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DESIGNING COST-EFFECTIVE HIGH-PERFORMANCE VERY LIGHT JET AIRCRAFTS — A REVIEW

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Recent advances in the configuration, materials, and market design of very light jet (VLJ) aircraft are reviewed; and recommendations are made for designing cost-effective high-performance VLJ aircrafts for today's aerospace market. Forecast technical information for various VLJ aircrafts in the market have been studied for competitor analysis purpose. It has been shown by graphical plots that direct operating cost (DOC) and aircraft price play an important role in designing a cost-effective aircraft for current aerospace market. The conventional and unconventional configurations in VLJs design has been discussed for designing VLJ aircrafts with improved performance. It has been recommended to adopt multidisciplinary design optimization (MDO) approach and to select appropriate/specific composite materials for designing high-performance VLJs. Smart aeronautical systems have been highlighted; and it has been suggested to integrate these smart systems into the aircraft systems to ensure safety and reliability for designing new high-performance VLJ aircrafts.

Keywords: Aircraft; Cabin; Aerospace market; Multidisciplinary design optimization; Low cost carriers; Aerospace design.

1. Introduction

Today's industrial engineers are expected to design cost-effective products with a high marketing potential. The performance and cost of a jet aircraft is strongly dependent on its payload, type of fuel used, aircraft configuration, engine power, and the structural material; these factors have led to the significant developments in VLJ aircrafts in recent years (Blakey, *et al.*, 2011; Luliano and Quagliarella, 2011). The term 'very light jet' (VLJ), also called micro-jets, refers to a single-pilot aircraft with seating capacity of 3-7 passengers with a maximum take-off weight (MTOW) not exceeding 10,000 lbs (Ponticel, 2008). They are designed and built to cruise at higher speeds and altitudes as compared to traditional piston-powered light aircrafts. The low cost of operation and manufacture of VLJs, allow for mass production and sale to potential operators at costs lower than the traditional lightweight aircrafts (Croft, 2006).

The efficiency and convenience of corporate jet aircrafts have been supplanted by hub-and-spoke gridlock with agonizingly long check-in and transfer procedures. Owing to these inefficiencies and the high cost of acquiring and operating corporate and charter jets, the interest and demand for VLJ aircrafts have dramatically increased in recent years. The first batch of VLJ aircrafts (*Citation Mustang*) appeared in market to provide air passengers service to and from remote locations in 2006 (Miller, 2006; Cessna Aircraft Company, 2011). Since then there has been a number of VLJ players have made significant developments; some notable VLJ aerospace industries include *Honda Aircraft Company, Eclipse Aerospace, Inc.*, *Diamond Aircraft*, *Piper Aircraft,* and of course ***Cessna***). For instance, recently the *FAA* VLJ aircraft conforming *HondaJet* has reached the maximum operating altitude of 43000 ft (VLJ News, May 2011).

Although there are excitements associated with the debut of VLJ aircrafts, there are limitations in cabin size, and passenger & baggage capacities in VLJs (see Table 2). These limitations have left many private jet travelers wondering what it is all really about. Is a VLJ a good option? How does it compare to larger private jets? But one must not give up on VLJs altogether. They have been engineered for their economy — not their size. The variable operating cost per hour of the Eclipse 500 (insurance, maintenance, fuel, and replacement parts) is estimated at just $372 (the Hawker 400XP VLJ aircraft costs $1,447). The drastically low operating and acquisition costs indicate attractive features associated with the debut of VLJs. There is a definite size-cost trade-off, but for the private jet traveler looking for an economic option, a VLJ may be the perfect choice (Peeta, 2008).

2. Designing Cost-Effective VLJ Aircrafts

The design of cost-effective VLJ aircrafts involves a number of cost-related considerations; the two main factors are direct operating cost (DOC) and aircraft price. 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). It is important to first conduct a market survey for comparatively analyze the demands of various business jet aircrafts. The Rolls-Royce forecast illustrates a strong market for various business jet aircrafts over the next 20 years. Figure 1 shows the long-term forecast projection indicating the need for 23,000 aircraft with a delivery value of $284 billion for micro-jets through business liners (Rolls-Royce, 2004).

Business jet operators have shown a considerable interest in the market prospects for VLJ aircrafts 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 during the past two decades (Jane's, 2008; Cobb, *et al.* 2007; Fujino, 2003). The strong market prospects revolve around the likely demand for jet air taxis that

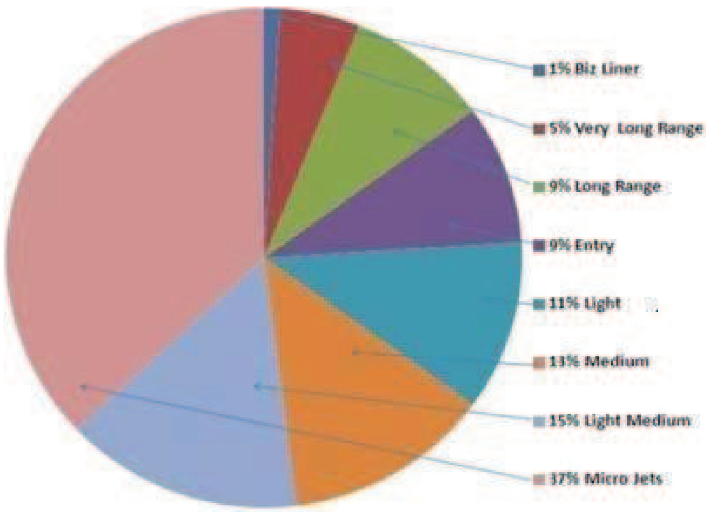


Fig. 1. Forecast of various VLJ aircraft deliveries for 2004–2024.

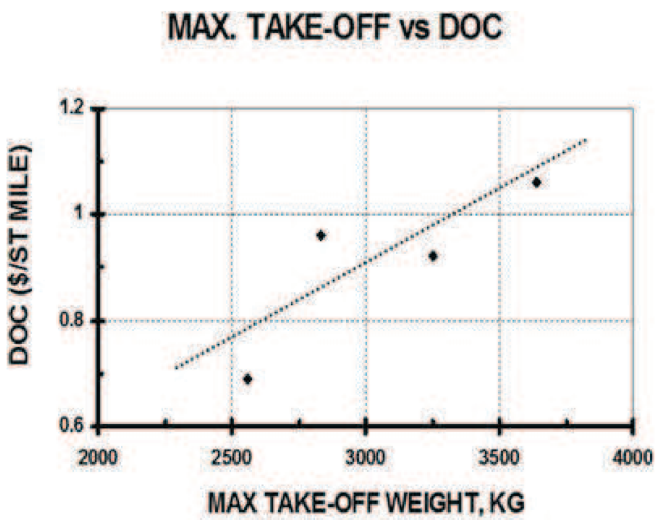
can collect customers at short notice "at an airfield near you," and deliver them to sales prospects, remote factory sites or that fishing and hunting lodge in the wilderness not too far from a usable air strip. A notable market prospects for cost-effective VLJ aircrafts has been achieved by ***Embraer Phenom 100*** with a cost of around $2.85 million.

Now we compare weights and costs of some VLJ aircrafts (see Table 1). The Cessna's Citation Mustang, priced at US $3 million, weighs 10,800 pounds (4,900 kg) at take-off; the Cessna Citation Mustang is technically one size above the VLJ niche, and Cessna itself denies being in the VLJ business (Cobb, *et al.* 2007). Now we look at the smaller end, *Embraer* has offered its *Phenom 100* light jet series with the maximum take-off weight of 10472 lb (4750 kg); its price is US$ 3.6 million as on January 1, 2009 with the first aircraft delivered in December 2008 (Embraer, 2009). Although the *Phenom 100* burns a bit more fuel than the *Citation Mustang*, it also cruises faster so that the fuel cost per mile over the ground remains almost the same.

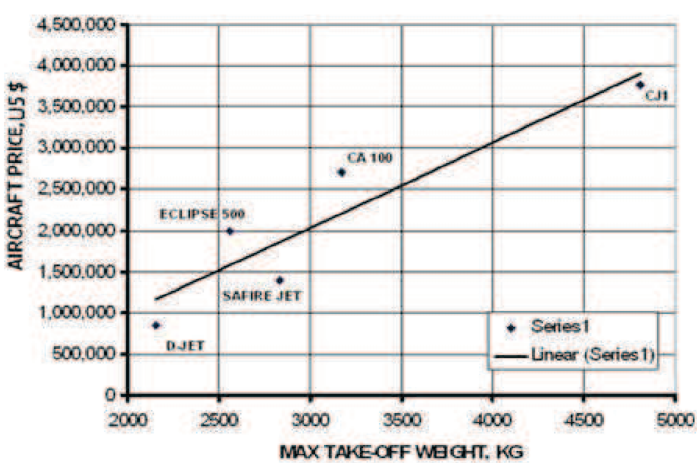
Table 1. Maximum Take-Off Weights (MTOW), Capabilities and Prices of Typical VLJs.

VLJ Aircraft	**Eclipse 500**	**Cessna Citation Mustang**	**Phenom 100**	**HA-420 HondaJet**	**Diamond D-Jet**
MTOW	2,600 kg	4,900 kg	4750 kg	4173 kg	n/a
Cruise speed	425 mph	400 mph	450 mph	480 mph	n/a
Altitude	41,000 feet	41,000 feet	41,000 feet	43,000 ft	n/a
Range (nautical miles)	1,200	1,170	1,185	1,400	1,350
Price (US$)	$2.15 million	$2.9 million	$3.6 million	$4.5 million	$1.9 million

Recently Japanese motor manufacturer Honda has developed the *Honda HA-420 HondaJet* VLJ aircraft with its certification. It carries up to 5 passengers having a range of 1,400 nautical miles with a maximum cruise speed of 480 mph. This VLJ has world class leading fuel efficiency. The price is around the $4.5 million



(a)



(b)

Fig. 2. (a) Variation of MTOW versus DOC, (b): Variation of MTOW versus aircraft price (US$).

mark. Austria's Diamond Aircraft is developing the D-Jet; which is to be manufactured at its plant in Ontario, Canada. The very light D-Jet will carry 4 passengers plus 1 pilot having MTOW of only 2,000 kg with a range of 1,350 nautical miles (AicraftCompare.com, 2014). The approximate price will be $1.9 million.

In order to design cost-effective VLJ aircrafts, it is important to know the trends of the significant characteristics of existing aircrafts. This trend can be used to check whether the design is in the improvement sense or degradation [Torenbeek, 1982; Raymer, 1992; Roskam, 1989; Nicolai, 1975; Stinton, 1985, 1983]. The two important cost-related characteristics plots include: direct operating cost (DOC), and aircraft price as shown in Figs. 2(a,b) [Eshelby, 2000; Torenbeek, 1987; Mair and Birdsall, 1992; Lowry, 1999].

The market design features mentioned in Figs. 2(a,b) can be used to see competitiveness of the existing design as compared to the competitors; and hence new market designs can be developed for VLJ aircrafts for today's aerospace market.

3. Comfort and Operating-Cost Comparisons

It is difficult to compare all available VLJs to dozens of larger private jets, so for simplicity's sake we consider a few of them: the VLJ Eclipse 500, the light Hawker 400XP, and the mid-sized Citation Sovereign. The most obvious difference between the jets is in size. The term "very light" may also be referred to as "very small cabin." In Eclipse-500, the cabin's maximum height and width are 4 ft 2 in. and 4 ft 8 in., respectively. Now we compare that to the Hawker 400 XP's height/width/length dimensions of 4 ft 9 in/4 ft 11 in./15 ft 6 in., or the Citation Sovereign's measurements: 5 ft 8 in/5 ft 6 in/24 ft 3 in (see Table 2).

The difference in dimensions of the VLJ aircrafts can be partly attributed to their difference in maximum passenger seating – six, nine, and twelve, respectively (see Table 2). Baggage space is sometimes a concern with VLJs. The *Eclipse 500* has the least baggage space of all the VLJs, 16 cubic feet. Others, such as the *Citation Mustang*, have as much as 63 cubic feet available, but lose a little speed and economy of fuel burn. Baggage capacity in the *Sovereign* is uncharacteristically high for a private jet of its size at 135 cubic feet; the Hawker offers 53 cubic feet. It is evident from Table 2 that the operating cost per hour in *the Sovereign* flight is the highest whereas that of the *Eclipse 500* is the lowest; it means the latter is the

Table 2. Comfort and Operating Cost of Some VLJ Aircrafts.

VLJ Aircraft	Eclipse 500	Hawker 400XP	Citation Sovereign
Cabin dimensions	Height: 4' 2" Width: 4' 8" Length: n/a	Height: 4' 9 " Width: 4" 11" Length: 15' 6"	Height: 5" 8" Width: 5' 6" Length: 24' 3"
Passenger capacity	6	9	12
Baggage capacity	16 cu. ft	53 cu. ft.	135 cu ft
Operating Cost/h	$372	$1,447	$1,974

best choice (the most economical) for a small family. However, cost is not always a limiting factor; for instance, royal families looking for roomier cabins and baggage capacities may opt for larger private VLJ jets (such as *the Sovereign*).

4. Configuration Design of VLJ Aircrafts

In order to design a VLJ aircraft, the designer must determine where the wing goes, how big to make the fuselage, how to put all the pieces together, and how to select the lightweight fail-safe materials [Edi and Fielding, 2006; Huda et. al, 2010a,b]. A new VLJ 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. A number of configurations are possible in designing a VLJ aircraft; and usually trade studies between several possible configurations will be required before the choosing the best configuration [Torenbeek, 1982; Edi, 2005a,b; Edi, 2006]. There are two main types of configurations for business jet aircrafts: (1) conventional and (2) unconventional configuration design.

4.1. *Conventional Configuration Design for VLJ Aircrafts*

In conventional configuration, the engine is mounted on the aft fuselage of the VLJ aircraft; this design involves a low-wing T-Tail/Cross-Tail configuration. The conventional configuration is the most common for most VLJ aircraft owing to the engine ground clearance requirements. The notable advantages of the conventional configuration include aerodynamically-clean wing, less control power for one engine out trim, better engine rotor burst and engine ground clearance. However, there are some limitations; which include no wing root bending moment relief, relatively higher cabin noise levels, heavier fuel system, difficult aircraft C.G management & engine accessibility. A typical example of conventional configuration is the *Cessna Citation Mustang* VLJ aircraft (Fig. 3). There is a good combination of performance, good look and efficiency in this aircraft; some features include: take-off from just 3,110 feet (948 m) of runway, climbs swiftly to 41,000 feet (12,497 m) and flies at 340 knots (630 km/h). The main landing gear offers superior shock absorption on landing; the latter is facilitated by the anti-skid brakes.

4.2. *Unconventional Configuration Design for VLJ*

In the unconventional design the engine is mounted over the wing of VLJ aircraft; this configuration eliminates need of any carry-through structure in the aft fuselage for its engine pylons. The unconventional configuration allows a full-width cabin farther aft thereby maximizing interior dimensions (Fujino, 2003). The advantages of unconventional configuration include: relief of wing root bending moment, relatively lower cabin noise levels, lighter fuel system, easy aircraft centre-of-gravity

Fig. 3. Conventional configuration design for a VLJ aircraft.

(CG) management (since engine is close to aircraft CG), and engine accessibility. Some limitations of the unconventional configuration include: aerodynamically unclean wing, greater control power for one engine out trim, and the like. A typical example of unconventional configuration includes *HondaJet* VLJ aircraft; which *features* a natural-laminar flow wing and fuselage nose and an all-composite fuselage structure (Fig. 4). The *HondaJet* proof-of-concept aircraft has accumulated more than 500 flight test hours and attained both a top speed of 420 knots (483 mph) and a maximum altitude of 43,000 ft. in flight testing (Internet Source: aircarftcompare.com, 2011).

Fig. 4. Unconventional configuration design for a VLJ aircraft.

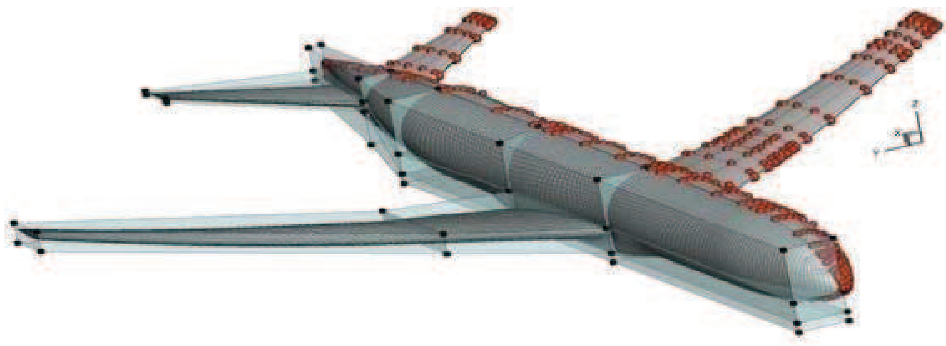
5. Designing High-Performance VLJ Aircraft

5.1. *Multidisciplinary Design Optimization (MDO) Approach*

The design of a new high-performance VLJ aircraft requires a multidisciplinary design optimization (MDO) approach. MDO is a design system environment where it is possible to perform the design optimization of complex engineering systems team of engineers to perform the preliminary design of a new aerospace system in a period of one to two weeks, instead of the several months currently required by a much larger team of engineers (see Fig. 5(a,b)). The major technologies in MDO include: computer aided design (CAD), aerospace structural design, advanced aerodynamic, lightweight materials design, and electronic systems. The MDO is a more cost-effective and efficient design technique as compared to serial design approaches since it simultaneously takes into account mutually dependent design elements from various fields, and has the advantages of reduced time and cost (Kim *et al.* 2009). The modern MDO design approach is important owing to a broad variety of applications of computer technology in all aspects of aviation. In particular, computational fluid dynamics (CFD) software must be employed while designing wings of the aircrfat [Edi *et al.*, 2008]. In addition to computer applications, the widespread development of the use of lightweight composite materials in aircraft structures has also strongly influenced the cost and legal considerations in the design of VLJ aircarfts.

5.2. *Structural Material Technology for High-Performance VLJ Aircrafts*

In selecting material for aircraft design, it is important to comparatively analyze strength characteristics of various lightweight aerospace materials (Huda *et al.* 2009; Wadley *et al.* 2003; Hinrichsen, 2000; Immarigeon, *et al.* 1995). The basic structure of VLJ aircrafts might be built around a composite laminate skeleton; the bi-directional graphite/epoxy plain weave or uni-directional plies for ease of fabrication (Shirk *et al.*, 1986). The mechanical behavior of a laminated composite should be stress-analyzed as reported in the literature (Almajid, *et al.* 2001; Gibson, 1994; Taya 1989). In developing prototype VLJ aircrafts made of the bi-directional laminar composite, simulation testing must be carried out to ensure the material is strong enough to withstand the stresses during flight. For instance, Epic Aircrafts (the *Epic Elite and the Epic Victory)* are constructed of carbon fibre technology (Epic Aircrafts Inc, 2010). The structure of VLJ aircrafts must be designed with durable, corrosion-resistant, low-weight, high-stiffness, high-strength, and ease-to-fabricate composite materials. Figure 6 shows a comparison of the specific modulus and specific strength of *Al-Be* (62%Be-38%Al) alloy with boron/epoxy and Ti, and Carbon/epoxy composites [Williams and Starke Jr., 2003]. The authors recommend IM7/977-3 carbon-Epoxy (carbon fibre polymer) composite material in view of its high specific strength (450 GPa/kg/m^3) and high stiffness (50 GPa/kg/m^3) for new high-performance VLJ aircrafts.



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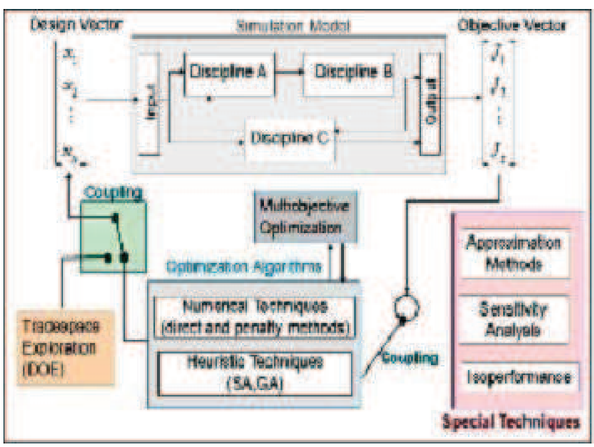

(b)

Fig. 5. (a) Analysis for a new aircraft system using multi-disciplinary optimization (MDO), (b): Frame-work of the many different components of MDO.

5.3. *Engine Design for High-Performance VLJs*

In order to improve performance of a VLJ, new families of small turbofan engines should be developed to power them. Some recently developed VLJs have been certified. The first two VLJ's to be certified are: the Eclipse 500 and the Cessna Citation Mustang; both use engines from the PW600 family. For example, business VLJ aircrafts employ Pratt & Whitney Canada PW610F turbofan engines (Eclipse, 2004) whereas Williams International Inc employs FJ44-2A fanjets (Sino Swearingen, 2004). Another high-performance VLJ engine is 1,670-pound-thrust HF118 turbofan developed by Honda and General Electric (Fujino, 2003). In PW610F, The two-spool design features a single-stage high pressure turbine driving a mixed–flow

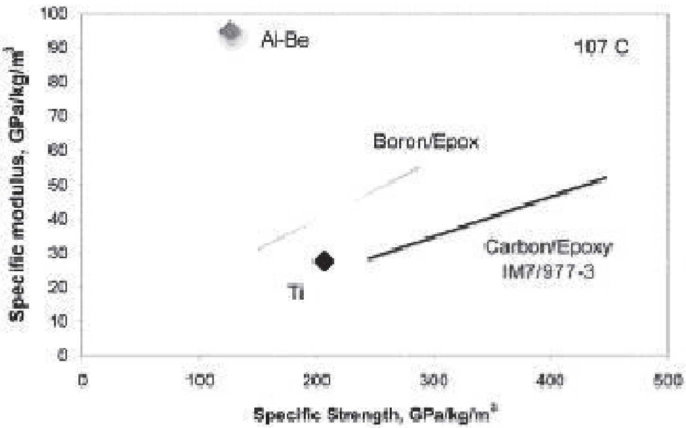

Fig. 6. Plot of density normalized stiffness vs. strength for lightweight aerospace materials (Williams and Starke Jr., 2003).

and centrifugal high pressure compressor and a single-stage low pressure turbine driving a 14-inch one-piece titanium integrated bladed rotor fan. In the PW610F, engine control is provided by a Full Authority Digital Engine Control (FADEC); and thrust is managed through power lever input signal to the FADEC, which controls a fuel metering unit. Since VLJs are lightweight machines, an attempt should be made to design the engines using lightweight materials; significant developments in lightweight engine material technology for aerospace applications has been reported [Gurrappa and Reddy 2005; Allen, 2003].

5.4. *Safety Considerations in VLJs*

The safety of the VLJ airframe and its systems must be assured through the FAA certification processes. Some of the aerodynamic designs for new generations very light jets (VLJs) have phenomenally forgiven flight characteristics and approach speeds. It is important to avoid the compromises between flight handling characteristics and performance; the latter were experienced with the early VLJs, such as *Learjets* and *MU2s*.

Smart Systems

Smart aeronautical systems ensure safety and reliability in high-performance VLJs. The designers of the VLJs aircrafts must integrate safety into their aircraft's systems. They should aggressively sought ways to reduce pilot workload and improve the information available for situational awareness and critical decision making. A few of safe and reliable VLJ's avionics and smart systems innovations should include: (a) Computerized trend monitoring and aircraft system fault tracking and troubleshooting, (b) Dual Primary Flight Displays, (c) Dual Multi-Function Displays,

(d) Reversionary display capabilities, (e) Integrated electronic flight bag, (f) Highway in the Sky flight path guidance, (g) The equivalents of Enhanced Ground Proximity Warning System, (h) Real-time weather data and display uplink; and (i) Lightning strike information.

6. Conclusions and Recommendations

Having reviewed the recent advances in designing cost-effective high-performance very light jet (VLJ) aircarfts, the following conclusions are drawn and recomendations are made:

- In order to design cost-effective VLJ aircrafts for today's market, the trends of direct operating cost (DOC) and aircraft price versus MTOW of existing aircrafts must be considered.
- The price of a VLJ aircraft should be judged by considering its cruise speed, the fuel cost per mile, cabin size, and the passenger & baggage capacities.
- In designing a high-performance VLJ aircraft, it is recommended to adopt the multidisciplinary design optimization (MDO) approach.
- Lightweight high-stiffness high-strength composite materials must be selected. The authors recommend IM7/977-3 carbon-Epoxy (carbon-fibre-polymer) composite material possessing high specific strength (450 GPa/kg/m$^{\mathbf{3}}$) and high stiffness (50 GPa/kg/m$^{\mathbf{3}}$) for new high-performance VLJ aircrafts.
- Smart aeronautical systems should be integrated into the aircraft systems to ensure safety and reliability in new high-performance VLJ aircrafts.

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