Aviation

Dipankar Banerjee (Defence Research and Development Organisation, India)

Aviation accounts for about 3% of the current global energy consumption of 15 terawatts (TW).[1–3] The global annual growth of energy use in the aviation sector is likely to be around 2.15% and will exceed that in other transportation sectors, although land transport will continue to consume the largest amounts of fuel. **Figure 1** displays the historical improvements in energy efficiency in the aviation sector.[4] Fuel use is determined by both operational and technological factors.[5–7] The former includes the passenger load factor, ground efficiencies, taxi procedures, take-off and landing paths and circuitry (actual distance traveled versus a great-circle distance), and changes in the mixture of old and new aircraft and propulsion systems with time. Technology factors, focusing on materials issues, are described in greater detail herein.

Technology

The Breguet range equation (Equation 1) provides metrics for the evaluation of technology factors contributing to fuel efficiency

$$\text{aircraft range} = (\text{velocity/SFC}) \times (\text{lift/drag}) \times \ln[1 + W_f/(W_{pl} + W_o)] \qquad (1)$$

where SFC is the fuel consumption per unit thrust of the propulsion system, W_f is the fuel weight, W_{pl} is the payload weight, and W_o is the empty operating weight. Improvements in technology derive from aerodynamics (that is, an increase in the lift-to-drag ratio for various flight conditions), increases in the propulsive and thermodynamic efficiencies of gas turbine engines, and reductions in airframe and engine weights.[7]

Airframe

Increases in fuel efficiency due to weight reduction of airframes were estimated to be between 2.5% and 7.5% from a 10% decrease in aircraft weight.[6] The prime airframe material, aluminum, has been gradually replaced by carbon fiber/polymer matrix composites that are significantly superior in specific strength, modulus, and fatigue resistance. Fighters such as the F22 and the Eurofighter use up to 70% composite materials by weight (**Figure 2**), and commercial aircraft such as the Boeing 787 use nearly 50%.[8] The Airbus A380 design is more conservative in materials usage, but still employs an aluminum alloy–carbon fiber/polymer matrix composite sandwich configuration extensively for primary structures.[9] The structural efficiencies of airframes could be improved through increased sophistication in the manufacturing of polymer matrix composites. Automated textile weaving processes that precisely control fiber spacing, directionality, dimensionality, and volume fraction can be utilized to allow designs that provide local rather than global responses to loads. Co-curing and co-bonding processes together with localized joining through electron beam or irradiation curing will eliminate metallic fasteners and rivets, thus providing increased structural integrity in addition to a reduction in weight. The temperature capabilities of polymer matrix composites need to be enhanced from their current limits of about 525 K, through molecular engineering or perhaps the use of matrix and fiber surfaces modified with carbon nanotubes, enabling further replacement of metallic parts in hotter sections of aircraft at temperatures higher than 600 K. A key challenge in this task will lie in ensuring that the toughness (about 0.04 design compression strain) and environmental resistance do not degrade with increasing temperature capabilities.

Increases in fuel efficiency have, of course, been derived from aerodynamics. The challenge has always been to resolve the conflicting demands of wing design to reduce induced drag (arising from wing tip vortices) in the low-speed regime to parasitic (form, skin friction, and interference components) and supersonic wave drag effects that increase exponentially with speed. Concepts that seek to maintain laminar flow over the wing profile[6] and a variety of wing profiles and geometries that

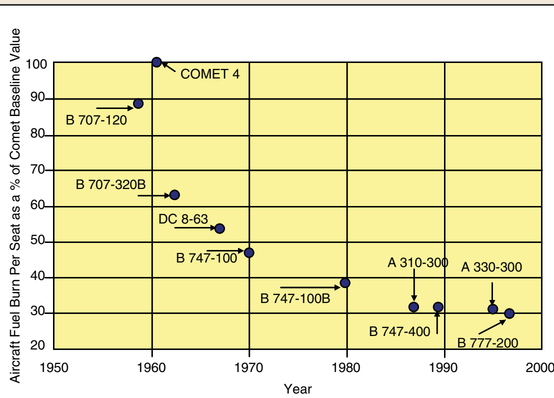

Figure 1. Historical improvements in energy efficiency of passenger aircraft.

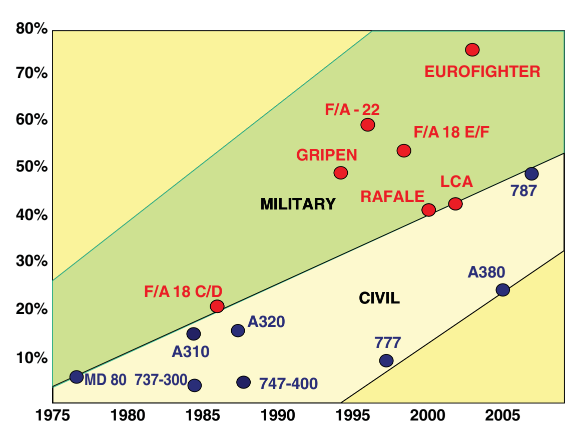

Figure 2. Use of polymer matrix composites in military and passenger aircraft. *Source:* Reference 8.

reduce drag over differing flight regimes have been evaluated, including most recently the Boeing unmanned blended-wing aircraft, which uses a flat, wide body that tapers out to thin wing tips. These designs will culminate in adaptive or morphing wings that acquire optimal configurations during flight much like the wings of a bird. The realization of such advanced concepts will demand an intensely multidisciplinary effort, combining aerodynamics, control, sensors, and actuation, and will require the use of multifunctional materials systems that combine structural functions with those of sensing and actuation. Thus, materials ranging from piezoelectrics to shape-memory materials, magnetostrictive materials, and electroactive polymers will play a significant role (**Table I**) in the sensors and actuators of such morphing wings. Their choice will be determined by their frequency, stress and strain, and hysteresis response.[10] Skin materials (which are largely polymer matrix composites) of such morphing wings will combine with novel structural forms[11] to be sufficiently elastic to deform reversibly but stiff enough to withstand aerodynamic loads.

Table I: Smart Materials for Actuator Applications in Morphing Structures.

Material	Strain (%)	Stress (MPa)	Energy Density (J/g)	Actuation Speed
Dielectric elastomers	215	7.2	3.4	medium
Piezoelectric materials	0.2–1.7	110–131	0.013–0.13	fast
Shape-memory alloys	>5	>200	>15	slow
Magnetorestrictive materials	0.2	70	0.007	fast
Conducting polymers	10	450	23	slow
Human muscle	>40	0.35	0.1	fast

Source: Reference 10, © 2003, Springer and the Minerals, Metals and Materials Society.

Propulsion

Two key concepts have driven performance and efficiency improvements in gas turbines. The thrust-specific fuel consumption has steadily improved through increases in the bypass ratio (the fraction of the total airflow through the fan of the engine that directly contributes to thrust without being burned with fuel to drive the turbine) from the turbojet configuration. It has been estimated that the ultra-high-bypass configuration might contribute as much as 10% to efficiencies in seat miles per gallon.[6] Further improvements in propulsive efficiency will arise from the geared turbofan concept, which sets fan and low-pressure turbine rotor speeds to their respective optimal values for very high bypass ratios, and from variable-cycle-engine concepts. The turboprop also has a very high efficiency, albeit at much lower aircraft speeds. An alternative pathway lies in the use of the unducted fan (without a casing) or the propfan, which combine the efficiencies of the turboprop with the thrust of a turbofan, an approach being pursued by Rolls Royce in a European consortium. Significant materials innovation has kept engine weights down even as engine sizes have increased to accommodate greater thrust and bypass ratios. The most striking of these innovations are the use of wide-chord, hollow titanium fan blades in Rolls Royce's Trent engines and the use of polymer matrix composite fan blades in the GE 90 and GEnx engine, as well as polymer matrix composite front casing in the GEnx engine. The GEnx engine also represents probably the first service use of the γ-TiAl intermetallic compound in replacement for nickel-based blades in the low-pressure turbine.[12]

Engine weights have also been kept down through increases in the thermodynamic efficiency of the engine that enable higher thrust for the same mass flow and through the development of high-temperature materials for the turbine. The temperature capability of turbine airfoils used today, made of a single-crystal nickel-based superalloy, coated with a thermal barrier, and cooled internally, approaches 1800 K, but improvements are becoming increasingly harder to obtain. The elimination of cooling can provide further enhancements in efficiency. Ultra-high-temperature materials represented by those shown in **Figure 3** (that is, intermetallic compounds based on Mo–Si and Nb–Si, platinum-group metals, SiC/SiC ceramic matrix composites, or even $Al_2O_3/GdAl_2O_3$ eutectic composites) provide possibilities in this direction, perhaps allowing increases of about 100 K.[13] The use of higher turbine entry temperatures, in turn, demands higher temperature capabilities in low-pressure turbine and compressor materials. Advanced cores using γ-TiAl and orthorhombic intermetallic composites and monoliths have been evaluated, as have SiC/SiC composites for combustors.[14,15] Weight reductions enabled by integrated blading on disks of titanium alloys (rotor disk and blades machined from a solid piece of material, as opposed to mechanically joined configurations) are now standard on modern fighter engines, as are SiC/SiC or C/SiC composite materials on nozzles and other jet pipe parts.

Conclusion

Innovations in materials technology, primarily through the increasing use of polymer matrix composites and titanium, have played a key role in decreasing airframe and propulsion system weights, even while enabling higher thrust levels through the use of materials that can withstand very high temperatures. Smart, multifunctional materials will also play a role in enabling adaptive aerodynamic concepts for greater flight efficiency. Although the driver for improvements in energy efficiency in the

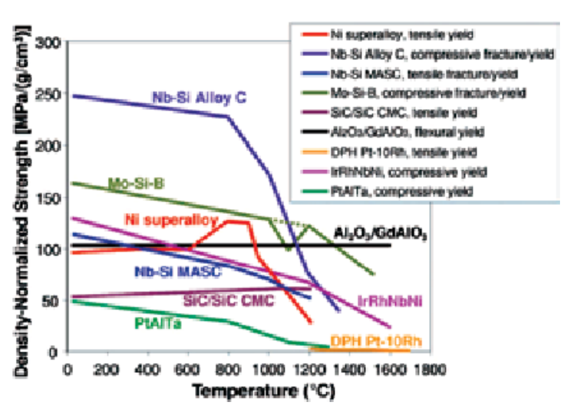

Figure 3. Potential ultra-high-temperature materials (*Source:* Reference 13).

aviation sector has usually been the high cost of jet fuel, other factors such as the depletion of fossil fuel reserves and global warming will increasingly dominate. About 60% of aircraft emissions are in the upper troposphere, and 20% are in the stratosphere; these emissions are unregulated. Alternative fuels, such as biofuels and hydrogen, and alternative propulsion systems based on fuel cells are being evaluated in response to these drivers. These will be associated with a different set of materials challenges, as will the reemergence of supersonic transport and possible development of hypersonic transport. The advent of unmanned air vehicles will provide relatively safe opportunities to test advanced technologies. It is possible that improvements in energy intensity in the aviation sector will continue to outpace those in the automobile sector, as has been the case in the past.

References

1. *International Energy Outlook 2007* (Energy Information Administration, U.S. Department of Energy, Washington, DC, May 2007); http://tonto.eia.doe.gov/FTPROOT/forecasting/0484(2007).pdf (accessed January 2008).
2. *IEA Estimates* (International Energy Administration, Paris, 2001).
3. *The Sustainable Mobility Project: Overview 2004* (World Business Council for Sustainable Development, Geneva, 2004); www.wbcsd.ch/web/publications/mobility/overview.pdf (accessed January 2008).
4. "Aircraft Emissions: Current Inventories and Future Scenarios," in *Aviation and the Global Atmosphere*, J.E. Penner, D.H. Lister, D.G. Griggs, D.J. Dokken, M. McFarland, Eds. (Cambridge University Press, New York, 1999); chap. 9, Figure 9-3; www.grida.no/climate/ipcc/aviation/avf9-3.htm (accessed January 2008).
5. A. Vedantham, N. Oppenheimer, *Energy Policy* **26**, 625 (1998).
6. D.L. Greene, *Ann. Rev. Energy Environ.* **17**, 537 (1992).
7. R. Babikian, S.P. Lukachko, I.A. Waitz, *J. Air Transport Manage.* **8** (6), 389, (2002); available at http://web.mit.edu/aeroastro/people/waitz/publications/Babikian.pdf (accessed January 2008).
8. P. Sparaco, *Aviat. Week Space Technol.* 59 (April 26, 2004).
9. D. Hughes, *Aviat. Week Space Technol.* 66 (April 5, 2004).
10. S.G. Wax, G.M. Fischer, R.R. Sands, *J. Met.* 17 (December 2003).
11. L. Christodoulou, J. Venables, *J. Met.* 39 (December 2003).
12. G. Norris, *Flight Int.* (June 13, 2006).
13. J.-C. Zhao, J.H. Westbrook, *MRS Bull.* **28** (9), 624 (2003).
14. S. Kandebo, *Aviat. Week Space Technol.* 50 (September 1, 2003).
15. S. Kandebo, *Aviat. Week Space Technol.* 37 (May 10, 2004). □