AIAA Journal
Vol. 52, No. 5, May 2014

Aeropropulsion for Commercial Aviation in the Twenty-First Century and Research Directions Needed

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DOI: 10.2514/1.J052713

Two driving imperatives of 21st century commercial aviation are improving fuel consumption and reducing environmental impact. The research important to aeropropulsion's advancing these goals is shaped both by physics of the design space and by design choice. As fuel becomes increasingly more expensive, engine architectures and design details evolve to reflect the new balance between engine fuel consumption, weight, and manufacturing and maintenance costs. The evolution of engine architectures changes the relative value of specific technologies. The engines of the future will be advanced gas turbines due to their superior fuel burn at the aircraft level. They will be fueled by sustainable liquid hydrocarbons. Both the thermal and propulsive efficiency of the gas turbine can be significantly improved. The need to improve propulsive efficiency has driven engine bypass ratio up, to 12 recently, and higher in the future. This is a different, less familiar design space than the 5 to 8 bypass ratio, which characterized the last 40 years of engine experience. Realignment of research priorities is required to address 21st century challenges, such as the knowledge needed to realize efficient engines at very small core sizes. The new challenges open up new opportunities for both designers and researchers.

I. Introduction

IT HAS been more than 70 years since the flight of the first jet airplane and over 50 years since the first successful commercial jet airliner, the Boeing 707, entered service. Reflecting R&D investments of tens of billions of dollars over this period, the jet engine has improved enormously: efficiency up by three times, power to weight ratio up by of two to four times, and reliability and life improved 100 200 times and 5 10 times, respectively. The turbofan jet engine is now the aeropropulsion system of choice. It is appropriate now to ask how much further jet engines can be improved. Will continued investments here be fruitful, and if so, what should they be? In a broader sense, the gas turbine is now the aircraft engine of choice because of its high efficiency, low weight, low emissions, and extraordinary reliability. How much longer will this continue?

This paper considers these questions with the aim of identifying and prioritizing research paths relevant for advancing aeropropulsion. There are very diverse applications for airplanes, including commercial, military, and general aviation. Commercial aviation is focused on the transportation of people and goods and represents the majority of the economic value that aircraft bring to the world. It is also responsible for the majority of the environmental impact of aviation and most of the business revenue associated with aviation engines. This discussion is thus focused on commercial aviation. Needs and opportunities peculiar to military applications or general aviation are not considered here.

II. Defining Aeropropulsion

Aircraft propulsion can be considered as consisting of two necessary elements. The first is a motor to convert stored energy to mechanical power, typically in the form of a rotating shaft. The second is the conversion of mechanical power into propulsive power. Excluding rockets, to date we have identified only two methods of propelling an airplane: flapping wings or spinning a propeller. The flapping of wings has not been notably successful for airplanes and so may be safely neglected here. Indeed, theoretical analysis suggests that flapping is less efficient than a propeller in converting mechanical power into propulsive power [1]. A propeller may be operated in free air, installed in a duct to produce a jet and called a fan, or canted to the flight direction and called a rotor (as in a helicopter). Herein, we will adopt the term propulsor as referring to a device which converts shaft power to propulsive power, inclusive of propellers, fans, and rotors.

Propulsors are turned by motors: internal combustion in the old days, gas turbines for the past half century. Recently, there has been consideration of using electric motors, so care must be taken to distinguish between power and energy. Power and energy requirements for a wide variety of land, sea, and air vehicles are

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Presented as Paper 2013-0001 at the AIAA Aerospace Sciences Meeting, Grapevine, TX, 7 10 January 2013; received 4 April 2013; revision received 17 October 2013; accepted for publication 31 October 2013; published online 28 March 2014.

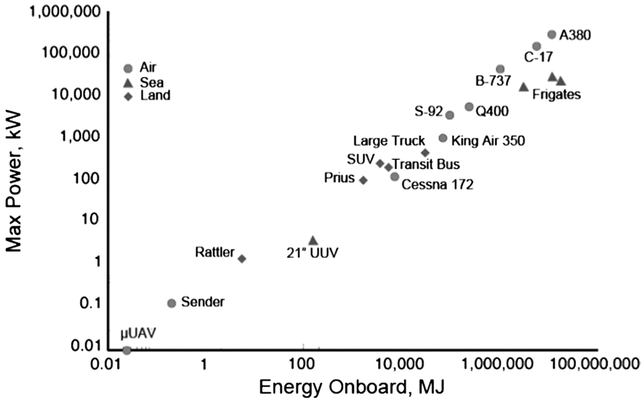


Fig. 1 Energy and power of air, land, and sea vehicles.

shown in Fig. 1. Clearly, large aircraft flying long distances at high speed require prodigious amounts of both power and energy.

III. Energy Sources and Energy Storage

Will we use the same fuel in the future as we use now? Engineering criteria for jet aircraft fuel selection changed little in the 20th century. In the last decade, increased concern for the environment, climate change in particular, has added a new imperative for aviation: reduction in greenhouse gases, especially CO_2. Thus, it is prudent to consider whether we will continue to use the same aircraft fuels in the 21st century as we did in the 20th. Current jet fuel is chemically similar to kerosene. The technical attribute of fuel most important to airplane design and performance is energy density, both gravimetric and volumetric. Cost and emissions are very important as well, with additional concerns of thermal stability, lubricity, etc. Over the past 70 years, research on improved fuels has yielded relatively minor gains, mainly in slightly increased density (JP 10) and thermal stability (JP 7, JP 8 + 100).

The energy density and energy cost for a variety of "fuels" are shown in Table 1 [2]. In terms of room temperature liquids, Jet A has the highest energy density and lowest cost. Although the gravimetric energy density of methane is close to that of Jet A, and hydrogen is 2.7 times greater than Jet A; these are gases at room temperature and thus must be stored as cryogenic liquids or at high pressure. The weight of high pressure containment makes the latter option impractical given tank materials available today. Cryogenic storage as liquid is possible but introduces many questions including routine handling and safety, especially in accidents. Liquid hydrogen has less than 10% the volumetric density of Jet A. For equivalent onboard energy, liquid hydrogen fuel requires storage volume 10 times greater than today's liquid fuel with a concomitant increase in aircraft weight, drag, and energy consumption. This suggests that liquid hydrogen is not an attractive fuel for high speed aircraft, a lesson first learned in the 1950s [3]. Hydrogen might have a role for low speed surveillance applications when persistence is a dominant design criterion [4].

Combustion motors derive their energy from chemical energy stored in fuel. Electric motors need electric power. Conceivably, this can be generated by combustion motors driving generators, by fuel cells from chemical energy in fuel, from chemical energy in batteries, or from solar cells on the vehicle. The latter is impractical on this planet for transport aircraft given the level of solar irradiance falling on the Earth. This irradiance is insufficient to support aircraft wing loading above 20 lb/ft^2 (98 kg/m^2), far below that needed for all but the slowest speed flight. Thus, we can safely rule out solar cells powering commercial airplanes. This means that aircraft of the future, as those of the past, must be fueled.

Batteries are a different approach to energy storage and present their own challenges. The theoretical energy density of lithium chemistry is about 10% that of kerosene. When batteries are engineered with current technology for such practical considerations as safety, performance over a wide temperature range, and long life, their energy density is 10% of the theoretical maximum and thus only about 1% that of kerosene. Thus, even a several hundred percent improvement in battery technology would still leave batteries many times inferior to hydrocarbon fuels in terms of energy density. Furthermore, the weight decrease during flight of fueled aircraft is an important factor in establishing aircraft range (the Breguet range equation [5]). Fuel weight decreases during a mission but battery weight does not, implying an additional penalty for a battery powered vehicle. Given the previous considerations, pending the discovery of as yet unknown battery chemistry, it is unlikely that batteries will replace fuel on commercial aircraft.

To significantly improve its climate change impact, aviation must reduce both the amount of fuel burned on each flight and the net CO_2 produced by that fuel. This means a switch from fossil fuel. Currently, hydrocarbon fossil fuel serves as both the energy source and the energy storage medium on the airplane. This must change. Rather than depend on fossil energy, aviation must move to a sustainable energy source such as solar, wind, or nuclear. Whatever the energy source, the previous discussion implies that energy is best delivered to and stored on the aircraft as a liquid hydrocarbon. Current focus is on capturing solar energy in the form of renewable biofuels. Here, the CO_2 exhausted by the engine is that absorbed from the atmosphere by plants or algae. With current technology, the growing, processing, and transportation of fuel produces an amount of CO_2 somewhat less than that in the engine exhaust, and so the net reduction from a biofuel is greater than 50% [6]. Biofuel supply chain technology should be able to improve this considerably.

Many ground and flight tests have shown that drop in biofuels are technically feasible, and a blend of up to 50% of a biofuel is now approved for use on commercial aircraft. The fuels approved to date are in relatively short supply and expensive. One reason is that they use expensive feedstock, basically vegetable oil. With current crop yields and processes, the net efficiency of the conversion of solar energy to jet fuel in this manner is only about 0.05%, implying that there is considerable room for improvement. Improvement requires research in such areas as increasing crop yields, new or modified organisms engineered for biofuel production, and new processes suited to low cost feedstock. Promising avenues include cellulosic biomass, algae, and halophytes. Also, as society greens, the CO_2 overhead associated with the growth, processing, and transportation of biofuels should improve.

IV. Motors to Power Propulsors

Energy will continue to be supplied to and stored on aircraft as liquid fuel, but will the gas turbine continue as the device of choice to convert that energy to shaft power? Other candidates might be fuel cells powering electric motors, different thermodynamic cycles (Otto, Rankin, Sterling, etc.), or some hybrid combination. This question can best be addressed by considering why gas turbines are the current motor of choice, physical constraints and limitations, and metrics by which aircraft motors are now and will be assessed. To potentially replace an existing approach, a new approach must be

Table 1 Gravimetric (GED) and volumetric energy density (VED) and cost of liquid fuels

Fuel type	GED, MJ/kg	VED, MJ/l	Cost, $/MJ
Li battery (rechargeable)	0.3	0.3	0.03
Li Battery (primary)	0.6	0.6	170
Honey	14	20	0.29
Goose fat	38	35	0.26
Kerosene (Jet A)	44	36	0.018

A. Thermal Efficiency

The limit to the ideal thermal efficiency of Brayton cycles such as a gas turbine is readily estimated at about 80% for flight in the lower stratosphere. How close to that theoretical maximum these devices can practically reach is not as simple a question. In the gas turbine industry, there are several definitions of efficiency that are defined for different uses. Koff [7] defined the thermodynamic efficiency of the core as the fluid power available at the core exit divided by the heat added from the fuel's chemical energy and plotted that against the propulsive efficiency times the transmission efficiency (transmission includes the losses in the turbine driving the fan, the fan itself, the fan duct, etc.). This is shown in Fig. 2 at cruise and illustrates the progress to date. The product of the two efficiencies is shown as arcs, which represent the total efficiency of the conversion of chemical energy in the fuel to propulsive power. Since Whittle's first engine, this thermodynamic efficiency has improved from about 10% to over 50%. When weight and drag are not an issue, as in ground based power plants, then gas turbine combined cycle plants (a gas turbine whose exhaust heat runs a steam cycle) can now deliver efficiencies above 60%. Propulsive efficiency has improved as well, from 50 to 70%. Overall, gas turbine aeroengine total efficiency has climbed from 10% to almost 40%.

Koff's definition of thermal efficiency is useful for comparing among jet engines. Another useful definition of gas turbine thermal efficiency for comparing with other engines or motors is one used for turboprops that accounts for all of the core fluid power as shaft power deliverable to a propulsor, designated here as "motor efficiency". The evolution of commercial aircraft gas turbine motor efficiency is shown in Fig. 3. This efficiency has improved by about 16 points over four decades and now approaches 55%. (The considerable scatter implies that thermal efficiency has not always been the primary design driver.) By contrast, diesel engines now range from 30 to 50% motor efficiency, with the higher efficiencies at the largest sizes, 10 60 MW [8]. A practical advantage of diesels over gas turbines in

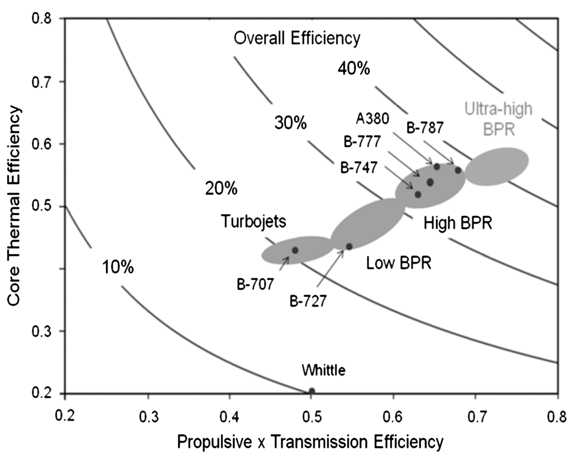
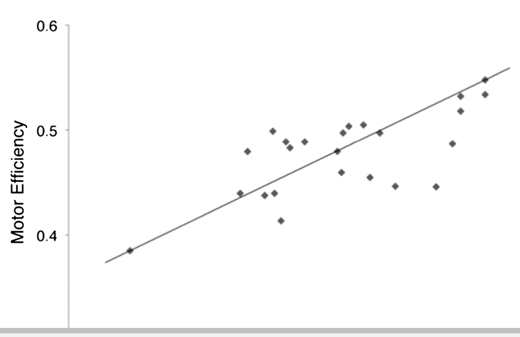


Fig. 2 Core thermal and propulsive efficiencies for commercial aircraft engines.



some applications is that diesels retain relatively more of their peak efficiency at part power. Because most transport aircraft engines are designed for peak efficiency at cruise, where most of the fuel is burned, this attribute has much less importance for airplanes than for ground vehicles or power generation.

Current fuel cells combine H_2 and O_2 to generate electricity. How the H_2 is generated varies widely. If the fuel cell is to operate from a complex hydrocarbon fuel, then the definition of efficiency must include all of the reforming processes that convert the fuel into H_2. Current ground power generation systems [9] operate at about 40% overall efficiency. In a practical aviation application, the efficiency implications of the electric motors, drive train, and their cooling would need to be considered as well, consistent with the definition of motor efficiency.

In summary, modern, large gas turbine engines are the most efficient devices in service to convert hydrocarbon chemical energy to mechanical power. They are by no means mature, and so considerable improvement in efficiency can result from focused research, as is discussed later.

B. Weight

Airplanes are all about weight, and so airplane engines must be as well. The Wright brothers built their own engine out of aluminum for just this reason, even though aluminum was a very expensive material in those days. Thirty seven years later in 1940, American technical luminaries were very skeptical of the concept of gas turbines for this same reason [10]:

> "The gas turbine could hardly be considered a feasible application to airplanes mainly because of complying with the stringent weight requirements imposed by aero nautics . . . The present internal combustion engine used in airplanes weighs about 1.1 pounds per horsepower, and to approach such a figure with a gas turbine seems beyond the realm of possibility with existing materials."

This report was issued a year after the first jet plane had flown in Germany, unbeknownst to the authors. The designers of the German engine used air cooling to circumvent ". . . the realm of possibility with existing materials". This illustrates both the role that materials play in determining engine weight and the skill of engineers and designers in circumventing what scientists may regard as fundamental barriers, such as material properties.

Since the early days of turbofan development, commercial turbofan power to weight ratios have improved by a factor of 4 or more, to 9 hp/lb (15 kW/kg). In contrast, a 10 60 MW diesel engine is more than 400 times heavier. Part of this weight difference is a result of aeroengine applications favoring light weight over low cost and thus embracing relatively expensive materials such as titanium.[‡] However, the most important factor influencing the relatively low weight of a gas turbine is that the average air velocity through a gas turbine is very much higher than that through other combustion or electrochemical (fuel cells) motors. At the same thermal efficiency, motors consume the same fuel and thus need the same air for combustion. To first order, the motor with the higher average through flow velocity will have the smaller cross section and weight. For a consistent comparison, the weight of an electrochemical motor must include the complete fuel cell system, electric drive train, cooling system, and structure needed to produce shaft power at all altitudes. On a weight basis alone, fuel cells appear to be highly unattractive for commercial aircraft propulsion.

C. Emissions and Noise

Since the 1960s, both the chemical emissions and the noise of jet engines have been regulated to improve well being around airports, with regulations becoming increasingly stringent over time. Noise has been the bane of aviation from its inception over 100 years ago [11] and continues to be so to this day. Takeoff and landing noise in the immediate vicinity of an airport is regulated; cruise noise is not. Lack of viable noise reduction technology has been a recognized barrier to the introduction of commercially viable supersonic transportation since the 1960s.

Currently, oxides of nitrogen (NOx), particulates, and unburned hydrocarbons are regulated during landing and takeoff. Gas turbines inherently produce much less NOx than internal combustion (IC) engines, so that IC engines need considerable exhaust treatment such as catalytic converters. Fuel cells that operate from hydrogen or methanol produce no regulated emissions. Fuel cells that internally produce hydrogen from hydrocarbons, such as solid oxide cells or fuel reformers, operate at higher temperature and may produce NOx and unburned hydrocarbons, but this area has yet to see much study.

D. Reliability and Maintainability

Reliability and maintainability are important measures of airplane engine value. The first influences safety, while both influence operating cost. One measure of reliability is in flight shutdown (IFSD) rate. This metric has improved dramatically, by a factor of 200, over the past 50 years; see Fig. 4. Extended operations requires an IFSD rate better than 0.020 shutdowns per 1000 h of operation. Today's state of the art (SOA) is better than 0.002. Time between overhauls and time on wing are useful measures of maintainability. These, too, have improved from 400 800 h in the days of the large piston engines to 6000 14,000 h today. Now, engines may stay on the wing seven to 10 years before they need be removed for overhaul.

E. Engine Economics: Cost, Price, and Value

Engine related costs are one of the most important factors affecting the economics of aircraft ownership and airline operations, and so these costs are an important consideration in engine selection. Engines account for about 15 20% of the list price of a new aircraft, over 50% of the maintenance cost, and of course, they determine the amount of fuel burned. Therefore, operators' cost is always a major design criterion for engine designers. Researchers often do not consider product cost because of the difficulty of connecting it to engineering fundamentals and the paucity of available data.

For many decades, fuel was significantly less than $1 per gallon. One widely used airline cost measure is cash airplane related operating cost (CAROC), which includes fuel, airframe and engine maintenance, crew costs, fees, and ground handling but excludes capital related costs. Figure 5 shows the spot jet fuel price over the past 20 years and illustrates wide body aircraft operating cost as a function of that fuel price. At $0.50 per gallon, the fraction of CAROC attributable to engines is 22%. This rises to 60% at $4 per gallon. In the past five years, fuel has been as high as $5 per gallon. An extrapolation of CAROC to prices well above the historical record is shown in Fig. 6, suggesting that high fuel prices may overwhelm other considerations. Prediction of future aircraft fuel prices is well beyond the capability of this author. However, if fuel prices continue above $3 per gallon, then the historical balance among operating costs remains disrupted, and fuel consumption will continue as the overriding economic concern.

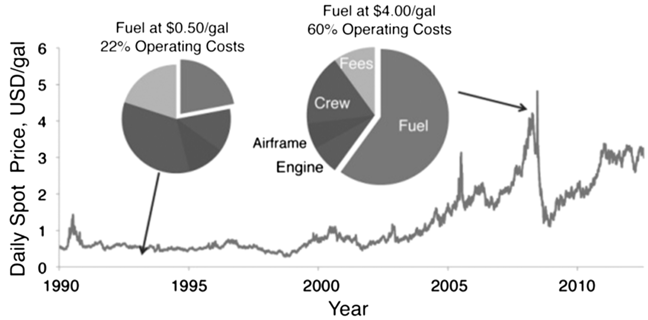


Fig. 5 Fuel price and wide-body airplane cash operating cost in then-year USD.

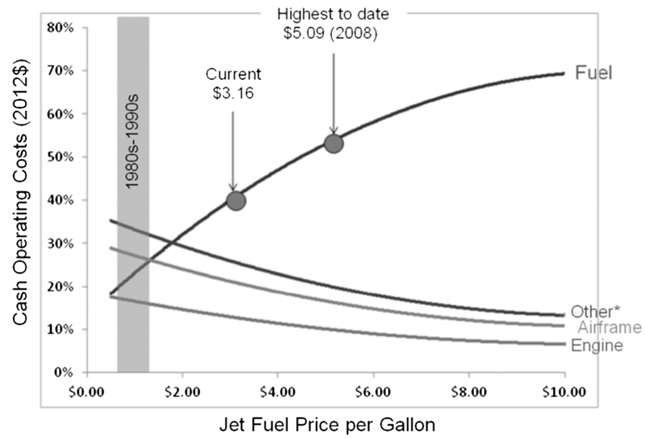
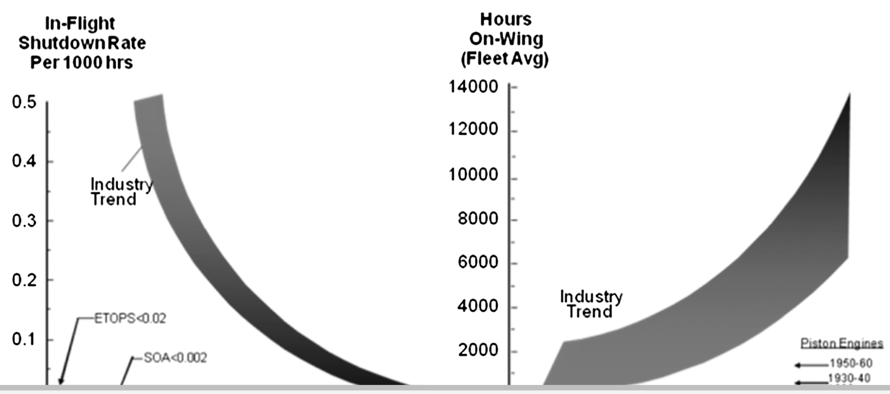


Fig. 6 Wide-body cash operating cost as a function of fuel price in 2012 USD ("other" costs include flight crew, insurance, and landing, navigation, and ground fees).

The cost of manufacturing a jet engine and its list price scales with engine sea level static (SLS) thrust. Figure 7 shows an estimate of the list price per unit of thrust of commercial jet engines over an order of magnitude in engine size. Prices range from about $200 to $400 per pound of thrust. The smaller engines are more expensive because items such as an electronic fuel control are needed independent of engine thrust. At the very high thrust size, mechanical scaling is unfavorable such that engine weight per unit thrust rises. To keep the weight of large engines under control, more expensive construction is used, such as hollow metallic or composite fan blades. Also, the largest engines power very long range aircraft, which are most sensitive to fuel price, so that a reduction in fuel burn may offset an increase in engine cost to the owner.



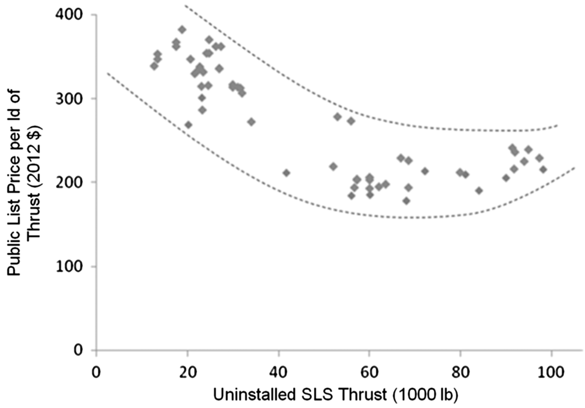


Fig. 7 Bare engine list price per pound of thrust.

The economics of aircraft manufacturing constrain the fraction of the airplane cost that aircraft manufacturers have been willing to allocate to the engines. Cross plotting engine list price with airplane list price reveals that the engines on current commercial aircraft are about 15 to 22% of the price of the airplane. This ratio has been constant since at least the 1980s.

The price of new aircraft has been constrained by competition, the availability of used aircraft, and airline economics. Since the mid 1960s, corrected for fuel price variation, new technology has dropped the operating cost of narrow body aircraft by 30 ~ 40%, but net aircraft selling prices have remained constant. Technology has added value but this value has not been recovered by aircraft manufactures and their engine suppliers in the form of higher prices. Therefore, innovations and technology that raise engine production cost are avoided by industry. This suggests that new technology should avoid adding net cost to manufacturing an engine.

V. Aircraft Engines of the Future

Appropriate metrics for aircraft engines are efficiency, weight, emissions, noise, and reliability. In all of these, the large aircraft gas turbine is unmatched, with no successor on the horizon. Thus, hydrocarbon fueled, Brayton cycle driven propulsors appear to be the most promising approach for commercial aeropropulsion over the next few decades. What this means for specific aeropropulsion research directions is dependent on application, engine thrust class, and design choices. Indeed, the interplay between the clever designer and the insightful researcher is perhaps the least appreciated dynamic in propulsion. Design approaches can determine the relative value of a research topic. Designers can obviate, or at least delay, the need for fundamental understanding. The World War II German designers who used turbine air cooling in the Jumo 004 because they did not have access to high temperature materials illustrate this point. Another example is that a fundamental understanding of nacelle drag is much more important for a high bypass ratio turbofan than for a turboprop of the same thrust because the turboprop's much smaller nacelle is a relatively minor factor in propulsive performance. Thus, the relative importance of a technology is often very dependent on design approaches and engine architecture. The converse is true as well; a good designer designs from strength and eschews approaches that are poorly understood.

One example of how design approach can influence research directions concerns takeoff and landing approach noise. The exhaust jet has been the major takeoff noise source, and so it has been the focus of considerable research effort and resulting literature since the 1960s. Although this research has resulted in greater understanding of the physical processes involved, it has not resulted in significant jet noise reduction technology. Nevertheless, jet noise is no longer the dominant noise source. Figure 8 illustrates the relative magnitude and direction of important turbofan engine noise sources as they have evolved over 40 years. This evolution resulted from technologies that

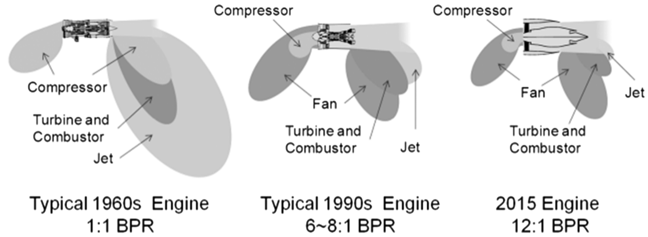


Fig. 8 Turbofan noise source evolution.

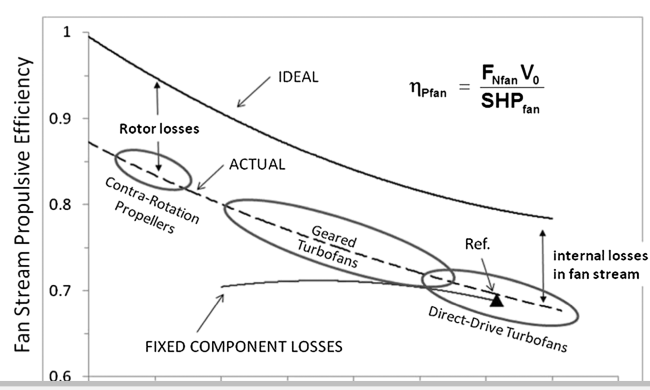
to takeoff noise, which is now dominated by fan noise. Thus, research on jet noise is no longer warranted for this purpose. On approach and landing, the engine noise is now less than that of the airframe in some cases, suggesting that noise researchers may be wise to focus mainly on fan and airframe noise.

In light of this background, the following sections consider the current state of the art and speculate on future design directions and the research necessary to realize them. Although predicting the future is an inexact art, thermodynamics is quite clear. We know that improved thermal efficiency will demand higher cycle pressures and temperatures, improved component efficiency, and reduced cooling and secondary air. We know that increasing propulsor efficiency requires low pressure ratio propulsors with low drag nacelles and perhaps variable geometry blading or exhaust nozzles. All of this must be accomplished at weights and overall costs that do not outweigh the advantages of improved efficiency. We know where we must go with some clarity. How to get there requires research.

A. Propulsors

Commercial aircraft built over the last 50 years have been gas turbine powered, and either turbofan or propeller propelled. At the most basic level, the differences are the total fan pressure ratio (FPR) produced across the rotor (FPR) and whether the rotor operates in a duct or in free air. The pressure ratio determines the propulsor exhaust velocity and therefore the propulsive efficiency. It also sets the propulsor diameter. For example, at the 25,000 30,000 lb takeoff thrust level, a currently flying turbofan engine with a FPR of 1.7 has a rotor diameter of about 1.6 m. Reducing the FPR to 1.2 at constant thrust grows the rotor diameter to 2.3 m. A two rotor, contra rotating propeller is 4.3 m in diameter, while a single rotation propeller needs a 5.2 m diameter to produce the same thrust. Clearly, engineering considerations for these configurations may be different in detail.

We define propulsion efficiency, as is commonly done for propellers, as the thrust power delivered to vehicle (thrust $F_{N\mathrm{fan}}$ times flight velocity V_0) divided by the mechanical power input to the shaft, $\mathrm{SHP}_{\mathrm{fan}}$. Figure 9 shows the variation in fan stream propulsive efficiency, $n_{P\mathrm{fan}}$, with fan pressure ratio, FPR, at a flight Mach number of 0.80 [12]. Three curves are shown: the ideal relation between FPR and propulsive efficiency ("ideal" solid line), a curve fit to practical designs for which the overall propulsor geometry was optimized for each pressure ratio ("actual" dashed line), and a curve



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