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CONCEPTUAL DESIGN STUDY OF QUAD-BUBBLE-BUSINESS JET

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Abstract

Realizing that air transportation markets in the business jet type are potential, the present work is devoted for exploring the possibilities of introducing some of a number of visionary and pioneering ideas and upcoming enabling technologies in a Conceptual Design Study of Quad-Bubble Business Jet (QB-BJ). In view of and driven by the vision for a fuel efficient, environmentally friendly and technology driven aircraft to meet global need within the next 15 years, the characteristics of the conceptually designed aircraft will be assessed in comparison to an appropriately chosen business jet as a reference. Major ideas derived from D.8 concept will be appropriately applied and further elaborated. The work is carried out starting with fuel efficient motivation, and followed by the selection of Wing Aerodynamics, and other critical factors related to the Design Requirements and Objectives.

1 Introduction

Vision for a fuel efficient, environmentally friendly and performance and technology driven aircraft to meet global need and N+ 3 goal-setting within the next 15 years have been recently developed or proposed in progression [1-4]; the most attractive of these novel transport aircrafts are the Blended-Wing-Body, Joined-Wing and Double-Bubble Wing configurations. The latter configuration concept has also been developed to address needs and anticipate available enabling technologies progressive for three successive periods up to 2030. Realizing that the upcoming air transportation markets in the business jet type are also potential, the present work is devoted for exploring the possibilities of introducing some of a number of visionary and pioneering ideas and upcoming enabling technologies in a Conceptual Design Study of Quad-Bubble Business Jet, which is inspired by Double-Bubble (D.8) [1-4] configuration, and assess its characteristics in comparison to an appropriately chosen business jet as a reference. The term Quad-Bubble is adopted here since essentially, among the technologically developed fuselage configurations, the selected fuselage cross section has the quad-bubble features. Major ideas derived from N+3 aircraft technologies, which have been incorporated and translated into D.8 concept introduced by Drela, will be selectively applied as appropriate and further elaborated in the Conceptual Design Study of a Quad-Bubble Business Jet. The Conceptual Design and Aerodynamic Study of Quad-Bubble Business Jet (QB-BJ) is carried out focusing on its Aerodynamics which includes Wing Planform Configuration and profiles, and their relationship to the Design Requirements and Objectives. Possible Configuration Variants, Mission profile, Flight Envelope requirements, performance, stability, as well as the influence of propulsion configuration of QB-BJ aircrafts are considered and elaborated. Parametric study is performed on wing planform, thickness, and twist optimization, with design variables including overall span plus chord, sweep, thickness, and twist at several stations along the span of the wing prior to more structured optimization scheme. Considerations are also given to range, maximum lift, stability, control power, weight and balance. A statistical study and review on prevailing market demand leads to the choice of conventional Subsonic Business Jet candidate, which will be used as a Reference Conventional Business Jet (RC-BJ) for the aerodynamic and configuration of the conceptual design of QB-BJ. The chosen business jet accommodates 18 passengers as a baseline. Some aerodynamic and performance improvement is then carried out through parametric study to arrive at the best solution meeting the design requirements and objectives.

Particular attention has been given to identify and adopt concepts and technologies needed for reduction in fuel per passenger-mile from current technology baseline that may be available by 2035, and the adaptation of Drela's [1-3] wide “double-bubble” fuselage with beneficial pitching moment and carryover lift characteristics and high Aspect Ratio nearly-unswept laminar wing. Other factors which have been identified to be necessary for achieving N+3 goals are reviewed, selected and utilized, such as the reduction of secondary structure weight, the twin “pi-tail” configuration similar to that utilized for wing-mounted engines; at the present stage, conventional high efficiency engine with the appropriate choice of high bypass ratio will be utilized.

Cruise velocity and altitude will be optimized commensurate with environmental requirements for ten years to come [5, 6, 7]. Considering cruise altitude acceptable by environmental regulation, cruise velocity for 10 years to come can be assumed to be the same as at present, i.e. M = 0.8 and altitude between 33000 to 40000ft [8]. The merit of each feature is evaluated in terms of mission fuel burn. The choice of wing profile and fuselage is carried out selectively, first by comparing their characteristics as specified, and later by using XFLR5 simulations [9, 10].

At the present stage of the development, the conceptual design started with Drela’s Fuel Burn considerations [1] which utilized Breguet’s formula for fuel weight as initial driver to look for target lift to drag ratio of the QB-BJ, then follows the author simplified preliminary conceptual design approach as elaborated in [11]. Further conceptual design cycle will follow the scheme described by Raymer [12], and Djojodihardjo and Kim [13], taking into considerations the relevance, motivation and the importance of the Quad-Bubble business jet mission and design requirements and objectives. To some extent, the conceptual aircraft design procedure incorporates Drela's approach [1-4], with critical iterative cycle to arrive at plausible primary structure, aerodynamic performance, engine performance, trim and stability as well as flight trajectory and takeoff performance.

2 Motivation and Objectives

Research and development of transport aircraft technology in the upcoming period known as N+3 aircraft has been in progress; one inspiring work in this direction is the work of Drela [1-4], in particular for several variants of large commercial aircraft similar to that Boeing 737-800 in capacity. As a baseline, such aircraft is intended to carry 180 passengers over a range of 3000 nautical miles at cruise Mach number of 0.80, and to fly within altitude agreeable to environmental concern and target for that period onward. It is a very innovative and revolutionary transport aircraft with significant performance benefits in comparison to contemporary conventional aircrafts. Aerodynamic advantages are achieved through positioning the engines to the rear fuselage for noise reduction, efficient performance and bird impact avoidance, structurally efficient use of fuselage for lift to drag ratio increase, load distribution and passenger accommodation. Noting that business jet transport aircraft is also potentially significant, the present study attempts to apply the host of novel ideas offered by D8 (double-bubble) aircraft configuration as appropriate to its application for medium-to-large class business-jet with a conceptual design of a Quad-Bubble medium size business jet. The current conceptual design study of QB-BJ Configuration will be challenging since it faces more stringent geometrical as well as other design and operational limitations compared to the large airplane.

Hence the main objectives of the present paper are the following.

1. To take a critical look at the salient features and technologies of Double-Bubble aircrafts, with an emphasis on their aerodynamic and fuel burn performance as well as other green aircraft criteria, and project these into the envisaged Quad-Bubble- Business Jet Conceptual Design.
2. To carry out a conceptual design of 'Quad-Bubble Business Jet (QB-BJ)' for 18 passengers. In particular, the concptual design will first address minimal technology insertion as implied by D8.1 which offers N+2 level reductions in fuel burn, noise, and emissions
3. To compare the features and advantages of Quad-Bubble Business Jet (QB-BJ) with the baseline (reference) Business Jet, as well as with the Blended Wing Body Business jet (BWB-BJ)[11] and Joined Wing Business Jet (JW-BJ)[13] worked out by the first author and colleagues at conceptual phase.

3 Systematic and Methodology: Conceptual Design Approach

The steps followed in the overall conceptual design process will first determine a baseline reference aircraft that can be used as the basis of comparison for each of the concepts generated. It will be followed by establishing a well-documented mission scenario (including aircraft requirements such as payload capacity, fuel burn and range) to identify comparative parameters of the different aircraft concepts, and developing metrics and tools for designing and evaluating vastly different aircraft configuration architectures. Then the candidate technologies and concepts of the technologies that could have the greatest impact in terms of the evaluated metrics will be identified, followed by the evaluation of aircraft performance using the mission scenario. Finally a comprehensive assessment of the QB-BJ will be made.

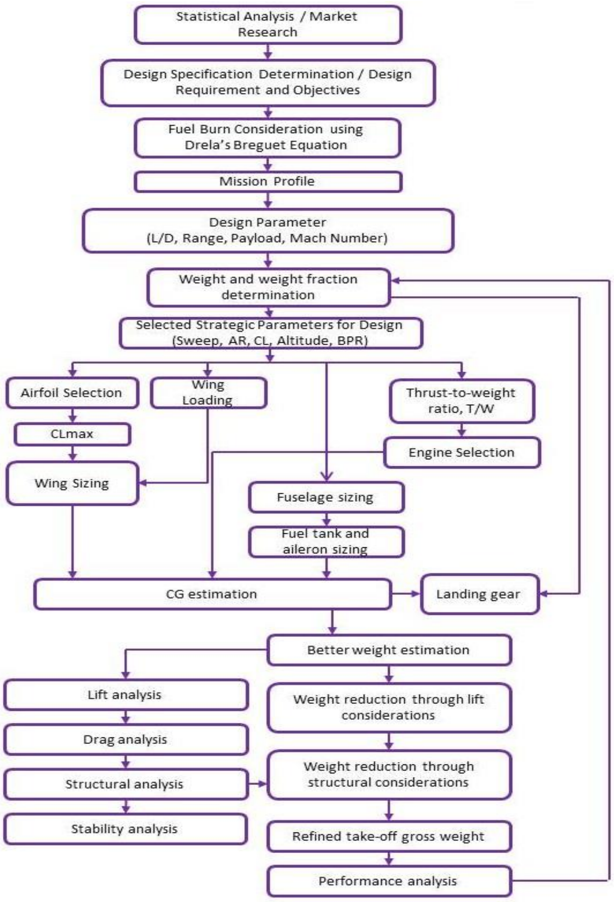


Fig. 1: Design Philosophy Flow Chart

The conceptual design of the Quad-Bubble aircraft configuration includes the mission profile, weight and weight fraction determination, wing loading determination, airfoil selection, thrust loading determination, engine selection, comprehensive wing sizing, centre of gravity determination, and landing gear /undercarriage configuration determination. To arrive at plausible design configuration, the procedure is carried out iteratively with careful judgment. Better estimation of aircraft design configuration follows through meticulous analysis. Structural and stability analysis are considered as well. A performance analysis is then carried out followed by the summary of the reassessed design specifications. The first phase of the Conceptual Design Approach is summarized in Fig.1.

The appeal of Quad-Bubble Business Jet (QB-BJ) aircraft technology is the promise of improved performance because of a higher L/D than can be obtained with a conventional "tube and wing" aircraft. Using the fuselage structure as both a passenger compartment and producing higher lift than conventional aircraft fuselage has the potential to decrease the wetted area and improve L/D.

4 Statistical Studies for the search of Reference Aircraft Configuration and Design Specifications

From statistical study and identification of favorable N+3 characteristics, a Baseline (Reference) Conventional Business Jet Aircraft (RC-BJ) is selected. Without loss of generalities, statistical analysis carried out for the selection of candidate RC-BJ in the class of 18 passengers has led to the selection of Gulfstream 550.

This result is a preliminary outcome of the design study exhibiting various characteristics of DB-BJ, BWB-BJ and JW-BJ [14], while Fig. 6-8 exhibits ergonomic and configuration design study of lifting body fuselage. Further detail is elaborated in [9].

The selected RC-BJ will be utilized as a reference for and post assessment of

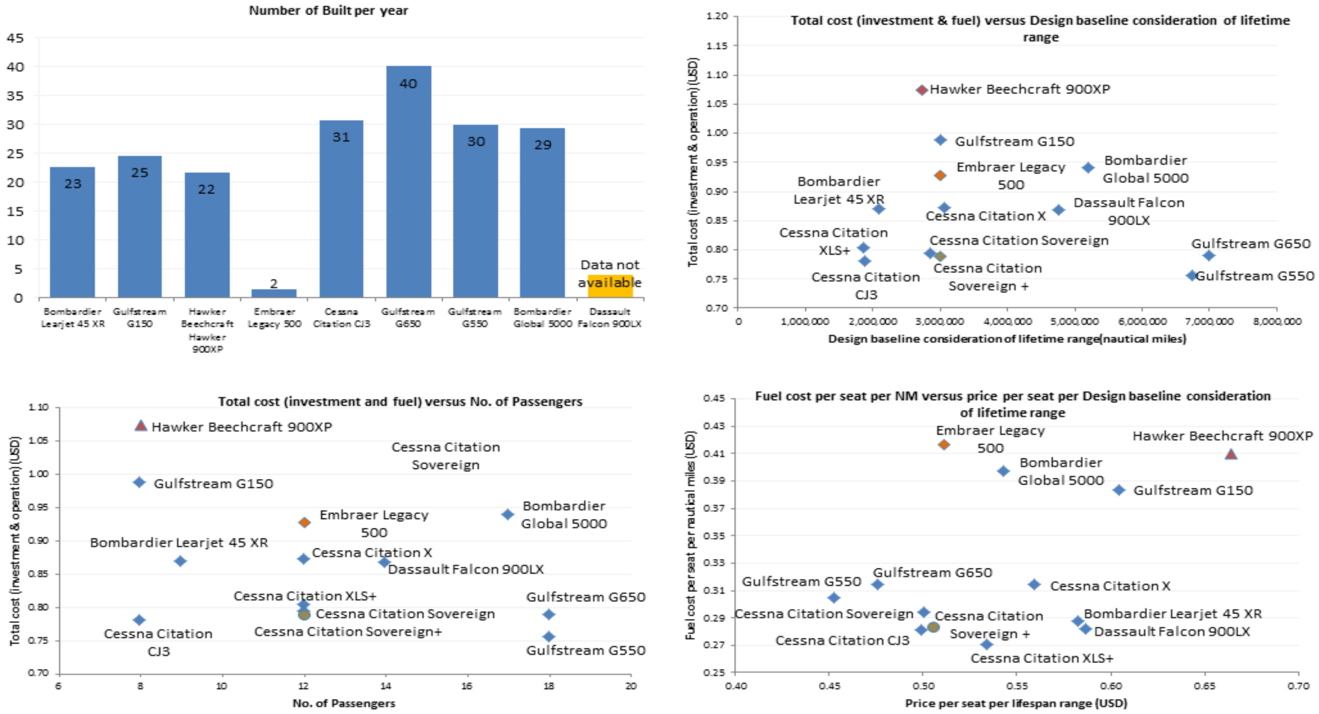
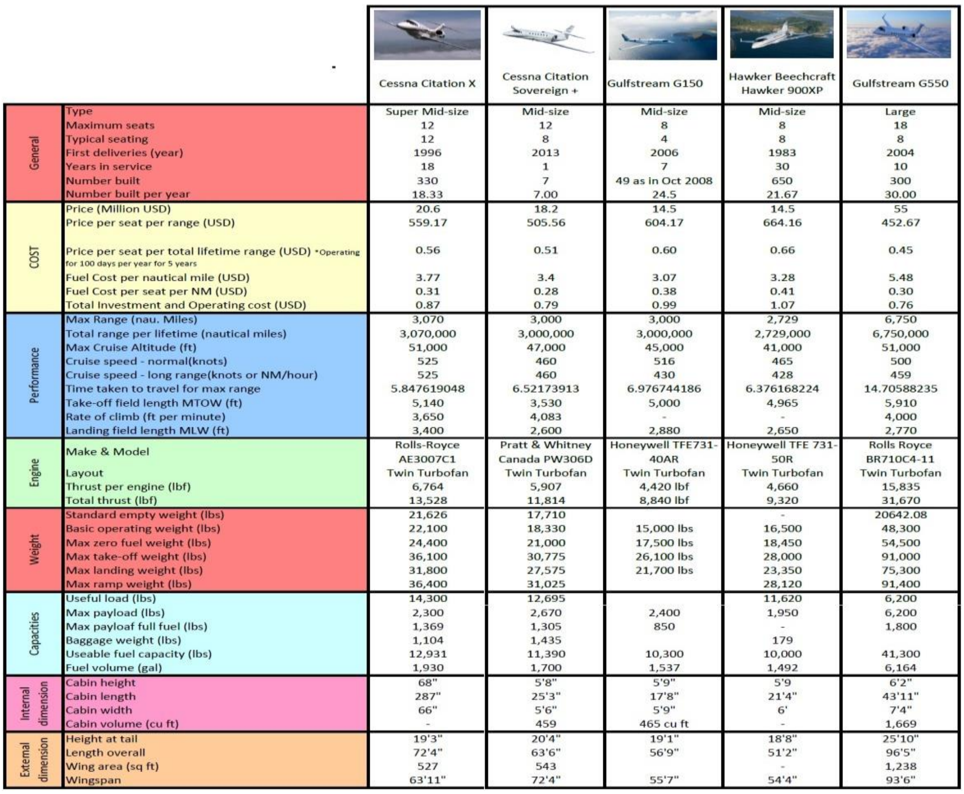


Fig.2: Market Statistical analysis

Table 1: A selection of business jet aircraft candidate's for RC-BJ and QB-BJ study



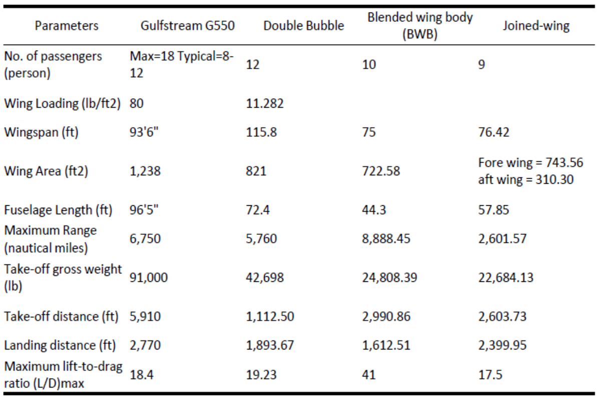
		Cessna Citation X	Cessna Citation Sovereign +	Gulfstream G150	Hawker Beechcraft Hawker 900XP	Gulfstream G550
General	Type	Super Mid-size	Mid-size	Mid-size	Mid-size	Large
	Maximum seats	12	12	8	8	18
	Typical seating	12	8	4	8	8
	First deliveries (year)	1996	2013	2006	1983	2004
	Years in service	18	1	7	30	10
	Number built	330	7	49 as in Oct 2008	650	300
	Number built per year	18.33	7.00	24.5	21.67	30.00
COST	Price (Million USD)	20.6	18.2	14.5	14.5	55
	Price per seat per range (USD)	559.17	505.56	604.17	664.16	452.67
	Price per seat per total lifetime range (USD) *Operating for 100 days per year for 5 years	0.56	0.51	0.60	0.66	0.45
	Fuel Cost per nautical mile (USD)	3.77	3.4	3.07	3.28	5.48
	Fuel Cost per seat per NM (USD)	0.31	0.28	0.38	0.41	0.30
	Total Investment and Operating cost (USD)	0.87	0.79	0.99	1.07	0.76
Performance	Max Range (nau. Miles)	3,070	3,000	3,000	2,729	6,750
	Total range per lifetime (nautical miles)	3,070,000	3,000,000	3,000,000	2,729,000	6,750,000
	Max Cruise Altitude (ft)	51,000	47,000	45,000	41,000	51,000
	Cruise speed - normal(knots)	525	460	516	465	500
	Cruise speed - long range(knots or NM/hour)	525	460	430	428	459
	Time taken to travel for max range	5.847619048	6.52173913	6.976744186	6.376168224	14.70588235
	Take-off field length MTOW (ft)	5,140	3,530	5,000	4,965	5,910
	Rate of climb (ft per minute)	3,650	4,083	-	-	4,000
	Landing field length MLW (ft)	3,400	2,600	2,880	2,650	2,770
Engine	Make & Model	Rolls-Royce AE3007C1	Pratt & Whitney Canada PW306D	Honeywell TFE731-40AR	Honeywell TFE 731-50R	Rolls Royce BR710C4-11
	Layout	Twin Turbofan	Twin Turbofan	Twin Turbofan	Twin Turbofan	Twin Turbofan
	Thrust per engine (lbf)	6,764	5,907	4,420 lbf	4,660	15,835
	Total thrust (lbf)	13,528	11,814	8,840 lbf	9,320	31,670
Weight	Standard empty weight (lbs)	21,626	17,710		-	20642.08
	Basic operating weight (lbs)	22,100	18,330	15,000 lbs	16,500	48,300
	Max zero fuel weight (lbs)	24,400	21,000	17,500 lbs	18,450	54,500
	Max take-off weight (lbs)	36,100	30,775	26,100 lbs	28,000	91,000
	Max landing weight (lbs)	31,800	27,575	21,700 lbs	23,350	75,300
	Max ramp weight (lbs)	36,400	31,025		28,120	91,400
Capacities	Useful load (lbs)	14,300	12,695		11,620	6,200
	Max payload (lbs)	2,300	2,670	2,400	1,950	6,200
	Max payloaf full fuel (lbs)	1,369	1,305	850	-	1,800
	Baggage weight (lbs)	1,104	1,435		179	
	Useable fuel capacity (lbs)	12,931	11,390	10,300	10,000	41,300
	Fuel volume (gal)	1,930	1,700	1,537	1,492	6,164
Internal dimension	Cabin height	68"	5'8"	5'9"	5'9	6'2"
	Cabin length	287"	25'3"	17'8"	21'4"	43'11"
	Cabin width	66"	5'6"	5'9"	6'	7'4"
	Cabin volume (cu ft)	-	459	465 cu ft	-	1,669
External dimension	Height at tail	19'3"	20'4"	19'1"	18'8"	25'10"
	Length overall	72'4"	63'6"	56'9"	51'2"	96'5"
	Wing area (sq ft)	527	543		-	1,238
	Wingspan	63'11"	72'4"	55'7"	54'4"	93'6"

the conceptual design efforts. For such purpose, a host of business jet aircraft data has been compiled and summarized in Table 1.

The design of QB-BJ configuration for business jet will start with the survey and statistical analysis of the current medium size business jet available in the market. A statistical analysis is carried out to find the spread of data and determine an acceptable target aircraft design specification, whereby various performance and design parameters of the baseline business jet aircrafts were determined and listed. The state of the art and progress of conventional Business Jets as found in the market are also considered.

This comprehensive statistical study produced some candidate business jets to be utilized as reference design requirements and objectives, in-lieu of market study. The design parameters and performance specifications of several business jets were compiled and organized systematically. One of these candidate business jets is selected as the conceptual design target, subject to further overriding considerations.

Table 2 :RC-BJ, DB-BJ, BWB-BJ and JW-BJ parameters



Parameters	Gulfstream G550	Double Bubble	Blended wing body (BWB)	Joined-wing
No. of passengers (person)	Max=18 Typical=8-12	12	10	9
Wing Loading (lb/ft2)	80	11.282		
Wingspan (ft)	93'6"	115.8	75	76.42
Wing Area (ft2)	1,238	821	722.58	Fore wing = 743.56 aft wing = 310.30
Fuselage Length (ft)	96'5"	72.4	44.3	57.85
Maximum Range (nautical miles)	6,750	5,760	8,888.45	2,601.57
Take-off gross weight (lb)	91,000	42,698	24,808.39	22,684.13
Take-off distance (ft)	5,910	1,112.50	2,990.86	2,603.73
Landing distance (ft)	2,770	1,893.67	1,612.51	2,399.95
Maximum lift-to-drag ratio (L/D)max	18.4	19.23	41	17.5

The analysis includes the review, classification and structured grouping of the aircrafts' specification and performance such as number of passengers, maximum range, takeoff gross weight, empty weight, cruise speed, service ceiling, takeoff distance and landing distance.

The specification and performance of these aircrafts was plotted in graphs to facilitate identification of potentially appealing characteristics or performance. A tolerance of 25% was set for the potential points. Aircrafts with the specification and performance within the tolerance point are tabulated. By inspection, the baseline aircraft or aircrafts to be chosen as a reference can be identified. Statistical analysis for the search of the baseline or reference aircraft is carried out by considering various relevant parameters such as Passenger capacity, Range, TOGW, Take-off and Landing distance, Wing Loading, L/D, Engine Power, Service Ceiling and rate of climb. From such statistical analysis, a list of baseline parameters for the reference aircraft(s) is tabulated in Table 1.

Following the design procedure and application of Quad Bubble concept, the first trial result of the DB-BJ has the characteristic, compared to the RC-BJ, as exhibited in Table 2, which exhibits the characteristics of the candidate *Reference Conventional Business jet (RC-BJ)* in the first column. These data will be used as a reference for determining the Design Requirements and Objectives (DR&O) in the present conceptual design of *Quad-Bubble-Business Jet (QB-BJ).*

5 Design Mission

To reach our mission statement goals, the idea of a long range business aircraft was chosen. By looking at long range business aircraft currently in production and choosing attributes that are believed will contribute to improvements, the design missions are identified:

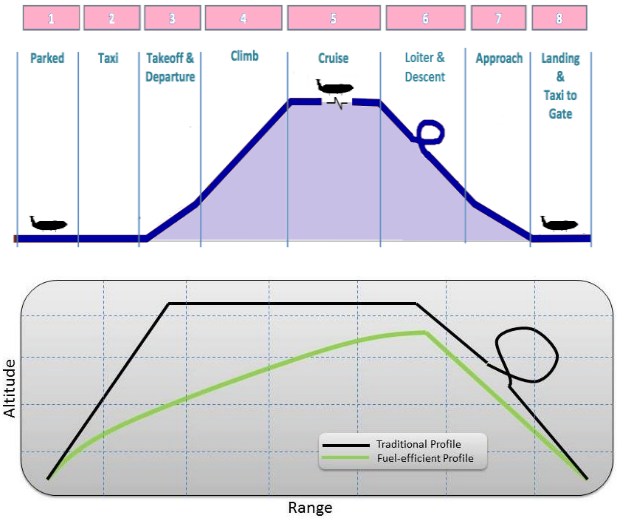
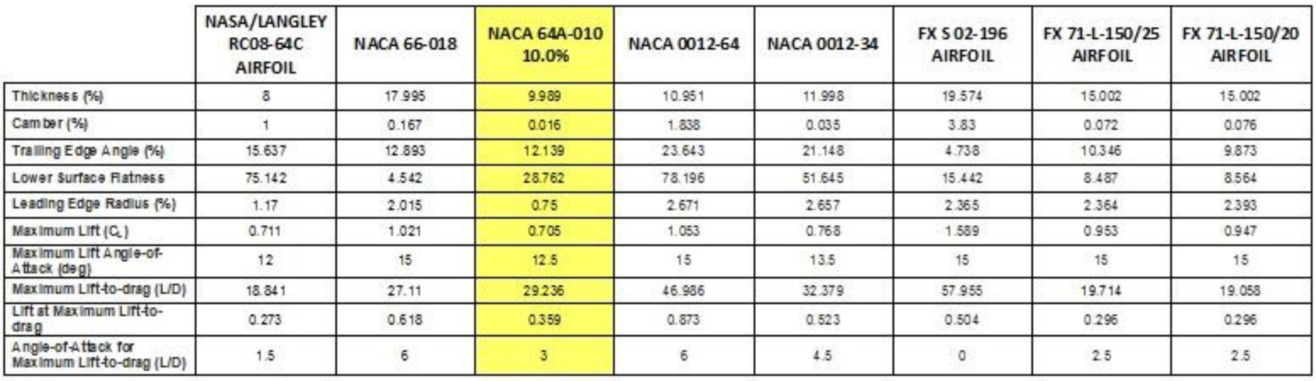


Fig. 3: Mission profile; (Top) Conventional one for first estimate; (Bottom) Recommended profile for fuel-efficient aircraft [15] in successive iteration.

- 12 – 18 Passengers + 4 Crew
- Cruise Altitude at 40,000ft
- Cruise Speed 0.80 Mach
- Range of 12,501 km
- Takeoff Field Length 800-850 m
- Landing Field Length 1700-1800 m

Mission profile utilized in the present conceptual design is illustrated in Fig. 3. The first iteration refers to conventional one, while in the successive iteration, the mission profile recommended for environmental concern [14] is utilized.A high operating ceiling has many benefits. By choosing a cruise altitude of greater than 40,000 feet (although within green aircrafts altitude requirements), the business jet will operate above the majority of air traffic altitude allowing for higher speeds and a cruise/climb method, increasing altitude as the aircraft becomes lighter from burning fuel. This method improves the overall efficiency of the engines and decreases fuel burn. Timely flights are a desirable characteristic that consumers desire in a business jet. High cruise speed directly correlates to the flight duration. Therefore, a cruise speed of 0.80 Mach is chosen as a baseline based on statistical data of combined high speed and fuel efficiency. Also considering cruise altitude acceptable by environmental regulation, cruise velocity for 10 years to come can be assumed to be the similar to the RC-BJ. A range of 12500 km is a typical design mission range for the aircraft.

Table 3: Comparison of several Airfoils considered for QB-BJ



	NASA/LANGLEY RC08-64C AIRFOIL	NACA 66-018	NACA 64A-010 10.0%	NACA 0012-64	NACA 0012-34	FX S 02-196 AIRFOIL	FX 71-L-150/25 AIRFOIL	FX 71-L-150/20 AIRFOIL
Thickness (%)	8	17.995	9.989	10.951	11.998	19.574	15.002	15.002
Camber (%)	1	0.167	0.016	1.838	0.035	3.83	0.072	0.076
Trailing Edge Angle (%)	15.637	12.893	12.139	23.643	21.148	4.738	10.346	9.873
Lower Surface Flatness	75.142	4.542	28.762	78.196	51.645	15.442	8.487	8.564
Leading Edge Radius (%)	1.17	2.015	0.75	2.671	2.657	2.365	2.364	2.393
Maximum Lift (C_L)	0.711	1.021	0.705	1.053	0.768	1.589	0.953	0.947
Maximum Lift Angle-of-Attack (deg)	12	15	12.5	15	13.5	15	15	15
Maximum Lift-to-drag (L/D)	18.841	27.11	29.236	46.986	32.379	57.955	19.714	19.058
Lift at Maximum Lift-to-drag	0.273	0.618	0.359	0.873	0.523	0.504	0.296	0.296
Angle-of-Attack for Maximum Lift-to-drag (L/D)	1.5	6	3	6	4.5	0	2.5	2.5

Destination flexibility is also important for a desirable business jet solution. With a takeoff field length of 800-850 meter and a landing field length of 1700-1800 meter, these aircrafts will have access to many small airports; this reduces the aircraft design's reliance on larger and more congested terminals and, thereby, improves turnaround time and decreases wait times.

It is not reasonable to expect the designed aircraft to operate at the full design mission at all times. Therefore, the typical operating mission is chosen to carry 12-18 passengers, with 4 crews, over approximately 12000 km. This mission allows for travel between many transcontinental cities. As a reference, a flight from London to New York is 5577 km.

While this mission does not fully utilize the aircraft's capabilities, the short takeoff and landing capacity will allow for more opportunities for shorter range flights in a given time frame. Typical Mission Profile is illustrated in Fig. 3 .

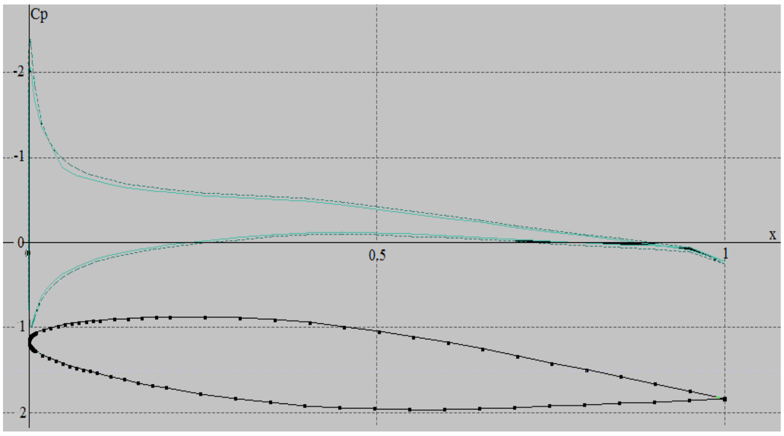


Fig. 4: NACA 64A-010 10% chordwise pressure distribution along

The bottom figure on the other hand provides a recommended fuel-efficient flight profile in

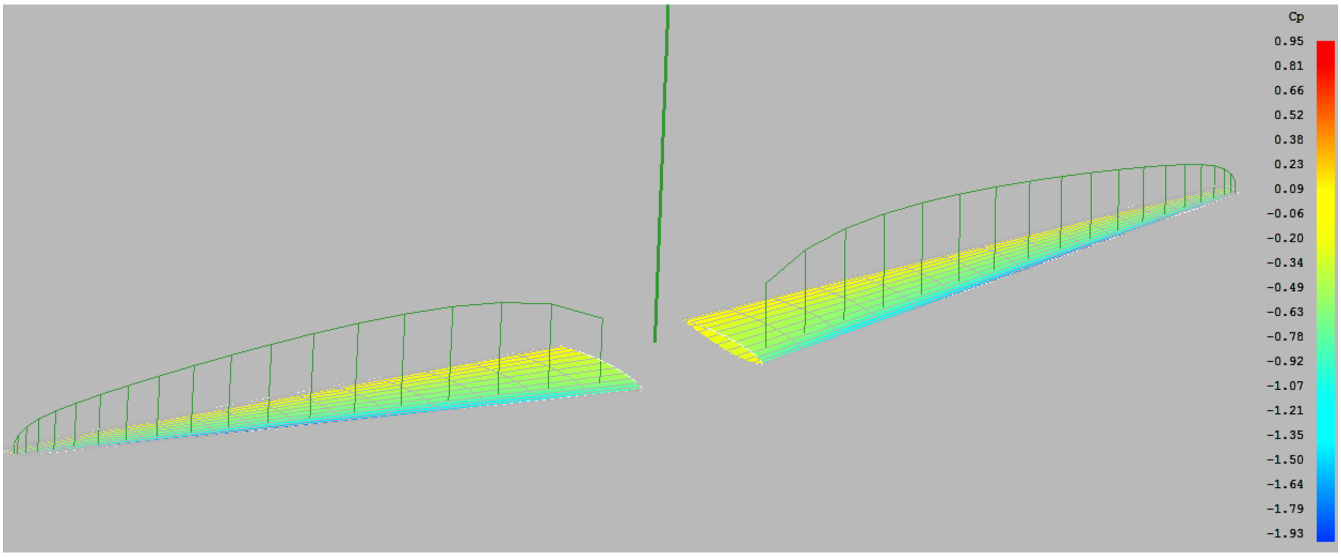


Fig.5: NACA 64A-010 10% airfoil lift and pressure distribution from XFLR5 [10]

comparison with the traditional one that would minimize emission and the fuel consumption. Although this profile will increase the aircraft performance, it is not currently being utilized due to several constraints that need to be considered in parallel with the fuel efficiency. Among them are the weather, safe aircraft separation, tactical and operational demands of airspace boundaries. Putting these constraints aside, this is the preferred flight profile for the QB-BJ in 10 years to come.

6 Airfoil Selection

For 2D airfoil selection in the conceptual design, a basic and simple approach was adopted by analyzing chosen airfoil using Airfoil Investigation Database [16] and on-line Airtool software [17], which are interactive database and programs. Eppler, Liebeck, NACA airfoil series were analyzed for the QB-BJ conceptual design. The airfoil selection process was focused on the airfoil characteristics to achieve favorable pressure distribution, maximum lift coefficient and lift-to-drag ratio. The required L/D is 25 and maximum lift coefficient is 0.85. The QB-BJ will have somewhat better L/D compared to RC-BJ for meeting the DRO. With that, six airfoils meet this requirements however only those that is classified as laminar flow airfoil are considered as in Table 3. Among them, the thinnest possible super-critical airfoil is selected in order to reduce critical Mach number and to reduce drag divergent Mach number. Thus such choice will allow the aircraft to fly in the higher part of the transonic range while avoiding the presence of shock wave on it, thus avoiding undesirable drag rise as well as environmental noise propagation. By inspection, the NACA 64A-010 10% was selected for current conceptual design of QB-BJ as in Fig. 4. The lift and pressure distribution from XFLR5 analysis of such wing profile is presented in Fig. 5. In view of the criticality of the wing design, further iteration should be made for its improvement to achieve the desired and optimum aerodynamic and overall performance.

Table 4: Wing Loading Determination using from Stall Velocity and Landing Distance [9]

Constraints	Wing Loading, W/S (N/m^2)	Remarks
Stall Velocity	1380.3	Moderate
Landing distance 1	714.7	Low
Landing Distance 2	1400.0	High
XFLR5	3889.7	Highest

7 Wing Loading

The wing loading is computed based on two constraints:

i. Stall velocity, V_{stall}
ii. Landing distance

The typical stall for RC-BJ =51.44 m/s

Cruise altitude, h_{cruise}= 12192 m
Air density at cruise altitude = 0.302 kg/m^3

From Table 4, the lowest wing loading is chosen in order to obtain the maximum wing area for maximum takeoff gross weight. Also, when the wing loading decreases, the thrust required per unit wing area reduces as well. Besides, a lower wing loading is more favorable because the weight per unit area reduces; hence the need of more lift to counter the weight follows similar behavior. Thus, the wing loading for the QB-BJ design is taken to be 714.7 (N/m^2).

8 Thrust Loading and Engine Selection

The determination of the thrust loading is based on two constraints: Take-off Distance and Rate of Climb. The results of the thrust based on these constraints are tabulated in Table 5 as follows:

Table 5: Calculated thrust

Constraint Parameters	**Thrust Required [N]**	**Ratio (T/W)**
Take-off distance	2081.71	0.0254
Rate of Climb	12138.75	0.4104

Thrust loading based on rate of climb has been selected because the engines to be selected later should produce the thrust required at all points in the flights, which is critical during take-off and requires largest thrust. The maximum thrust T_{Max} required during climb just after lift-off is 12138.8 N with the intended range for this aircraft of 12500 km.Transport aircraft which travel in this range is categorized as long haul aircraft and it falls under the transport aircraft category. According to the design requirements regulated by FAR, the number of engines required for aircraft which falls under the transport aircraft category must be more than one engine. Hence, two engines are selected to meet this requirement, which incidentally similar to the number of engines of the RC-BJ. Thus the thrust required per engine is 6069.4N. An engine with high By-pass Ratio (BPR) and low Thrust Specific Fuel Consumption (TSFC) is recommended for selection. By considering safety factor and quantitative inspection from relevant candidates as in Table 6, among others, it is found that the Pratt & Whitney Canada JT15D meets these requirements at significantly lower weight and therefore selected for current conceptual design phase of the QB-BJ.

Table 6: Engine Candidates

Engine Candidates	Honeywell TFE731-2	P&W Canada PW300	P&W Canada JT15D	P&W Canada 535A	P&W Canada 530
Thrust [lbf]	3500	4750	3045	3400	2887
Thrust [N]	15575	21137.5	13550.25	15130	12847.15
Bypass ratio	3.34	4.5	3.3	2.55	3.7
Dry weight [kg]	333	563	290	317	280
TFSC [lb./hr/lbf]	0.5	0.675	0.56	0.44	0.44

9 Requirements on Cabin and Fuselage aerodynamic and structural Design

The fuselage serves a multitude of functions and should meet various requirements. Since it houses the cabin, it should meet safety, passenger and crew members well-being and airline requirements. The configuration and cabin lay-out should be acceptable to the passengers, and there are also psychological aspects considerations.

The Quad-Bubble (or D8) configuration

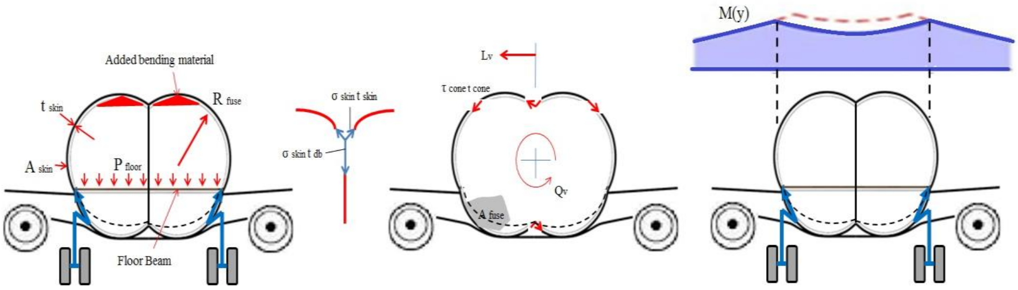


Fig. 6: Considerations for fuselage cross-section, shell/web junction tension flows, torsion shear flow from vertical tail load, and landing gear load, adapted from [4,16].

basically follows "tube and wing" configuration, and as such will follow closely the structural design considerations of [1-4, 18]. Aerodynamically, the fuselage should be designed to carry some lift (lifting body considerations) and have less drag.

The dimensions of the cabin are dictated by an aerodynamically optimized shape in which compromises are made concerning the efficiency of the structure.

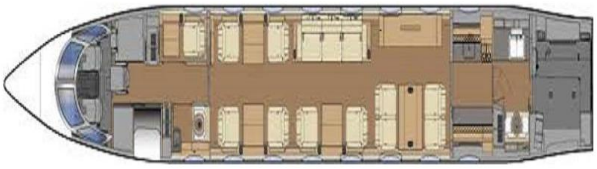


Fig. 7: Gulfstream G550 Cabin Compartment Arrangement

Following the philosophy of D8 transport aircraft, the airframe structural and weight models treat the primary structure elements as simple geometric shapes, with appropriate load distributions imposed at critical loading cases. The fuselage is assumed to be a pressure vessel with one or more "bubbles", with added bending loads, and sized to obtain a specified stress at specified load situations. The wing is assumed to be cantilevered or to have a single support strut, the resulting fuselage, wing, and tail material volumes, together with specified material density, and then gives the primary structural weight. The secondary structural weights and non-structural and equipment weights are estimated via statistical studies following historical weight fractions.

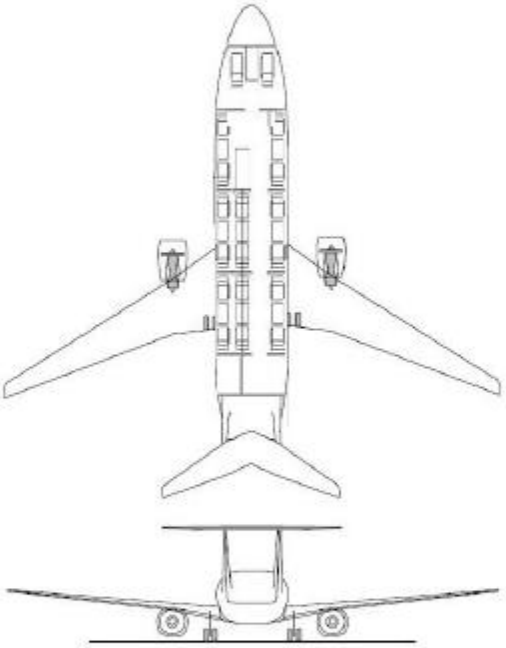


Fig. 8: QB-BJ Cabin Layout (Top and back view)

Following D8 philosophy, the fuselage is modelled as a side-by-side "Double-bubble" pressure vessel with an ellipsoidal nose end-cap and a hemispherical tail end-cap, which is subjected to pressurization, bending, and torsion loads. Due considerations are given to the placement of the landing gear which could reduce the bending load at the wing-fuselage junction.

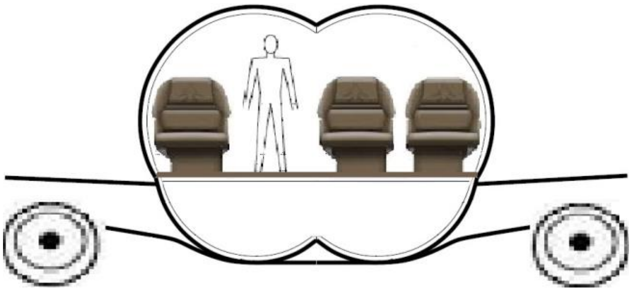


Fig. 9: QB-BJ cabin with seats (front view)

Fuselage cross-section, shell/web junction tension flows, and torsion shear flow from vertical tail load should be given careful considerations, with an optional bottom fairing.

Following the structural design philosophy of Drela [1-4] for the fuselage design, the conceptual design of QB-BJ arrives at configuration shown in Fig. 6 and Table 7. In addition the geometry also considers cabin design requirements as previously mentioned and ergonomics.

Table 7: Conceptual Fuselage Dimension [9]

Description	Dimension
Length	25.00 m
Width	3.54 m
Height	2.31 m

10 Cabin Initial Weight Estimation

The initial weight estimation is carried out based on best and conventional estimate. The results are shown in Table 8.

Table 8: Initial weight estimation

	No	Weight [kg]	Total Weight [kg]
Pilot	2	80	160
Flight Crew	2	70	140
Crew Hand Carry	4	7	28
Crew Luggage	4	15	60
Passenger	18	80	1440
Passenger Hand Carry	18	7	126
Passenger Luggage	18	25	450
	Total		2404

11 Cabin Sizing

The pressurized cabin of the QB-BJ was designed considering combined bending, shear and torsion from aerodynamic loads. In comparison to the conventional circular fuselage, it was predicted that the non-conventional fuselage requires higher structural strength because of large bending stresses on the skin. For cabin passenger compartment sizing, we refer to Drela's approach [1-4]. The derivation of key requirements for cabin development follows the methodology as described in the following development.

Taking cabin standards displayed in Fig. 7 as a reference, standards for the QB-BJ cabin are tailored according to the requirements of the specific scenario. The main geometric standards (such as class ratios, seat pitch, seat width, aisle width, toilets per passenger, and stowage spaces) are influenced on the one hand by the relevant characteristics of the different scenarios, but on the other hand by general premises having impact on all of the scenarios as well. These are the continuous growth of human being's dimensions known as acceleration, enhanced in-flight safety and medical facilities (Eelman, [19]).

Table 9: Passenger Compartment for QB-BJ Configuration

Description	**Dimension**
Seat Pitch	1.016m
Seat Width	0.711m
Aisle Width	0.711m
Cabin height	1.829m

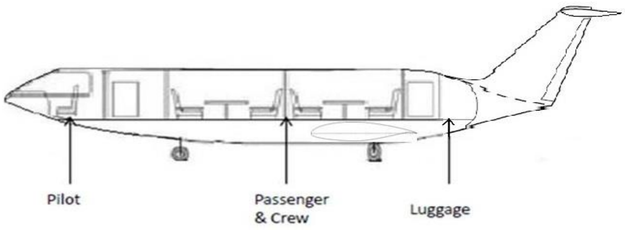


Fig. 10: Schematic of Weight Distribution along the Center Cabin Body

In the design of the present QB-BJ configuration for 12-18 passengers with first class quality, the aisle width, seat pitch and seat width will be based on the typical passenger compartment safety, comfort and airline requirements. For the Aisle height, reference will be made to the RC-BJ in Fig. 7. Thus, the passenger compartment for this QB-BJ configuration can be defined as shown in Table 9. Figs. 8 and 9 depict the cabin lay-out of the present QB-BJ conceptual design.

Table 10: Weights Arrangement due to Payload along the fuselage and CG calculation

	Quantity	Unit Weight (kg)	Total Weight (kg)	Distance from nose datum (m)	∑
Pilot	2	80	160	1.59	254.4
Passenger	18	80	1440	11	15840
Flight Crew	2	70	140	11	1540
Crew Hand carry	4	7	28	11	308
Passenger Hand carry	18	7	126	11	1386
Crew Luggage	4	15	60	10.74	644.4
Passenger Luggage	18	25	450	10.74	4833
Engine	2	290	580	12.38	7180.4
Wing	2	206.92	413.83	11.12	4599.81
			3397.83		36586.01

12 Center of Gravity

Computation of the center of gravity distance of the center body proper yields a value of 10.77 m from the nose datum. Fig. 10 exhibits the skeleton of the Weight Distribution along the

Center Cabin Body. This center of gravity excludes sections 2 and 3 which are located between the inboard and tip of the QB-BJ wing sections.

The location and length of the Mean Aerodynamic Center (MAC) of the QB-BJ wing is important because the wing is joined to the fuselage in this area so that careful considerations of the relative position (or alignment) of entire wing MAC with the aircraft center of gravity should be taken into account in the conceptual design. This provide first estimate of the wing position to attain the required stability characteristic. As first estimate for a stable aircraft, the calculation was done such that it follows Raymer's [12] approach and depicted in Fig.13; this will be followed by further iteration.

13 Lift Distribution

The fraction of the aircraft lift coefficient at cruise can be summarised as follows:

$$C_L = C_{L-wing} + C_{L-fuse} + C_{L-tail} + C_{L-nacelle}$$

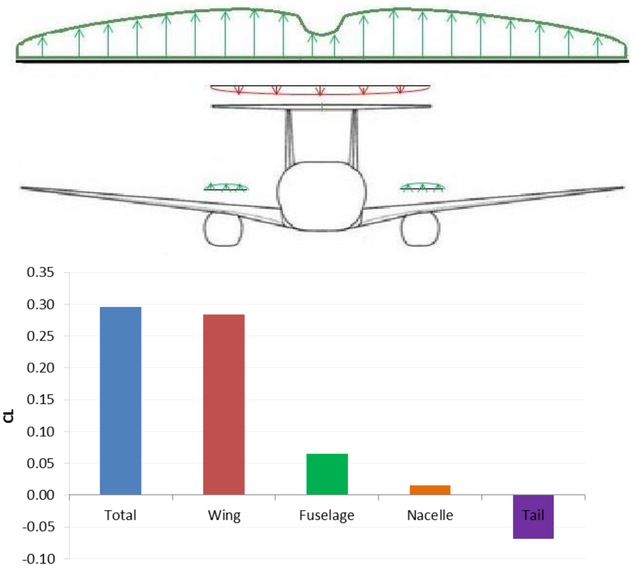


Fig. 11: Lift Distribution for QB-BJ at cruise

At cruise, the total C_L was calculated to be 0.295. With such information and considering suggestion from [1-4], the $C_{L\text{-fuse}}$ was found to be 0.065. Using the data from From Saltzman [15], the lift coefficient of lifting-body designed fuselage and the nacelles can be appropriately estimated. Based on typical fuselage angle of attack at cruise of 3^o, the lift coefficient is estimated to be 0.07. Based on centre of gravity estimation from previous analysis, it is found that the CG positon is at front of the Aerodynamics center (AC) with moment arm of 0.61m. An assumption is also made that the AC is located at about quarter-chord of the wing which is a typical value for a subsonic aircraft. The moment arm for the horizontal tail on the other hand was found to be 13.87m. Using this data and appropriate estimate of the tail aerodynamics and the longitudinal stability analysis [9], the C_L-tail can be estimated to be -0.068. With these values, the wing coefficient is then calculated and found to be 0.284. For validation, the $C_{L\text{-wing}}$ was analysed by using XFLR5 software and it is found that the value is 0.320 which suggest the calculated value is relevant. The lift distribution is depicted in Fig. 11.

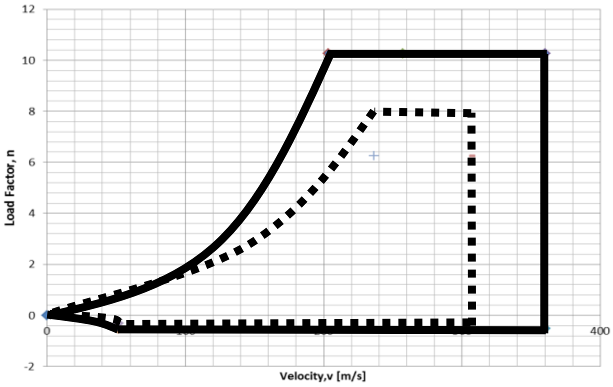


Fig. 12: V-n diagram for (Solid) QB-BJ and (dotted) RC-BJ

14 Detailed Analysis

14.1 Static Margin (S.M) Estimate

The estimation of the static margin for the QB-BJ is crucial in order to determine the stability of current conceptual design. Stated in terms of S.M, S.M>0 is favorable for stability criterion. From [9], it was calculated that the S.M for the QB-BJ is 1.08 which indicate that the aircraft is stable. Although this value been considered as

Table 11: Summary of QB-Business Jet Configuration and Performance in Comparison with RC-BJ

Parameters	**Unit**	**RCBJ**	**Intended Improvement**	**QB-BJ Conceptual Phase Outcome**
No. of Passengers	Person	18.00	18.00	18.00
Range	km	12501.00	12501.00	12501.00
MTOW	kg	41276.91	35952.00	29576.98
Cruise Altitude	m	13716.00	11500.00	12192.00
Cruise Speed	km/h	926.00	926.00	926.00
Wing Span	m	28.50	29.38	36.01
Wing Area	m^2	115.00	109.60	82.77
Sweep Angle	degree	27.00	25.00	30.00
Fuel weight	kg	23362.00	23362.00	5665.00
CL_{max}		1.35	1.00	0.85
Take-off Distance	m	1801.30	1700.00	1700.00
Fuselage Length	m	26.16	26.00	25.00
Fuselage Width	m	2.39		3.54
Fuselage Height	m	2.39		2.31
Landing Distance	m	844.30	800.00	800.00
Take-off T/W		0.34	0.40	0.41
Thrust at cruise	N	20199.00	20199.00	17259.95

normal in various commercial aircrafts, one can conclude that it is too stable which would render maneuverability. More refine and detail iterations are currently under progress for better performance.

14.2 Flight Envelope

The V-n diagram of flight envelop was determined according to the mission profile and FAR regulation. According to Sadraey [20] and Raymer [12], the envelop was constrained by aerodynamic limit curve and structural limit line. Meticulous and careful judgement was initiated into the calculation for the QB-BJ and also RC-BJ for comparison purpose as depicted in Fig. 12. Initial estimate suggest that the QB-BJ posses better performance compared to the RC-BJ. However for a transonic fying aircraft, drag contribution from the wave is an issue that need to be considered. Therefore further iteration is currently in progress to enhance performance especially to reduce this drag while maintaining the aircraft aerodynamic efficiency.

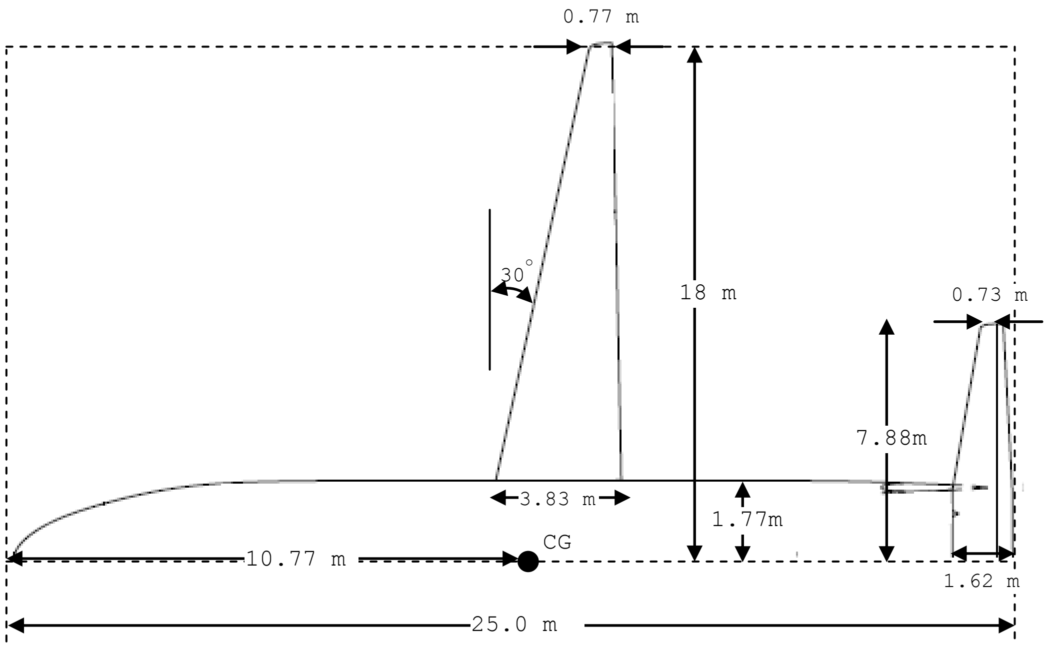


Fig. 13: QB-BJ Conceptual Design phase dimension [9]

15 Summary of Preliminary Conceptual Design

Refined weight estimation and detailed

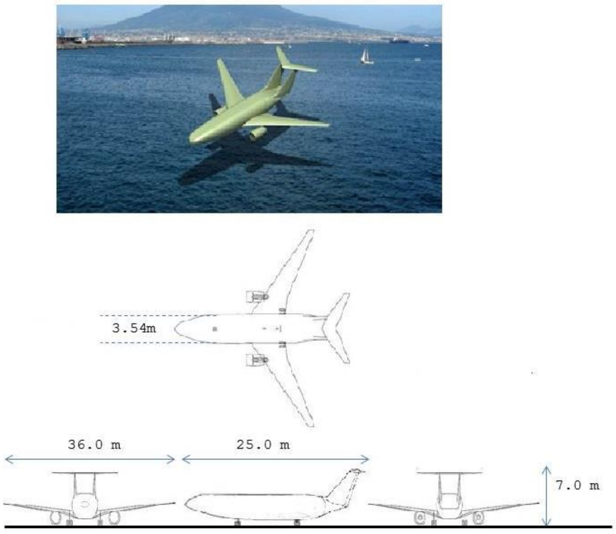


Fig. 14: Three-view Impression of QB-Business Jet

aerodynamic analysis using CFD are progressively carried out [10]. Table 10 exhibits the arrangement of weights based on conventional payload and engine along the fuselage.

The preliminary dimension of the QB-BJ is depicted in Fig. 13 along with the CG estimation. The Lift distribution along the QB-BJ is exhibited in Figs. 11, which has been meticulously computed using XFLR5 [10] and elaborated in [9]. A three-view impression of QB-Business Jet Configuration conceived is exhibited in Fig. 14. Table 11 compares the QB-Business Jet Configuration and Performance with RC-BJ.

16 Conclusions

The QB-BJ configuration was compared in Table 2 to the design baseline aircraft, RC-BJ, which is similar to the characteristics, specifications and performance to the candidate Conventional Business Jet chosen in the statistical study. In the aerodynamic analysis, the conservative estimate of the L/D ratio of the QB-BJ configuration is 25, which is 1.34 times higher than a typical conventional business jet aircraft represented by the reference RC-BJ.

More detailed comparison could be made in the computational approach and a simulation of flow on the simulated QB-BJ aircraft section by section. In the theoretical approach, preliminary calculations have been made based on lifting surface method on both QB-BJ and RC-BJ planform wing. Hence, it can be concluded that the QB- configuration is able to generate lift over wing span higher compared to conventional aircraft as represented by the RC-BJ. The conceptual QB-BJ has Quad-Bubble fuselage section that allows wide-body-like cabin. The design of QB configuration, similar to and inspired by the design philosophy of Drela [1-4], contributes towards significantly lower weight and fuel burn of the overall QB-BJ configuration. Overall, the QB-BJ as conceived has met or rated better than the intended improvement in comparison to the RC-BJ. Refined computation is currently in progress.

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