Contents

Brief Aviation History
Design Considerations
Aeromaterial Demand
Industry Trends
Over four decades, aviation evolved from concept to inception of modern aircraft

Early Aviation Advancements

- Otto Lilienthal
  Germany – 1890s

- Wright Brothers
  USA – 1903

- Louis Bleriot
  France – 1909
  (first flight across English Channel)

- Boeing 247
  USA – 1933
  (all-metal semi-monocoque construction)*

- Early aircraft were fabric covered wooden frames, including Lindbergh’s *Spirit of St. Louis* (1927) - wooden frame wings with metal tube fuselage

* Preceded Douglas DC-3 by 2.5 years
Airspeeds increased – with step change in 1942 – upon arrival of German Messerschmitt Me 262 jet fighter.

Evolution of Aviation Airspeed

Jet Age

What changes in materials facilitated these advances in aviation?
Contents

Brief Aviation History

Design Considerations

Aeromaterial Demand

Industry Trends
Four design considerations drive material selection in aviation

Key Design Considerations

Strength vs. Weight

Propulsion Efficiency

Decreasing Importance

Airframe

Engine

Manufacturability

Maintenance
Designer’s initial goal is structure to adequately withstands flight loads

Strength verses Weight

Typical Vn Diagram

- Primary challenge is to manage “design loads” for stress mitigation
- Secondary considerations includes designing (and substantiating) *fatigue, flutter, corrosion, damage tolerance, crashworthiness*
Designs include margin of safety, which considers both material strength and structural design.

Margin of Safety

- Aircraft are typically designed with margin of safety 1.5 to 2.0
- Automotive uses 3.0 and pressure vessels 4.0, by comparison
- Lower factor for aerospace is due to weight sensitivity
- Thus aerospace has stringent quality control and maintenance schedules
Design is substantiated/certified by both analysis and testing

Testing and Analysis

- Civil aircraft are certified by country governmental authorities
- Certification combines analysis and testing
- Complex finite element models (FEM) are used to facilitate testing
- The less known material allowables and design, the more rigorous testing
Testing is specified by FAA CFR requirements in US, and EASA equivalent in Europe

Certification Authority (1/2)

- The US authority is FAA; in Europe, it is EASA
- The FAA maintains CFRs (Code of Federal Regulations)*, governing all design, manufacture and operation
- CFR Part 23 address General Aviation and Commuter Category (MTOW <19K lbs)
- CFR Part 25 address Transport Category aircraft

Regulations that govern structural materials:
- 14 CFR 25.603 – 615 covers Materials, Fabrication, Design
- The MMPDS** is used for design information

* Formerly FAR (Federal Aviation Reg)
** Formerly Mil Hnbk 5
These CFR requirements ultimately address four areas covering design/build/test

Certification Authority CONT (2/2)

Material Specs: All materials purchased under approved documented control

Process Specs: Production method needs to demonstrate “stable and repeatable” structure (per approved documented control)

Design Values: Material properties must account for variability from both “as purchased” and “as processed”

Analysis: Models must accurately predict mechanical behavior of structure
Aircraft weight is particularly important to operators since fuel cost is primary expense.

Fuel Cost and Weight

- Fuel is roughly 30% of total operating cost of airline, depending on spot market, hedging, etc.
- Other costs – labor (25%) and maintenance (15%)
- Price of fuel has greatly increased over past decade
- American Airlines stated removing 1 lb from each aircraft would “save more than 11,000 gallons of fuel annually” fleet wide.

Source: American Airlines, secondary
Gas turbines are divided into “cold” and “hot” sections – both impact efficiency

Propulsion Efficiency

Cross-section of typical gas turbine

A gas turbine is divided into two sections:

- Cold section (intake/fan and compressor)
- Hot section (combustor and turbine/exhaust)

- In “low-bypass” engine (pictured), propulsion is produced by hot gas expelled out exhaust
- These have high thrust-to-weight ratios yet are not fuel efficient
Newer gas turbines have increasingly larger inlet diameters, allowing for greater fuel efficiency

**Geometry and Efficiency**

- Newer commercial engines have “high-bypass” ratios
- More air passes quickly/efficiently around core, “bypassing” the combustor
- Ratios of 10:1 or more are common – thus, 10 times air flows around core verses through it
- Large aft turbine recovers energy from escaping gas to drive fan, which produces >80% of propulsion
- P&W Gear Turbo Fan uses gearbox to slow fan and further increase efficiency

*Source: secondary*
Increasing hot section temperatures also affects efficiency

Temperature and Efficiency

- The propulsion efficiency (i.e. bypass) influences 50% of operating efficiency – remainder is function of thermal efficiency
- Increasing temperature improves fuel efficiency
- The hottest temperatures are around combustor (specifically, T41 – turbine inlet temp)
- Thus most new materials target “hot section”
Manufacturability and maintenance are additional design considerations

Manufacturing and Maintenance

- Aerostructure assembly more automated with advent of composites
- Computer numeric controlled (CNC) machining is increasingly sophisticated, creating monolithic structures
- OEMs are actively exploring additive manufacturing

Maintenance

- Thin design margins require strict preventative maintenance
- Aluminum structures inspected for cracks/fatigue/corrosion; composites, for non-visible impact damage
- Engines consume most of materials in form of “life-limited” parts (i.e. critical rotating parts)

Source: secondary, interviews
Contents

Brief Aviation History
Design Considerations
Aeromaterial Demand
Industry Trends
Early aircraft evolved from exclusively load-bearing frame, to loaded frame and skins

Evolution of Aerostructures

- Early aircraft were built with same philosophy as buildings/bridges, using internal frame for loading
- In 1913, paradigm shifted when Swiss man (Ruchonnet) designed skin to carry the load – known as “monocoque”
- Semi-monocoque is now standard, distributing load between skins and aerostructure (frame and stringers)
Aeromaterials followed similar path, evolving from wood, to aluminum, to carbon fiber composites

Evolution of Airframe Materials

- Aircraft aluminum was developed in Germany 1909, known as “duralumin”, containing copper/magnesium/manganese
- In 1917, German Junker military airplane was all duralumin
- Aluminum was standard for 80+ years – now aircraft are moving to carbon fiber reinforced plastic (CFRP) composites

Notes:
- Starship was first FAA certified all-composite aircraft
- Eurofighter was first military jet >50% composite
- B787 was first air transport category aircraft >50% composite
Aviation has trended towards greater composite use over past three decades

Entry into Service vs Percent Composites*

Airbus shortly followed Boeing’s foray into composites via the A350 widebody

* Air transport category only
Nevertheless, there are several challenges with composites

Considerations for Composites

**ADVANTAGES**
- Lighter weight structures
- Lower part count and labor content
- More complex geometries
- Fatigue resistant
- Corrosion resistant

**DISADVANTAGES**
- Structural properties highly dependent upon manufacturing, with variation of fiber and resin
- Higher recurring and non-recurring cost
- Damage detection and repair more complicated
- Contamination threat during lay-up and bonding process
- Limited materials database
- Raw materials are perishable
- Not compatible with aluminum

Source: D Cairns – MS Univ, L Illewich – FAA, secondary
Major shift in engine materials occurred in early 1960s

Historical Material Use in Gas Turbine

- Most new material involved in hot section, especially for blades
- The use of nickel (as “superalloy”) increased substantially since 1960
- Accordingly, operating temperatures and fuel efficiency increased
- Titanium increased in cold section, due to superior strength to weight
Turbine blades are subjected to highest temperatures, and are thus primary design consideration

**Turbine Blade Design**

- Principle concerns for material selection are resistance to creep (i.e. elongation) and corrosion
- Temperature capabilities have increased via: investment casting technology; cooling path design; thermal barrier coatings; and alloy development
- Consequently, blades operate 800°F above metals’ melting temperatures
- Peak turbine inlet temperatures exceed 3200°F

Source: interviews, secondary
When aggregated, total material required for aerospace is 265M lbs per annum – half is aluminum alloy.

Total Aircraft Material Fly Weight (2014)

- Total material weight for aircraft produced in 2014 is 265M lbs
- Although composites are increasing, aluminum alloy is still majority
- Engine constitutes 15% of total, affected by greater density of superalloys

Source: ICF Int’l, analysis
Corresponding material buy totals 1.4B lbs – Boeing and Airbus account for two thirds

Total Aircraft Material (Mill) Demand (2013)

- Boeing 37%
- Airbus 30%
- GE 5%
- CFMI 4%
- Bombardier 3%
- Gulfstream 1%
- LockMart 2%
- Rolls Royce 2%
- P&W 1%
- OTHER 11%

- When considering “buy-to-fly” ratio* for various process, total material demand is 1.4B lbs
- Boeing and Airbus aircraft (commercial/military) clearly dominate consumption
- Total value is estimated at $11B

*Buy-to-fly is the amount of material lost during forging, casting, and milling

Source: ICF Int’l
Demand anticipated to increase 1.1% per annum, with strong growth for titanium and composites.

- Total material demand will reach 1.6B lbs by 2023.
- Aluminum alloys will remain flat to decline.
- Growth in titanium and composites are correlated due to material compatibility.

Source: ICF Int’l
Most airframe materials under investigation involve aluminum alloy

Next Generation Materials – Aerostructures

- Aluminum-lithium (Al-Li) alloys vying for next generation narrowbody – likely Al-Li fuselage, with composite wing
- Various 7xxx AL and Al-Li “designer” alloys are being qualified for niche applications throughout airframe
- Fiber reinforced Al is under evaluation
- Coatings for Al and bonding methods (Al + Ti) are being studied to address galvanic corrosion

Source: interviews, secondary
Newer gas turbine materials have targeted titanium (cold section) and superalloys (hot section)

Next Generation Materials – Gas Turbine

- Composites – and now aluminum-lithium – are displacing titanium for fan blade
- Titanium-aluminide (TiAl), ceramic matrix composites (CMC), powder metal used increasingly in hot section
- TiAl is about half as dense as superalloys, though extremely difficult to machine
- CMCs are one-third weight, twice strength and 20% greater thermal capability (does not require cooling)
- GE is using CMCs statically in LEAP; looking at rotating parts (blades) for GE9X

Source: interviews, GE, secondary
Contents

Brief Aviation History
Design Considerations
Aeromaterial Demand
Industry Trends
Monolithic structure, increased tolerances, and near-net shapes are impacting design and production

Trend #1: Design and Production

**Airframe:** Movement towards larger “monolithic” structures to reduce part count and weight

**Engine:** Increased machined tolerances for components for greater operational efficiency

**Both:** More near-net shape since: hard alloys are difficult to machine; scrapping parts is expensive (Ti forgings $100Ks vs. AL blanks $10Ks)

Source: interviews
Russia’s VSMPO is a major supplier of aerospace titanium alloy – geopolitics are creating real concern

Trend #2: Global Sourcing

- VSMPO is responsible for 30-35% of the world’s titanium, and principle supplier to Boeing and Airbus

- VSMPO has its own 75Kt press

- In 2013, signed JV with Alcoa to collaborate with forgings on Alcoa’s 75Kt press

- In 2009, Boeing initiated JV with VSMPO – called UBM – to machine various forgings

- In 2013, Boeing announced a second JV facility, bring its total investment to $27B (from 1991 to 2021)

Domestic mills – ATI, RTI, TIMET – have benefited from this debacle

Source: WSJ, secondary, interviews
Additive manufacturing allows for greater design optimization for complex metal parts

Trend #3: Additive Manufacturing (1/3)

Additive manufacturing (AM) involves “growing” parts layer by layer*, typically via laser melting of powder metal – technology developed in 1980s for DARPA

**Advantages:** enhance design flexibility, reduced part count and weight, reduced scrap

**Disadvantages:** limited size, small batches, unit cost, material control

- **Targets:** complex geometries (e.g. casting and assemblies), metals difficult to machine (e.g. TiAL)

- **Adoption:** non-structural parts for new production, and “end-of-life” for repair parts – certification is a challenge

*Thickness < .001” (vs .004” for human hair)

Source: secondary

*33*
GE Aircraft leads in AM develop with LEAP fuel nozzle

Trend #3 CONT: Additive Manufacturing (2/3)

- On July 15, GE announced plans for factory in Alabama, first to mass-produce turbine parts using AM
- Production begins in 2015 with nozzles for LEAP engine to produce 1000 per year via 10 AM machines
- Goal is over 100,000 AM parts by 2020
- GE/Avio actively exploring AM using TiAl for LPT blades for GE9X engine – first application for rotating parts
- GE plans to invest $3.5B in AM by 2020

One piece CoCr fuel nozzle replaces 20 parts – 25% lighter, 5x life increase
GE believes weight reductions via AM design optimization will be significant

Trend #3 CONT: Additive Manufacturing (3/3)

- 2012 AM study by GE aircraft identified 1000 lbs of potential weight savings within 6000 lb gas turbine
  - By optimizing design via AM, GE claims 1000 lbs savings can be realized over 10 to 20 years
  - 1000 lbs of engine weight reduction can double/triple weight reduction of wing structure and pylons
    - The net result is 10,000s of gallons of fuel savings per aircraft per year

Source: Industrial-lasers.com
Thank you for your attention

- Aerolytics LLC -
Aerospace Analytical Market Research & Consulting

For more information:

www.aerolyticsllc.com