The Design of Advanced Very Light Jet Aircraft

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Abstract: - The current state of the art in aircraft design has shown that in order to be economically viable and competitive it is necessary to investigate technology, which may give an improvement in performance and operational flexibility goal, but must be shown to be cost-effective. The current competitive environment forces the potential customers to buy advanced technology aircraft and requires manufacturers to provide more operational flexibility, without drastic performance penalties. This is a challenging task, which might be solved by the use of new technologies. It is believed that the application of an advanced high-lift capability, high cruise Mach number and lower moment turbulent airfoils derived from MS (1)-0317 and MS (1)-0313 to a wing would assist in achieving such a task. This paper describes an investigation aimed to examine the suitability of an aerodynamic wing design, allowing for the use of an advanced turbulent wing section concept for advanced medium-speed Very Light Jet (VLJ) aircraft. The paper describes the phenomenon of configuration design and outlines the wing design process. Description is then given of the aerodynamic design of a wing incorporated with an advanced turbulent wing section technology, tail design and aircraft performances. It concludes with a discussion of the results and recommendations for future work.

Keywords: - business jet; very light jet; aircraft design; aerodynamic configuration; wing design

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1 Introduction

For VLJ aircraft, one of the basic aerodynamic performance objectives is to achieve the highest value of M(L/D)max at the cruise Mach number. Climb and descent performance, especially for short range missions, is also important and may suggest the "cruise" design conditions be compromised. In the past 20 years, much airframe development has been aimed at reducing lift-dependent drag, leading to higher-aspect-ratio-wings and winglets coupled with overall optimization of wing design [1].

To achieve further major advances, it is necessary to look at other aspects of design, in particular, the lift and cruise Mach number capability of advanced turbulent airfoil derived from MS (1)-0317 and MS (1)-0313. Medium-speed airfoils have been designed to fill the gap between the low-speed airfoils and the supercritical airfoils for application on light general aviation aircraft. The intention of medium-speed (MS) airfoil development was to combine the best features of low-speed and supercritical airfoil technology; this airfoil development is discussed in detail in reference [2 & 3]. The advantages of the medium-speed airfoils were to increase the cruise Mach number of the low-speed airfoils while retaining their good high-lift, low-speed characteristics and docile stall behavior.

This paper describes the continuation of previous work in these areas to assess their broad impact on configuration design parameters to produce major increases in aerodynamic efficiency.

2 Configuration Design

Designing an aircraft can be an overwhelming task for a new designer. The designer must determine where the wing goes, how big to make the fuselage, and how to put all the pieces together [1].

A sound choice of the general arrangement of a new aircraft design should be based on a proper investigation into and interpretation of the transport function and a translation of the most pertinent requirements into a suitable positioning of the major parts in relation to each other. No clear-cut design procedure can be followed and the task of devising the configuration is therefore a highly challenging one to the resourceful designer.

The study of possible configurations should result in one or more sketches of feasible layouts. They serve as a basis for more detailed design efforts, and they can therefore be regarded as a first design phase. Usually trade studies between several possible configurations will be required before the choice of the best configuration is made.

2.1 The market

Bombardier Aerospace's latest 20-year market forecast, released on Sunday at the Farnborough Airshow (14 to 20 July 2014), shows a significant drop in anticipated deliveries of business jets compared with its forecast from last year. The current forecast, which spans from 2014 to 2033, calls for deliveries of 22,000 business jets worth $617 billion. Last year Bombardier predicted demand for 24,000 business jets worth $650 billion from 2013 to 2032. These numbers are for aircraft segments in which the manufacturer competes, with its Learjets, Challengers and Globals. According to Bombardier, “Business aircraft orders are expected to remain challenging in 2014 across the industry, but projected to improve beginning in 2015.” The company sees demand shifting to emerging markets and thus driving growth of the medium and large jet categories, with the most rapid growth in the large segment. The largest number of jets during the forecast period will be delivered to North American customers, followed by Europe and then China. The forecast sees deliveries of 950 jets in China from 2014 to 2023 and 1,275 from 2024 to 2033 [44].

Bombardier Business Aircraft (BBA) believes that the long-term market drivers of growth for the business jet industry remain solid. These market drivers include: wealth creation, increasing penetration in high growth economies, globalization of trade, replacement demand, and market accessibility [45].

2.2 Design requirements and objectives

The following are the design requirements and objectives of the VLJ aircraft that need to be fulfilled during the design process in this project.

* Designation: VLJ-25

* Crew: 1 pilot

* Payload: 5 passengers

* Range: 1500 nm with design payload plus alternate flight as long as 100 nm and holding for 30 min before landing.

* Cruise Speed: 420 knots at 33,000ft (M = 0.70)

* All engine operative take-off distance at maximum take-off weight is 2625 ft; landing distance at a landing weight is 2297 ft.

2.3 Aircraft configuration

Based on an existing aircraft there are two main types of general arrangement for a business jet aircraft, namely: conventional and unconventional.

Conventional arrangement (aft-tail). The engine mounted on the aft fuselage, low wing and T-Tail/Cross-Tail configuration is the most common for most VLJ aircraft. This is because of the engine ground clearance requirements. This configuration has several advantages, i.e.: aerodynamically clean wing, less control power for one engine out trim, better engine rotor burst and engine ground clearance. The disadvantages include: no wing root bending moment relief, relatively higher cabin noise levels, heavier fuel system, difficult aircraft c.g. (center of gravity) management & engine accessibility. Typical general arrangement of this configuration is Eclipse 500.

Over the past few years, Honda has been quietly developing a six- to eight-place very light twinjet (Honda Business Jet). What makes the HondaJet particularly unusual is not its creator but its over-the-wing engine configuration. With no carry-through structure needed in the aft fuselage for its engine pylons, this configuration allows a full-width cabin farther aft, maximizing interior dimension [5].

Honda claims with nacelle located at the optimum position relative to the wing, the shock wave can be minimized, and drag divergence occurs at a Mach number higher than that for the clean-wing configuration. Compared to clean-wing configuration, over-the-wing engine configuration has better stall characteristics, the zero-lift angle increase by 1.2 degrees and maximum lift increase by 0.07.

Preliminary specifications include a 9,200 lb. max. take-off weight, 420-knot cruise speed, 44,000-foot ceiling and an NBAA IFR range of 1,100 nm.

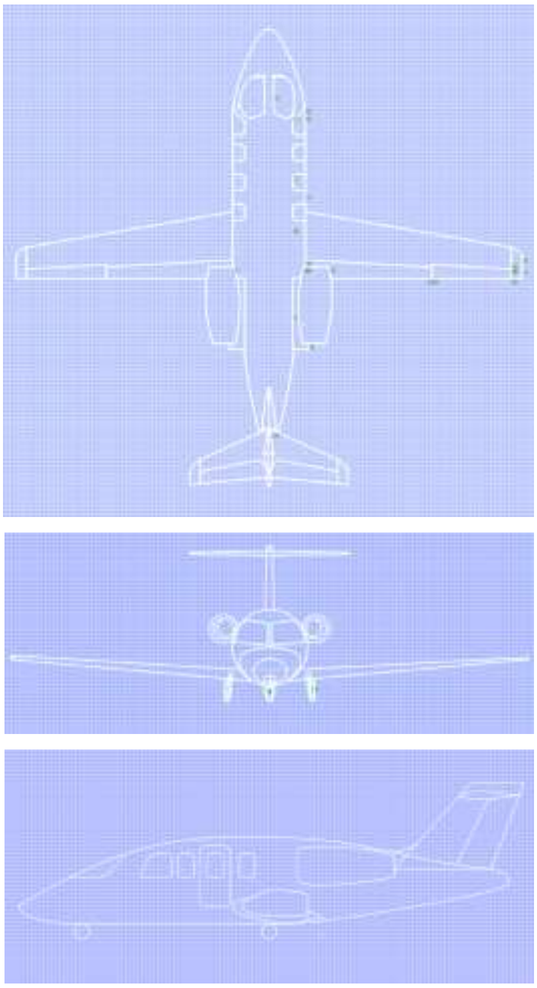

Fig. 1. Initial concept of VLJ-25-01

The above configuration also has several advantages, i.e.: wing root bending moment relief, relatively lower cabin noise levels, lighter fuel system, easy aircraft c.g. management (engine close to aircraft CG) & engine accessibility. The disadvantages include: aerodynamically not clean wing, more control power for one engine out trim, critical engine rotor burst and more wetted area hence drag and weight due to bigger engine pylon.

For this project (VLJ-25), the conventional arrangement was selected as shown in Fig. 1. Fig. 2 and Fig. 3 show the cabin cross section cross section and plan view respectively.

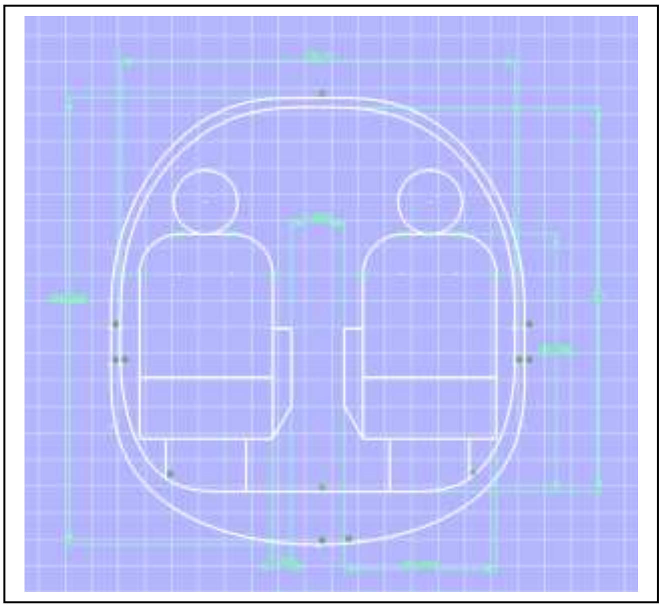

Fig. 2. Cabin cross section

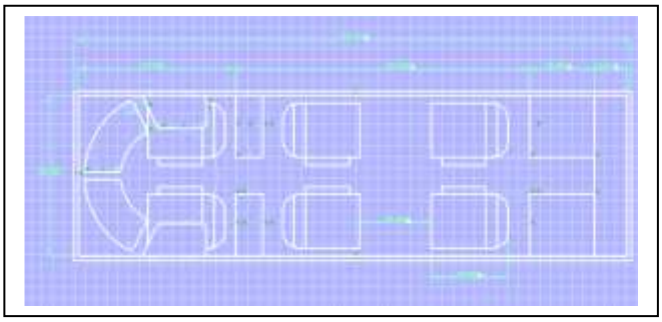

Fig. 3. Cabin plan view

3 Aerodynamic Wing Design

Wing design is a highly integrated process involving not only the aerodynamicists but also all other engineering disciplines, marketing, sales, manufacturing, and design groups.

3.1 General requirements

Basic requirements that must be achieved for a successful wing design include [1 - 43]:

a. The configuration must satisfy the performance goals in the design specifications whilst achieving good economic returns.

b. Flight characteristics, handling qualities, and aircraft operations must be satisfactory and safe over the entire flight envelope for all aircraft configurations (high speed, low speed, different flap settings, gear positions, power settings, and suitable ground handling).

c. Design of a structure must be possible within the defined external shape to meet the strength, torsion, fatigue, flutter, weight, life cycle, maintainability, accessibility and engine requirements, together with suitable development and manufacturing costs.

d. Sufficient space must be provided for fuel for the design range, for retraction of the main landing gear, and for the aircraft systems (flaps, ailerons, spoilers, fuel, gear, etc.), where appropriate.

Meeting all these requirements simultaneously is difficult and will most likely require compromise for a satisfactory configuration to be achieved.

Performance requirements will typically include the aircraft manufacturer company management's perception of the airline requirements for the design payload, cargo, range and speed. Objectives will vary from specific requirements, such as sea level and high-altitude field performance and span limitations, to constraints such as approach speed and initial cruise altitude capability. Compatibility with current flight operations (speed and altitude) must be considered. Design Mach number and lift coefficient will be based on either average cruise performance or on climb and descent conditions. Short range aircraft, which spend a majority of their flight time relatively in high speed, flaps up, climb and descent, should consider average climb and descent speeds, weights and altitudes for design conditions. Economic return is a direct function of aircraft purchase price, direct operating costs (DOC), and fuel efficiency and will significantly influence aircraft sales.

Flight characteristics and handling qualities influence wing design primarily in stall speeds and handling characteristics prior to and during stall, in initial buffet boundaries, and in longitudinal and lateral-directional stabilities.

The aircraft's structural design will impact the wing design primarily in its influence on aeroelasticity wing span limitations and landing gear storage. Structural efficiency for minimum wing weight is defined by not only span and chord but also by spar depth. Requirements for fuel volume, flap and control systems and actuator sizes all influence the spar depth and thus weight.

It is convenient to separate wing area and wing shape effects in the design process. Wing area and the high lift flaps are closely related to aircraft performance. Wing shape parameters such as planform, sweep, taper, twist, and airfoil sections will typically influence stall and buffet characteristics. This is complicated by span and aspect ratio, which are planform parameters that affect performance.

Parameters affecting wing design [1 - 43] are presented in Fig. 4.

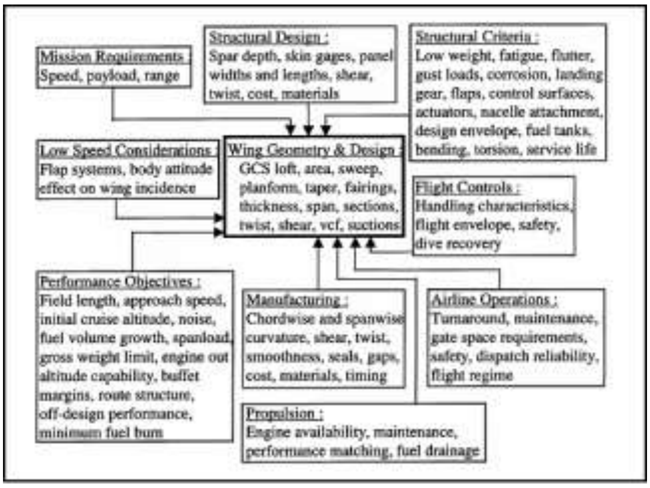

Fig. 4. Parameters affecting wing design

3.2 Aerodynamic design objectives

The main objectives of the wing design are:

a. To obtain a pattern of approximately straight isobar sweep at an angle at least equal to the wing sweepback angle, with the upper surface generally being critical for drag divergence. If this aim is achieved, the flow will be approximately two-dimensional and the drag-divergence will occur at the same Mach number everywhere along the span.

b. To obtain the highest possible wing efficiency (L/D) in cruise flight. The maximum reduction in drag for the wing must be obtained for the cruise CL corresponding to the design case for the proposed aircraft. To achieve the objectives for the design, it was required that the airfoil pressure distributions (suitably interpolated over the span) should be realized by the 3D wing.

c. To have a good performance in off-design operations.

3.3 Wing design

Wing design is of key interest to the aerodynamicist because of its dominant influence on aircraft performance. Early jet transport wing designs were based almost entirely on previous military flight experience and considerable wind tunnel testing. Computational aerodynamics is changing the design process so that more highly refined configurations are possible.

The transport wing design procedure is a continually evolving process. The process has evolved from one of only wind tunnel testing mixed with considerable experience to a procedure that includes tunnel testing, experience and analytical computational aerodynamics. With the advent of computational aerodynamics, the process used to achieve a successful wing design has been improved. Both wind tunnel testing and computational aerodynamics techniques are still required so that the wing design process will continue to change and improve with time.

Although many wing design procedures provide a first-cut try at a “good” wing design, the procedure is not substantiated well enough to guarantee a successful design without considerable wind tunnel testing. It should be anticipated that several cycles of wind tunnel testing will be required to achieve a successful wing design. The primary deficiencies in computational aerodynamics include inadequate modeling of separated and vortex flow, no detailed shock/boundary layer interaction scheme, no adequate drag calculations and no body boundary-layer simulation.

It is beyond the scope of this work to undertake a complete wing design, as described above. In this study, only the aerodynamic aspect will be considered.

3.3.1 Airfoil design

Selection/design of the outboard wing sweep and outboard airfoil section are made at the same time. Usually for most swept wings, the outboard airfoil section defines the wing Mach number capability. This is a result of the higher outboard wing section loading compared to the inboard wing. The lower inboard wing lift is due to wing taper and the lower lift curve slopes near the side of the fuselage. The outboard wing airfoil is selected/designed based not only on the design Mach number but also on the airfoil off-design characteristics. Good low Mach number lift capability is required for climb performance and for aircraft gross weight growth capability. High Mach number characteristics should exhibit low drag creep below cruise Mach number and still maintain gentle stall buffet characteristics. Shock position should remain fairly stable with small changes in Mach number or angle of attack to maintain good ride quality and handling characteristics.

Development of an airfoil is concerned mainly with the selection of the desired pressure distribution. Once this is done, the shape can be computed by a mathematical procedure. However, not all pressure distributions correspond to physically meaningful airfoil shapes; real flow constrains the pressure distribution to have a leading-edge stagnation point, low pressure forward, and gradually rising pressure aft, ending somewhat above ambient at the trailing edge.

However, airfoils described above are often prone to increased shock growth, which result in earlier occurrence of drag rise conditions, relative to an airfoil with an adverse ‘roof-top’ pressure gradient. In fundamental wing design terms, this implies increased sweep, reduced thickness/chord ratio, and/or reduced wing loading, all of which reduce the aerodynamic and/or structural efficiency of the wing for a specified design condition. An alternate approach may be to use an airfoil with a mildly adverse ‘roof-top’ pressure gradient to improve wave drag and lift capabilities. Careful consideration would be required to select/design an airfoil section to achieve maximum aircraft efficiency and minimum operating economics with turbulent flow and a suitable off-design performance.

Airfoil design requirements

In order to satisfy the above aerodynamic wing requirements, the airfoil design requirements are:

a. Low section profile drag coefficients are desired at cruise and climb conditions. Consideration should also be given to provide some operational margin. For this application, cruise performance is more important than climb performance, and so more emphasis was placed on low drag at cruise conditions.

b. The section maximum lift coefficient with no flap deflection should be at least 1.8. The loss in maximum lift coefficient due to leading edge contamination should be less than 7%. The stall characteristics should be docile.

c. At cruise condition, the section pitching moment coefficient should not be too negative to minimize the trim drag penalty. In addition, the hinge moment coefficient, that is, aileron floating tendency, should not be excessive.

d. Airfoil thickness must be 17% chord (root) and 13.5% chord (tip) to ensure sufficient fuel volume to satisfy the range requirement.

e. The drag divergence Mach number should be higher than 0.70 at cruise condition.

Clean airfoil.

It selected two airfoil types of NACA 65(3)-218 and medium speed airfoils MS(1)-0317 as shown in Fig. 5. The pressure distribution of MS(1)-0317 airfoil is predicted with XFOIL 1.0 code. XFOIL 1.0 was written by Mark Drela in 1986. XFOIL is an interactive program for the design and analysis of subsonic isolated airfoils. The results are as shown in Fig. 6.

The MS(1)-0317 has higher lift coefficient at zero angle of attack and 2-D maximum lift coefficient (clmax) than NACA 65(3)-218, as presented in Table 1. Fig. 7 shows the effect of the airfoils thickness to the maximum lift coefficient. The highest maximum lift coefficient occurs at 14% thickness ratio for medium airfoil series and 12% for NACA series.

A high-speed characteristic of Mach Drag Divergence (MDD) for various thickness ratios was analyzed using MSES code. As shown in Fig. 8, MDD for MS(1)-0317 is higher than for NACA 65(3)-218.

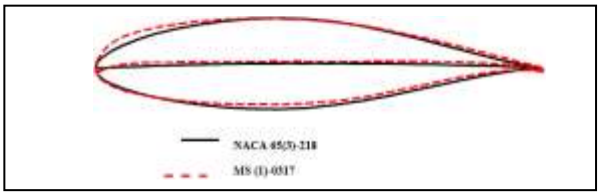

Fig. 5. Comparison of the airfoils candidate

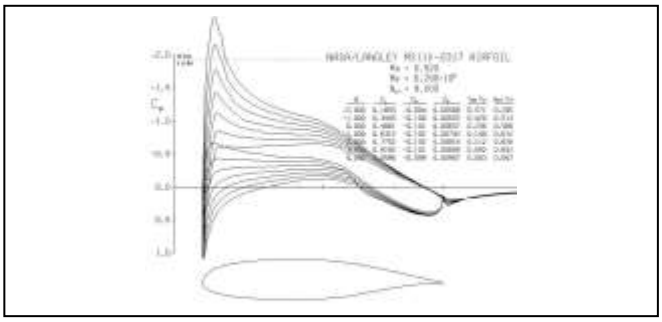

Fig. 6. NASA/LANGLEY MS(1)-0317 airfoil

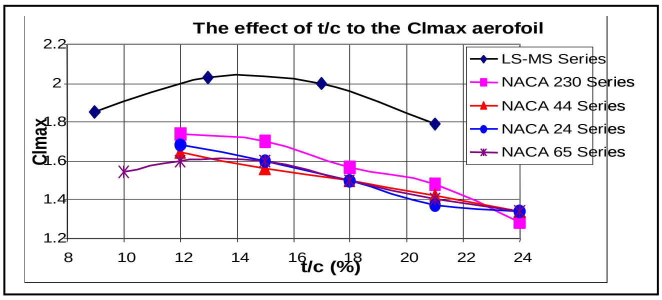

Fig. 7. The effect of thickness ratio to the maximum lift coefficient of the airfoils

For this study, the wing airfoils are derived from MS(1)-0317 and MS(1)-0313 with modifying the lower aft portion to decrease pitching moment. The root airfoil has a thickness ratio of 17% and 13.5% thickness ratio for the tip airfoil (it is a compromise between structure, maximum lift coefficient, lift-to-drag ratio, Mach drag divergence and to ensure sufficient fuel volume to satisfy the range requirement). The geometries of the above airfoils are as shown in Fig. 9.

Table 1 Comparison of the characteristics of the airfoil candidates

ITEM	**NACA 65(3)-218**	**MS (1)-0317**
Cl max	1.48	1.98
Alfa max	18	18
Cl at alfa = 0	0.15	0.35
Cd at Cl = 0	0.0045	0.0070
Cm at Cl = 0	-0.03	-0.075
Leading edge shape	Sharp	Blunt

Notes: Cd = drag coefficient
Cm = moment coefficient Cl = lift coefficient

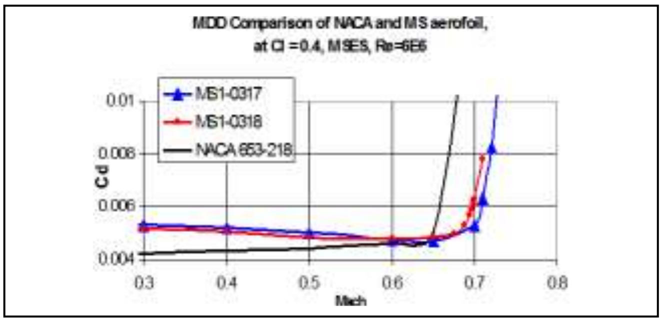

Fig. 8. Mach Drag Divergence (MDD)

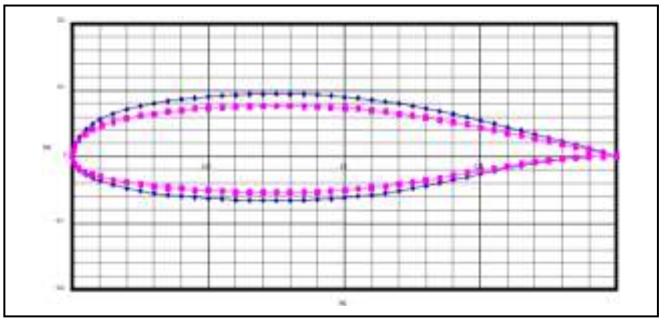

Fig. 9. Airfoils for wing root and tip

Flap.
For simplicity reasons, a single slotted flap to be applied in VLJ-25 to achieve the given requirement. The flap chord ratio is 28% airfoil chord.

Fig. 10 shows the flap deflection schedule for clean, take-off and landing configuration. MSES code is used to define the flap gap and overlap, the result is shown in Fig. 11.

3.3.2 Wing aerodynamic design

The wing is designed to satisfy the low and high-speed requirements. The wing performance presented in this section is for Wfx1-3 configuration, which is slightly different from VLJ-25-01 (Fig. 1). The wing geometric parameters are:

* Area (S) = 17 m2
* Aspect ratio (AR) = 9
* Span = 12.36 m
* c/4 sweep = 4.33 deg.
* Taper ratio
* Incidence = 2 deg.
* Twist = -3 deg.
* Dihedral = 5 deg.
* Root chord = 1.96 m
* Tip chord = 0.79 m
* Mean aerodynamic chord = 1.458 m
* Thickness ratio (t/c)root = 0.17
* Thickness ratio (t/c)tip = 0.135

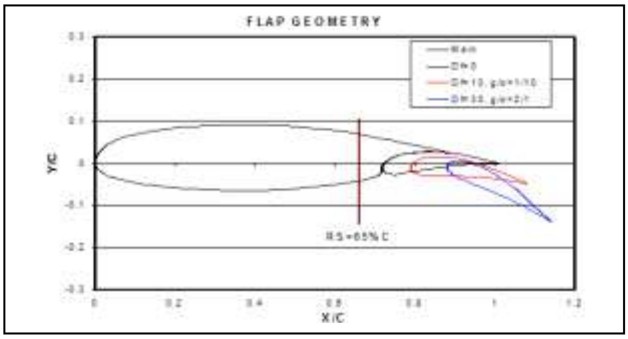

Fig. 10. Flap deflection schedule for clean, take off and landing configuration

The low-speed requirements are maximum lift coefficient (CLmax) and the stall characteristics; while the high-speed requirements are MDD (Mach Drag Divergence), shock wave and buffet (buffet is caused by unsteady separated flow at high and low speeds and large angles of attack, it can be caused by shock waves at high speed). For take-off and landing configuration CLmax (aircraft max. lift-coefficient) must be at least 2.2 and 2.5 respectively. These requirements are defined in the aircraft configuration sizing to achieve the required performances.

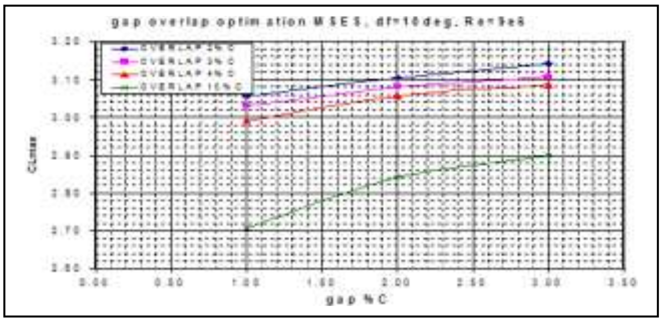

Fig. 11. Gap and overlap scheme for take off configuration

The stall characteristics can be defined by using the span load distribution calculated by VSAERO code for various angles of attack. At stall, clmax at root and at tip of the wing is a tangent line to the span load distribution at appropriate Reynolds number and certain angle of attack. It might be addressed/designed that the stall starting point will occur on a certain location of the wing for untwist and –3 degrees twist of the wing configuration.

For the untwisted wing, the stall starting point is at 56% semi span and for –3 degrees twisted wing the stall starting point is at 36% semi span, as shown in Fig. 12 - 15. Therefore, the twisted wing provides the good stall starting point as well as good stall characteristics.

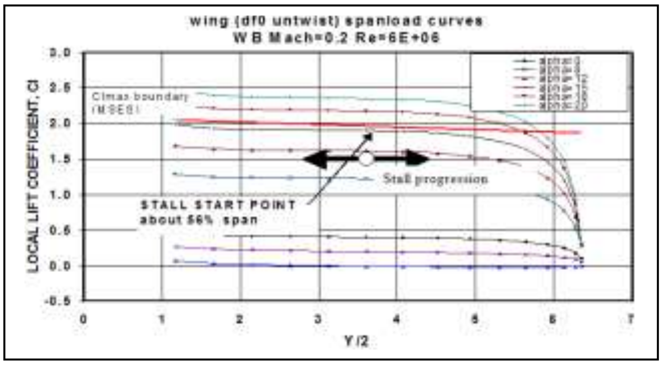

Fig. 12. Stall characteristics and progression over the wing (M 0.2, untwist and flap def = 0 deg.)

Based on the "Mach vs CD" chart, MDD is defined as Mach number where dCD/dM = 0.1. For this study, MDD was calculated using SYN88 code. As shown in Fig. 16, the value of MDD is about 0.72 at cruise lift coefficient of 0.310 for 7500 lbs maximum take off weight.

Comparison of chordwise pressure distributions on wing for several Mach number and angle of attack is shown in Fig. 17; it can be seen that at design point the shape of the chordwise pressure distribution is similar to its 2D (rooftop) and there is no strong shock wave until Mach number 0.7. The pattern of approximately straight isobar sweeps at an angle at least equal to the wing sweepback angle, with the upper surface generally being critical for drag divergence. Hopefully the flow will be approximately two-dimensional and the drag-divergence will occur at the same Mach number everywhere along the span (in the future need to be supported by 3D calculations).

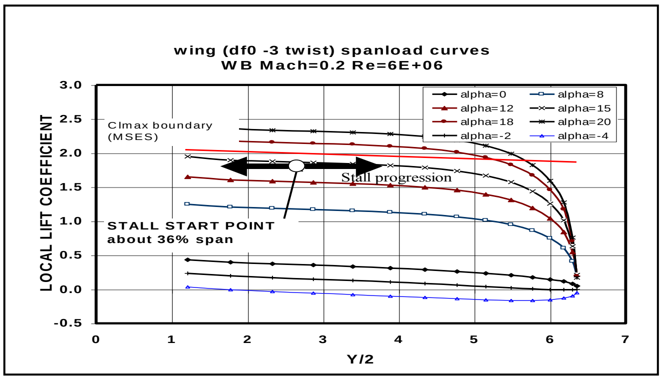

Fig. 13. Stall characteristics and progression over the wing (M 0.2, -3 deg twist and flap def = 0 deg.)

For wings with a varying maximum thickness ratio, the objective is to maintain isobars that are swept along constant percent chord lines. To achieve this goal will require camber modifications that will probably result in characteristics equivalent to thicker airfoil sections.

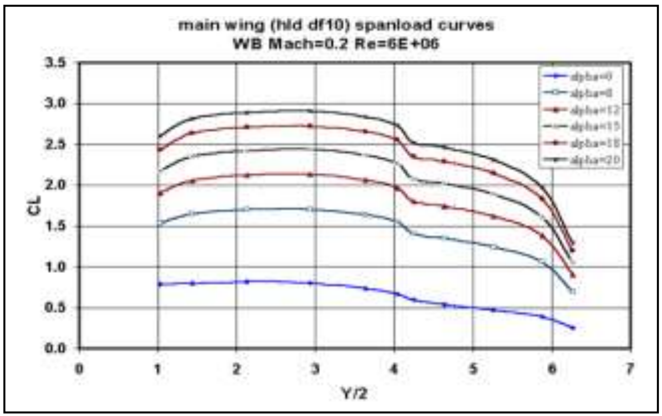

Fig. 14. Stall characteristics and progression over the wing (M 0.2, -3 deg twist and flap def = 10 deg.)

Wing upper surface isobars (constant Cp's) are the key to the wing performance and achievement of the equivalent 2D aerofoil performance. Usually isobars are defined to be swept along constant percent chordlines on the wing. Constant percent chordline isobars are desirable so that at transonic speeds the shock strength and location and section loading will be constant. This is relatively easy to achieve for a trapezoidal wing with constant thickness. The chordwise values of the isobars are directly a function of the aerofoil pressure distributions and are left to the discretion of the designer.

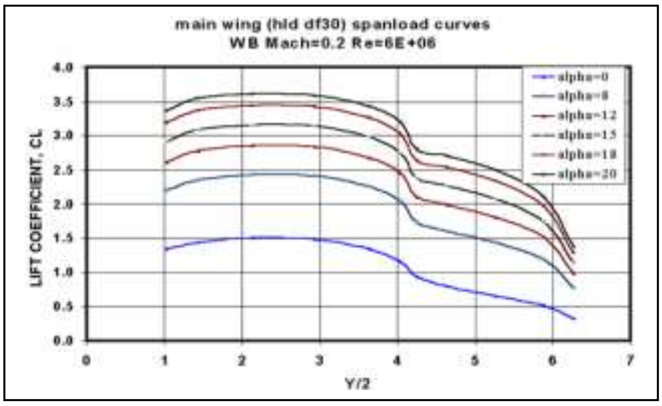

Fig. 15. Stall characteristics and progression over the wing (M 0.2, -3 deg twist and flap def = 30 deg.)

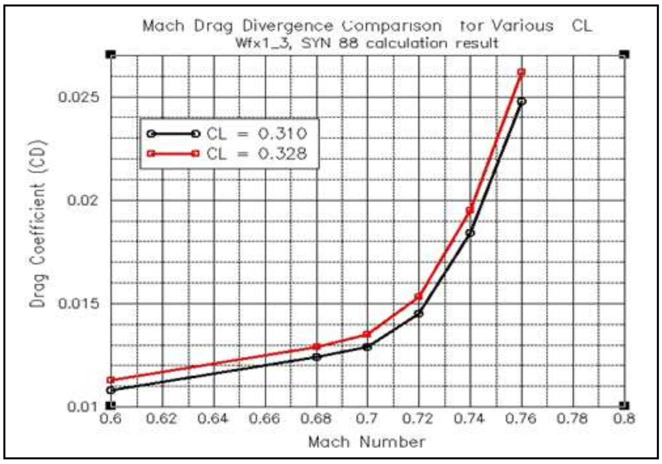

Fig. 16. Mach Drag Divergence

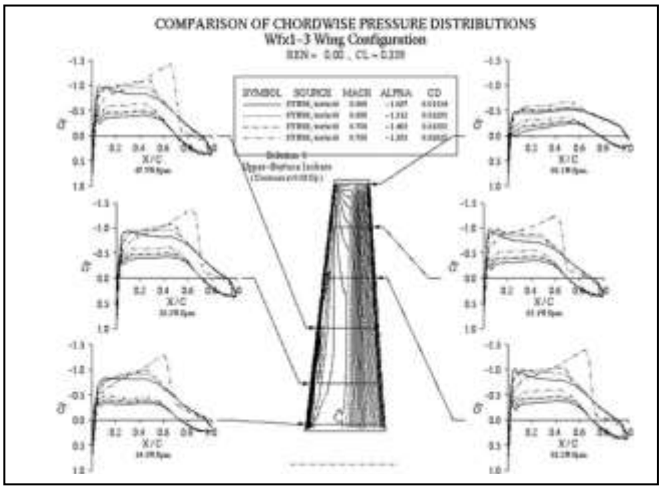

Fig. 17. *Chordwise pressure distributions on wing*

Fig. 18 shows wing-span-load distributions for several Mach number and angle of attack, where its shape is almost triangular.

Choice of the wing span-load distribution is an important decision in the wing design process. Ideally, an elliptic distribution is desirable at the cruise condition because of the implied minimum induced drag. However, several factors make a slightly triangular distribution very desirable. First, an elliptic loading at cruise will tend to overload the wing tip at the design load condition. This implies a more outboard center of pressure and associated increased wing structural weight. Also associated with the further outboard loading is the tendency for increased tip stall and its influence on pitch-up and handling qualities. Trade studies of increased drag and reduced wing weight for more triangular span-load distributions must be made.

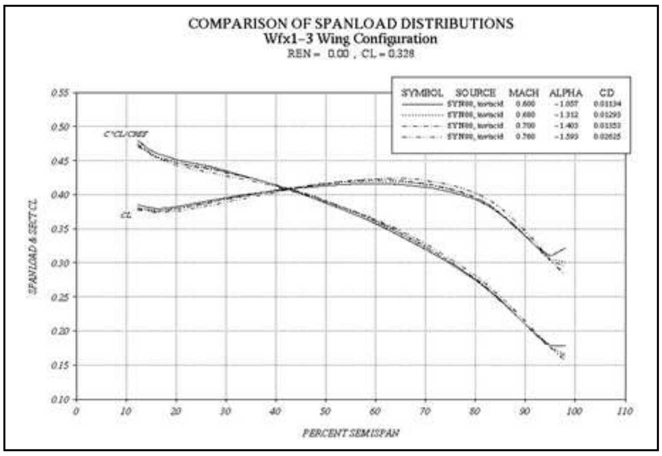

Fig. 18. Wing-span load distributions

4 Tail Design

The airfoils for horizontal and vertical tail are MS(1)-313 (installed inverted) and NACA 651A013, respectively.

The horizontal tail should be kept out of the wing wake at cruise (this may require significant tail dihedral). However, a high tail should be carefully evaluated because tail effectiveness at the stall may become inadequate (Fig. 19), resulting in pitch-up, and/or the possibility of a "deep stall" [4 & 43]. In a deep stall, the horizontal tail is immersed in separated flow from the wing, so that there is insufficient longitudinal control power to get out of the stall.

The pitch-up characteristics of the aircraft are as follows (Figure 19) [4 & 43]:

Region A	Pitch-up at high lift generally preceded by warning
Region B	Pitch-up without warning, avoid
Region C	Generally no pitch up at subcritical speeds
Region D	Generally no pitch-up

To prove the stability of the above VLJ configuration, further detail analysis, including wind tunnel test is needed.

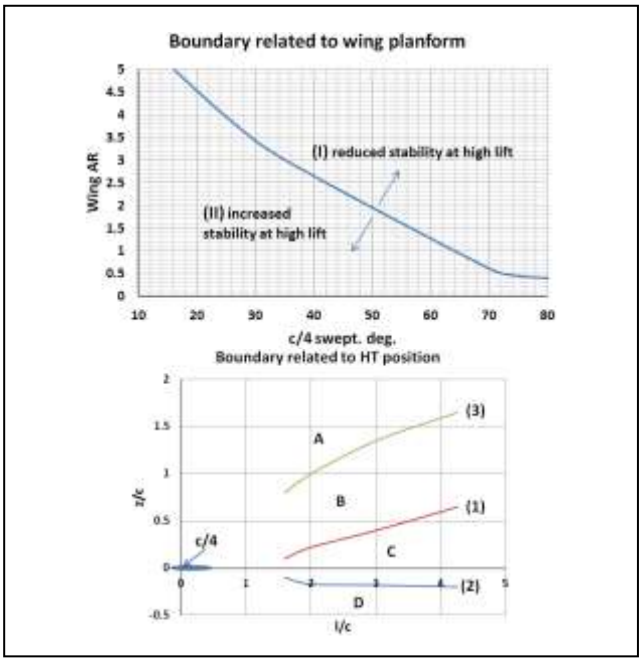

Fig. 19. Guidelines for wing design and horizontal-tail position in VLJ aircraft

5 Aircraft Performances

The aircraft performances (Fig. 20) are predicted at maximum take-off weight = 7,500 lbs., operating empty weight = 4,780 lbs., fuel weight = 1,695 lbs. and design payload (5 passengers @ 205 lbs.) = 1,025 lbs.

The summary of aircraft performances is:

* Range = 1,500 nm
* Max speed at cruise = 420 knots (M = 0.70)
* The payload-range diagram is presented in Figure 20.
* Take-off field length = 2,311 ft
* Landing field length = 2,225 ft

(with the assumption of maximum lift coefficient for take-off and landing are 2 and 2.6 respectively).

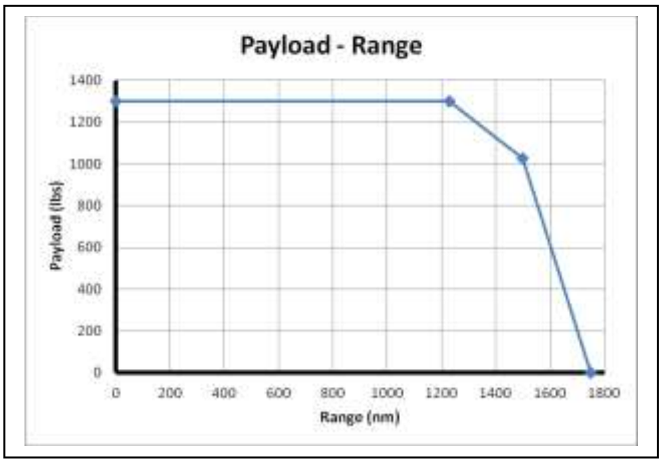

Fig. 20. Payload vs. Range diagram

6 Conclusions

A methodology has been developed for the aerodynamic wing design, allowing for the use of an advanced high-lift capability, high cruise Mach number and lower moment turbulent airfoils derived from MS (1)-0317 and MS (1)-0313 for VLJ aircraft.

To simulate the real flow, the grid should be fine enough, especially in the region of high curvature (e.g., leading edge), the grid adjacent to the wall and in the regions of high-pressure gradients.

The conclusion can finally be drawn, that the application of an advanced turbulent airfoils concept is feasible for a VLJ aircraft from an aerodynamic point of view, with the same reservations that apply to the feasibility of any advanced turbulent airfoils aircraft, i.e., that the economic aspects depend on manufacturing and operational data. Before advanced turbulent airfoils technology can be applied to VLJ aircraft, a large multidisciplinary research effort is needed in order to master the technology and to demonstrate it on flying test-beds, and during in-service operational tests.

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