The Design of Light Jet Aircraft

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Abstract: - This paper discusses the design of light jet aircraft (LJA) in the university level. The design process that covers by this paper is just from conceptual approach. Current technical information of the light jet aircraft in the market will be studied for competitor analysis purpose. After that, the calculation process will take part, like initial sizing, performance sizing, initial sizing of main component, weight breakdown, cg (centre of gravity) position and aircraft performance. It concludes with a discussion of the results and recommendations for future work. This paper will only concentrate on conceptual design, the next stage of design can be continuing in future with the data from this paper.

Key-Words: - conceptual design, wing design, aircraft design, aerodynamic configuration, light jet

1 Introduction

The days of commercial air travel being a glamorous experience are long gone. Efficiency and convenience have been supplanted by hub-and-spoke gridlock with agonizingly long check-in and transfer procedures. Even well intentioned, post-9/11 security procedures have only served to exacerbate these issues and add to the frustration.

While these inefficiencies have resulted in dramatically increased interest in private air travel, the high cost of acquiring and operating corporate and charter jets has hampered growth. Currently, the least expensive new private jet is priced at almost $4 million with direct operating costs of just under $2.00 a mile (Cessna CJ1). This puts private air travel out of the reach of most travelers. That is all about to change.

The next generation of business jet will have an acquisition cost of as low as approximately $ 1.07 million (projected price for delivery in March 2006) and direct operating costs estimated to be $ 0.69 a mile (Eclipse 500). This will enable a new generation of travelers to take advantage of the convenience, comfort, and flexibility of private air travel for a fraction of today's costs.

Imagine someday calling a taxicab in the shape of a tiny jet that seats six and can pick you up at your local municipal airport and deliver you to where you want to go for about the cost of an airline coach seat. Inside, it will resemble a luxury sedan and will be equipped with computerized flight controls and safety features rivaling a Boeing 777. It will be capable of flying almost 375 knots at altitudes of up to 41,000 feet, yet remain light (take-off weight as low as 5,640 lbs) and maneuverable enough to land and take off from virtually every small airport in the nation (take-off distance as short as 2155 ft). For the first time ever, private jet travel will become an affordable alternative to current air travel options (Eclipse 500).

The continuing popularity of travel by general aviation aircraft is partly due to the fact that these aircraft have access to nearly 5,300 airports in the United States, compared to the 558 served by the scheduled air carriers. Furthermore, approximately 70 percent of all airline passengers travel to or from the top 30 air carrier hubs.

The ability to use smaller, less-congested airports located closer to one's final destination is a vital part of the utility and flexibility of general aviation aircraft.

Traditionally, corporate/executive and business aircraft operators have compiled the best safety records of any segment of general aviation.

All currently manufactured business jets meet FAR Part 36 Stage 3 requirements, the most stringent of the FAA's three-tier rating system for aircraft noise. Therefore, new-production business jets are among the quietest airplanes operating today.

2 Configuration Design

2.1 The Market

According to Honeywell, this is the "most robust period in business aviation history." The popularity of business aircraft has increased as more companies realize the efficiency and productivity of this powerful business tool. The number of companies operating business aircraft (jets and turboprops) in the United States has grown more than 55 percent from 6,584 in 1991 to 10,191 in 2002.

The worldwide jet fleet as of the end of 2002 was 12,581 aircraft, more than double the fleet size in 1986. In fact, steady growth has occurred over the last 20 years. Since 1986, the worldwide turboprop fleet also has grown, reaching 9,995 aircraft by the end of 2002.

During 2002, 13,958 operators flew 22,576 turbine-powered business aircraft (jets and turboprops) worldwide. More than 75 percent of the operators (10,502) and 72 percent of the aircraft (16,319) were located in North America. Europe was home to the second largest concentration of operators (1,196) and aircraft (2,289), while South America ranked third in both categories, with 977 operators and 1,531 aircraft. The remaining 9 percent of the operators and 11 percent of the aircraft are scattered throughout Africa, Asia, Central America, the Middle East and Oceania (which includes Australia and the Pacific islands)

The fleet distribution among jets and turboprops varies greatly depending on geographic area (Figure 3). Operators in Asia have nearly equal proportions of jets and turboprops in their inventories. By contrast, operators in Africa, South America and Oceania utilize many more turboprops than jets, while in the United States, Europe and Central America, the fleet is more heavily weighted towards jets.

Rolls-Royce said today (October 11, 2004) that the market for business jets is on the upturn with stronger deliveries predicted beginning in 2005 and beyond. The company projects more than 500 aircraft deliveries for 2004, on par with 2003 levels.

Revealed in the company's latest business jet forecast "covering the 2004 to 2023 market" the industry is in the beginning of a stronger market for business aircraft as virtually the entire key market driver indicators have turned positive and are trending up.

"Economic indicators, coupled with a reduced inventory of viable used aircraft and growth of share purchases at fractional companies, support our increased delivery forecast," said Ian Aitken, President - Corporate & Regional Aircraft for Rolls-Royce.

The age profile of current in-service business jets also shows there will be a wave of replacement orders through the forecast period. Almost 40 percent of today's business jet fleet is 20 years of age or older

The Rolls-Royce forecast illustrates a strong market for all sectors across the business jet landscape over the next 20 years. The long term forecast projection shows the need for 23,000 aircraft with a delivery value of $284 billion for micro-jets through business liners. For the first time, Rolls-Royce has projected a new segment called "micro-jets". This segment, comprised of very small four to six seat jet aircraft, is forecast to have 8,000 aircraft deliveries over the projected period. The traditional business jet sector is forecast to have 15,000 aircraft deliveries through 2023 -- up slightly from the Rolls-Royce 20 year forecast published last year. While it is anticipated that all business jet sectors will see growth in deliveries, the medium to very long-range sector will have two-thirds of aircraft delivery value over the forecast period.

The forecast also indicates a rising proportion of new aircraft deliveries for fractional use relative to the total market. Today, fractional operators take delivery of about 10-15 percent of the annual market of business jet deliveries. The forecast shows this proportion increasing to as much as 22 percent of the market.

The North American market is forecast to keep its dominant share of business jet deliveries while other regions of the world will have higher growth rates relative to their historical performance as a result of growing regional economies.

Honeywell Aerospace's 11th Annual Business Aviation Outlook projects continuing demand for new business aircraft with customers accepting more than 7,600 units, valued at over $121 billion, for the period from 2003 to 2013.

Business jet operators have been arguing for the past decade [1] about the market prospects for very light jets, or VLJs - planes with a maximum gross takeoff weight of less than 4,500 kilograms and capable of flying as many as four passengers on direct routes between small airfields.

The arguments revolve around the likely demand for jet air taxis that can collect customers at short notice "at an airfield near you," and deliver them to sales prospects, remote factory sites or that fishing and hunting lodge in the wilderness not too far from a usable air strip.

As the debate has raged, several test aircraft, weighing less than 10,000 pounds, have reached at least first-flight development, but few have gone farther.

The first Eclipse 500 was delivered to its buyer last December 31 and 11 have been delivered to date. The company claims a backlog of 2,500 firm orders and options with nonrefundable deposits. Eclipse management takes a very bullish view of the VLJ market, forecasting demand for 500 of its planes every year.

Adam Aircraft, based near Denver, is not quite as far along with its A700 twin-jet. The company's management takes a cooler view of the potential market, saying it would be satisfied with annual deliveries of about 50 aircraft.

Like other manufacturers of VLJs, both Eclipse and Adam use small, lightweight jet engines originally developed to power U.S. Air Force cruise missiles on one-way trips toward their targets. Reliability was important, but the engines were not designed for long service or repeated takeoffs and landings.

However, the engine manufacturers - Williams International of Walled Lake, Michigan, and Pratt & Whitney Canada, a division of United Technologies - have reworked their products for safe and repeated civilian use.

Weighing in for takeoff at 10,800 pounds, the Cessna Citation Mustang is technically one size above the VLJ niche, and Cessna itself denies being in the VLJ business. Cessna's Citation Mustang, priced at $3 million.

At the smaller end, Embraer is offering its Phenom 100 light jet series. Luis Carlos Affonso, executive vice president for business aircraft at Embraer, said that sales of the two aircraft had reached nearly 400 combined. Its list price is $2.98 million.

It is important to know the trends of the significant characteristics of existing aircraft. This trends can be used to check how good the design, is the design in the improvement sense or degradation?

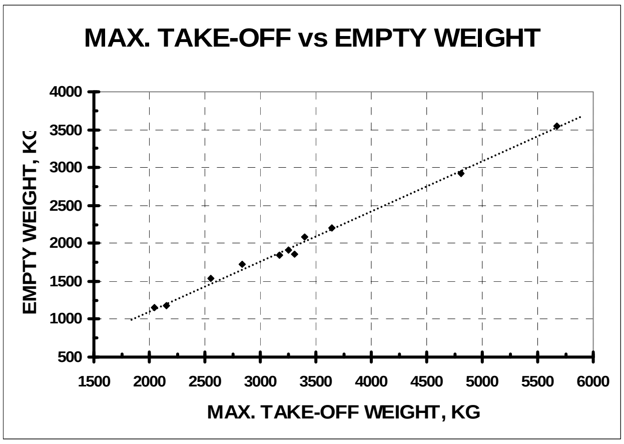

Figure 1. Max. take-off weight versus empty weight

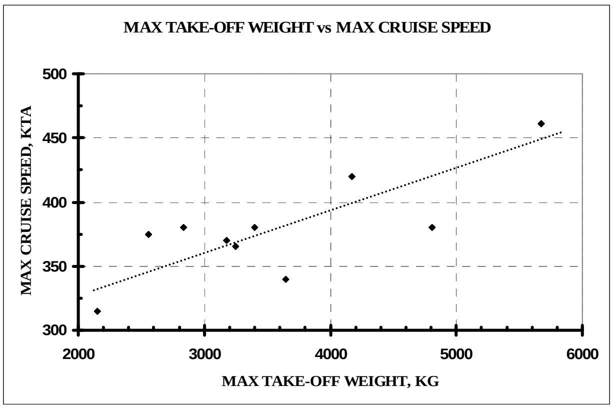

Figure 2. Maximum take-off weight versus maximum cruise speed

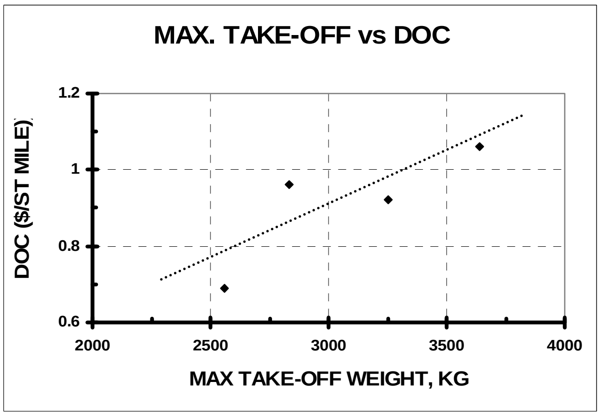

Figure 3. Maximum take-off weight versus DOC

It can be used also to see how competitive the design compare to the competitors. The characteristics plotted on this paper are : maximum take-off weight (MTOW), empty weight (WE), maximum cruise speed ($V_{cr.max}$), direct operating cost (DOC), and aircraft price as shown on Figure 1 – 4.

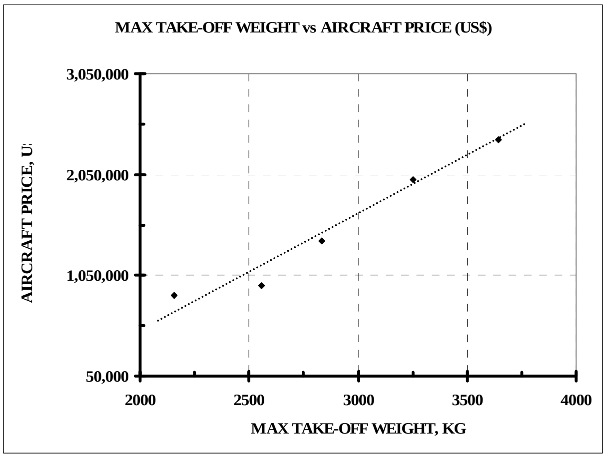

Figure 4. Maximum take-off weight versus aircraft price

2.2 Design Requirements and Objectives

The following is 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 : 1500nm with design payload plus alternate flight as long as 100nm and holding for 30 min before landing.
- Cruise Speed : 425 knots at 33,000ft (M = 0.73)
- 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

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 [2].

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.

Figure 5. Sino Swearingen SJ30-2

Figure 6. Honda Business Jet

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

Conventional arrangement. 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 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. management & engine accessibility. Typical general arrangement of this configuration is as shown in Figure 5.

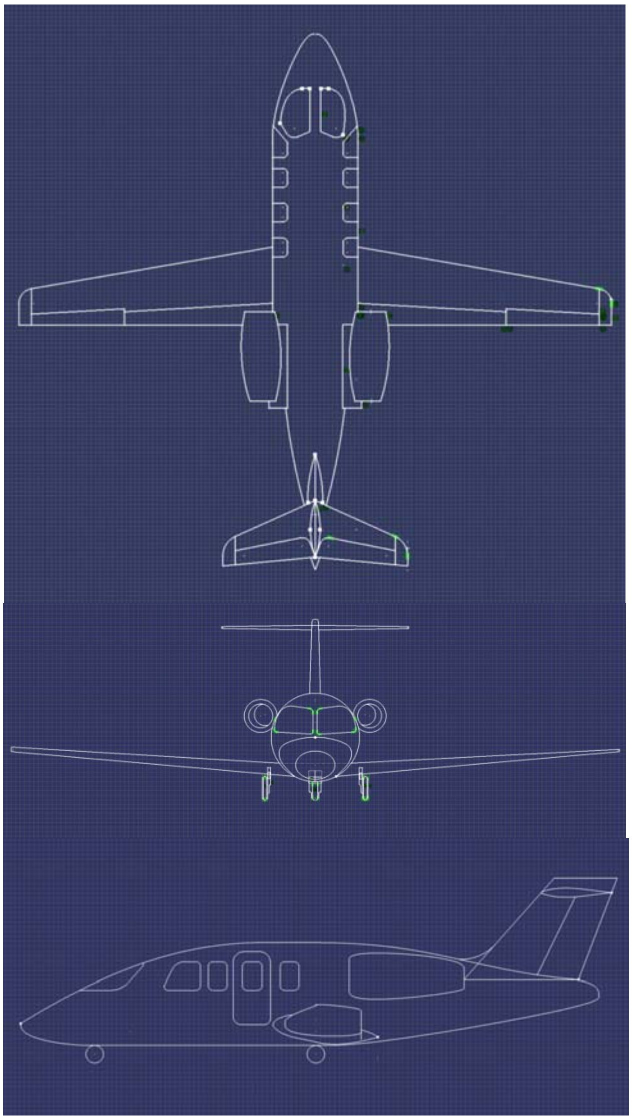

Figure 7. Conceptual sketch of VLJ-25

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Over the past few years Honda has been quietly developing a six- to eight-place very light twinjet (Figure 6). 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 [3].

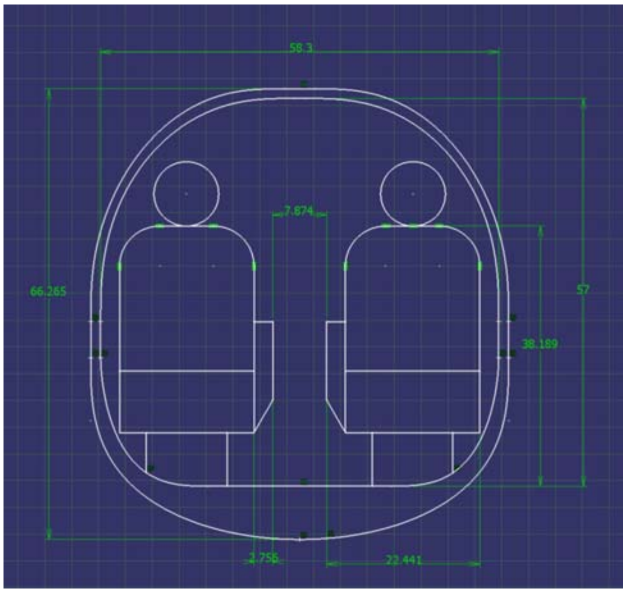


Figure 8. Cabin cross section

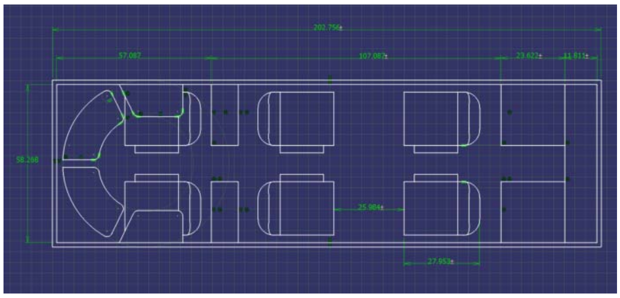


Figure 9. Cabin plan view

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. Compare 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.

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 Figure 7.

Figure 8 and Figure 9 show the dimension of the cabin in inch.

3 Aerodynamic Wing Design

3.1 General Requirements

Basic requirements that must be achieved for a successful wing design include [2, 4 - 7] :

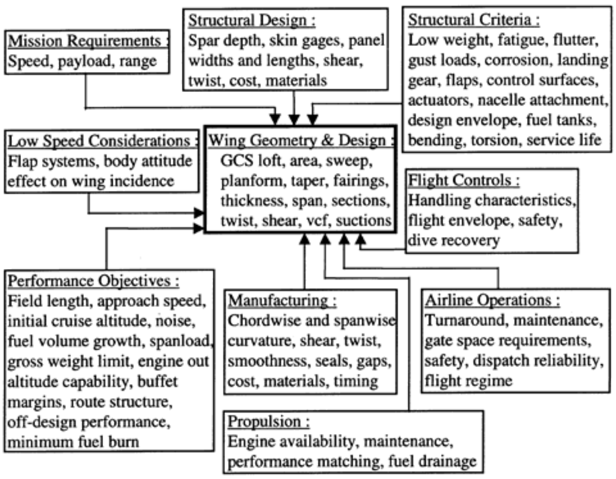


Figure 10. Parameters affecting wing design

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. Parameters affecting wing design are presented in Figure 10.

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 every where along the span.
b. To obtain the highest possible of wing efficiency (L/D) in cruise flight. The maximum reduction in drag for the wing must be obtained for the cruise C_L 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 Configuration Description

The wing geometric parameters are :
Area (S) = 191 ft^2
Asper ratio (AR) = 8.5
Span = 483.5 inch.
Leading edge swept = 9.66 deg.
Root chord = 77.52 inch.
Tip chord = 36.38 inch.
Taper ratio $\lambda = 0.47$
Thickness ratio $(t/c)_{root}$ = 0.17
Thickness ratio $(t/c)_{tip}$ = 0.13
Mean aerodynamic chord = 59.41 inch.

The pressure distributions of wing 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 geometric and its pressure distributions of wing airfoil at mid span is as shown in Figure 11 and Figure 12, respectively. The geometric and its pressure distributions of wing airfoil at inboard and outboard are as shown in Figure 13 and Figure 14, respectively..

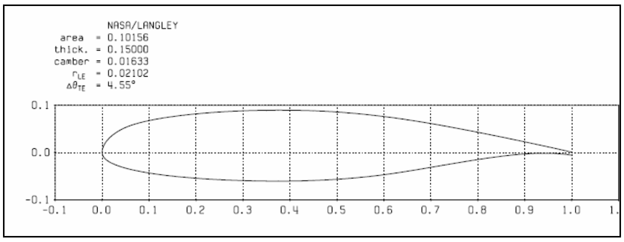


Figure 11. Airfoil at mid span

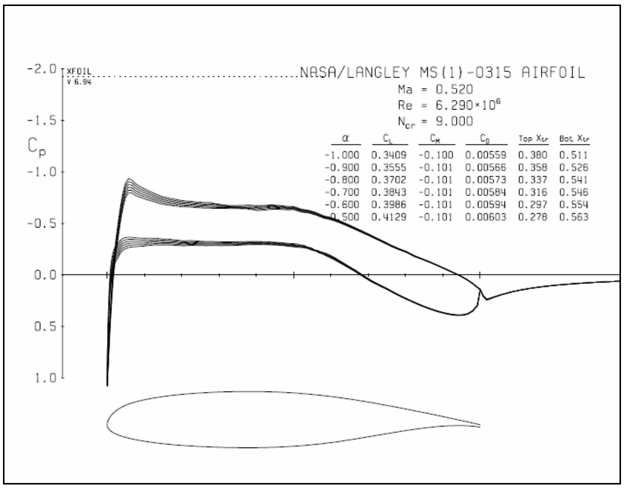
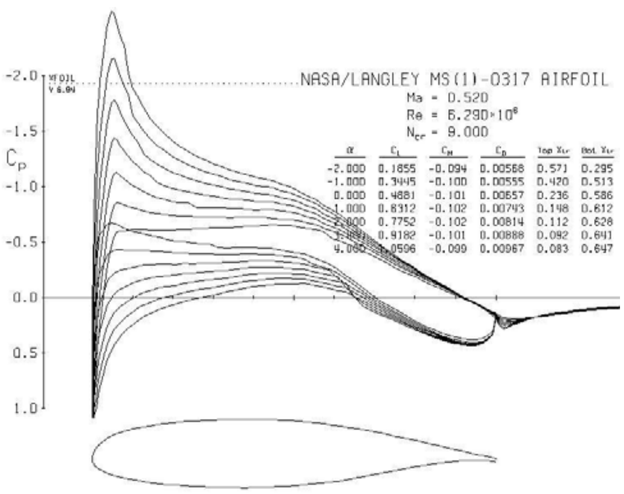


Figure 12. Pressure distributions of airfoil at mid span

X	Y
1.00000	.00125
.97500	.00720
.95000	.01302
.92500	.01873
.90000	.02444
.87500	.03013
.85000	.03576
.82500	.04132
.80000	.04687
.77500	.05225
.75000	.05755
.72500	.06269
.70000	.06763
.67500	.07232
.65000	.07672
.62500	.08079
.60000	.08448
.57500	.08777
.55000	.09073
.52500	.09323
.50000	.09535
.47500	.09700
.45000	.09826
.42500	.09909
.40000	.09956
.37500	.09972
.35000	.09952
.32500	.09901
.30000	.09815
.27500	.09694
.25000	.09536
.22500	.09339
.20000	.09096
.17500	.08805
.15000	.08454
.12500	.08033
.10000	.07511
.07500	.06840
.05000	.05893
.03750	.05210
.02500	.04322
.01250	.03099
.00500	.01950
.00200	.01248
0.00000	0.00099
.00200	-.00857
.00500	-.01366
.01250	-.02105
.02500	-.02866
.03750	-.03423
.05000	-.03865
.07500	-.04541
.10000	-.05058
.12500	-.05477
.15000	-.05817
.17500	-.06099
.20000	-.06330
.22500	-.06527
.25000	-.06685
.27500	-.06812
.30000	-.06909
.32500	-.06978
.35000	-.07021
.37500	-.07036
.40000	-.07019
.42500	-.06967
.45000	-.06880
.47500	-.06755
.50000	-.06591
.52500	-.06389
.55000	-.06138
.57500	-.05845
.60000	-.05501
.62500	-.05106
.65000	-.04674
.67500	-.04214
.70000	-.03735

.72500	-.03255
.75000	-.02780
.77500	-.02309
.80000	-.01857
.82500	-.01433
.85000	-.01049
.87500	-.00719
.90000	-.00460
.92500	-.00289
.95000	-.00232
.97500	-.00324
1.00000	-.00597

MS(1)-0317 airfoil : Airfoil coordinate



MS(1)-0317 airfoil : Pressure distribution

XFOIL Version 6.94

Calculated polar for: NASA/LANGLEY MS(1)-0317 AIRFOIL

1 1 Reynolds number fixed Mach number fixed

xtrf = 1.000 (top) 1.000 (bottom)

Mach = 0.520 Re = 6.290 e 6 Ncrit = 9.000

alpha	CL	CD	CDp	CM	Top_Xtr	Bot_Xtr
-2.000	0.1855	0.00568	0.00167	-0.0942	0.5711	0.2947
0.000	0.4881	0.00657	0.00222	-0.1012	0.2355	0.5862
1.000	0.6312	0.00743	0.00280	-0.1018	0.1483	0.6117
2.000	0.7752	0.00814	0.00339	-0.1018	0.1115	0.6284
3.000	0.9182	0.00888	0.00408	-0.1010	0.0918	0.6409
4.000	1.0596	0.00967	0.00486	-0.0990	0.0833	0.6471

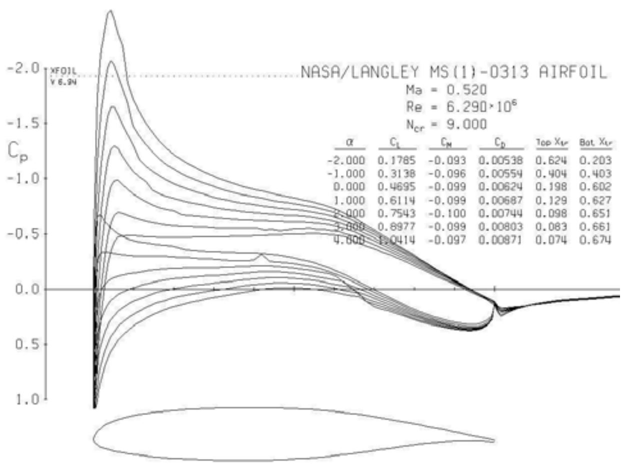
MS(1)-0317 airfoil : Aerodynamic coefficients

Figure 13. NASA/LANGLEY MS(1)-0317 airfoil

X	Y
1.00000	-.000471
.97500	.004699
.95000	.009822
.92500	.014950
.90000	.020079
.87500	.025177
.85000	.030259
.82500	.035288
.80000	.040179
.77500	.044899
.75000	.049418
.72500	.053710
.70000	.057745
.67500	.061488
.65000	.064903
.62500	.067958
.60000	.070636
.57500	.072934
.55000	.074868
.52500	.076464
.50000	.077753
.47500	.078763
.45000	.079517
.42500	.080026
.40000	.080293
.37500	.080324
.35000	.080119
.32500	.079678
.30000	.078991
.27500	.078033
.25000	.076777
.22500	.075199
.20000	.073274
.17500	.070963
.15000	.068189
.12500	.064805
.10000	.060608
.07500	.055169
.05000	.047433
.03750	.041872
.02500	.034450
.01250	.024286
.00500	.015120
.00200	.009475
0.00000	0.000986
.00200	-.006272
.00500	-.009977
.01250	-.015246
.02500	-.020594
.03750	-.024404
.05000	-.027454
.07500	-.032278
.10000	-.036076
.12500	-.039204
.15000	-.041819
.17500	-.044001
.20000	-.045806
.22500	-.047282

.25000	-.048471
.27500	-.049410
.30000	-.050129
.32500	-.050645
.35000	-.050960
.37500	-.051059
.40000	-.050919
.42500	-.050512
.45000	-.049814
.47500	-.048812
.50000	-.047511
.52500	-.045918
.55000	-.044024
.57500	-.041812
.60000	-.039274
.62500	-.036426
.65000	-.033315
.67500	-.030007
.70000	-.026571
.72500	-.023071
.75000	-.019568
.77500	-.016140
.80000	-.012881
.82500	-.009897
.85000	-.007286
.87500	-.005135
.90000	-.003535
.92500	-.002607
.95000	-.002523
.97500	-.003540
1.00000	-.006054

MS(1)-0313 airfoil : Airfoil coordinate



MS(1)-0313 airfoil : Pressure distribution

XFOIL Version 6.94

Calculated polar for: NASA/LANGLEY MS(1)-0313 AIRFOIL

1 1 Reynolds number fixed Mach number fixed

xtrf = 1.000 (top) 1.000 (bottom)

Mach = 0.520 Re = 6.290 e 6 Ncrit = 9.000

alpha	CL	CD	CDp	CM	Top_Xtr	Bot_Xtr
-2.000	0.1785	0.00538	0.00128	-0.0930	0.6245	0.2030
1.000	0.6114	0.00687	0.00221	-0.0995	0.1295	0.6268
2.000	0.7543	0.00744	0.00269	-0.0997	0.0977	0.6508
3.000	0.8977	0.00803	0.00324	-0.0991	0.0835	0.6607
4.000	1.0414	0.00871	0.00393	-0.0975	0.0744	0.6735

MS(1)-0313 airfoil : Aerodynamic coefficients

Figure 14. NASA/LANGLEY MS(1)-0313 airfoil

4 Aircraft Performances

The aircraft performances are predicted at maximum take-off weight = 8,600 lbs, operating empty weight = 4,946 lbs, fuel weight = 2381 lbs and maximum payload (5 passengers) = 1,025 lbs.

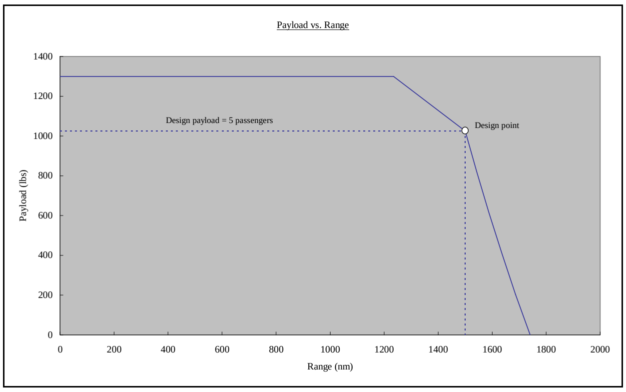


Figure 15. Payload vs. Range diagram

The summary of aircraft performances are :

- 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).
- Range = 1,500 nm
- Max speed at cruise = 420 knots (M = 0.722)
- The payload-range diagram is presented in Figure 15.

5 Conclusion

This paper is the first iteration of the project. The VLJ that designed had satisfied all the design requirement and objective (DR&O).

The design process is based on many historical data. Some of the value is assumed by taking the average value from competitor aircraft. For further design and performance improvement, further iteration is needed.

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