANNEX III

VERIFICATION OF THE DRAG CALCULATION

To verify the assumption of using the classical drag formulation with the same Oswald factor as the reference aircraft, a comparison with Kroo's theory on the minimum induced drag of canard aircraft was done. The assumption considered in the canard design phase II has to be conservative to be acceptable, drag must not be overestimated.

Classical induced drag equation

$$C_{Di} = \frac{{C_{L\ \text{aircraft}}}^2}{\pi e AR} \tag{AIII.1}$$

Kroo's minimum induced drag of canard configurations

$$C_{Di} = \frac{S_{ref}}{\pi}\left(\frac{{C_{Lw}}^2}{b_w^2} + 2\sigma\frac{C_{Lw}}{b_w}\frac{C_{Lc}}{b_c} + \sigma_*\frac{{C_{Lc}}^2}{b_c^2}\right) \tag{AIII.2}$$

For the low-deflection flap solution:

Table-A III-1 Input data based on the low-deflection flap solution for the drag verification

Swing	1069,0	ft^2
Bwing	88,9	ft
AR wing	7,4	
Scanard	298,0	ft^2
Bcanard	44,0	ft
AR canard	6,5	
Vertical gap	7,4	ft
Gap ratio (2·h/Bcanard)	0,34	
Span ratio	0,46	
Interference factor σ*	0,81	From Fig. 2, (Kroo, 1982)
Interference factor σ	0,42	From Fig. 2, (Kroo, 1982)
Assumed weight	MTOW	
Flight condition	Cruise trimmed conditions	
Assumed CL	Average Cruise value	
Assumed Oswald factor	Same as the reference aircraft	

Table-A III-2 Input data based on the low-deflection flap solution for the drag verification

	Aircraft CDi using Classical drag calculation	**Aircraft CDi using Minimum induced drag of canard configurations from KROO**
At aft-CG	ref. value	+16%
At mid-CG	ref. value	+20%
At forward-CG	ref. value	+24%

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