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FLOW CONTROL OPPORTUNITIES IN GAS TURBINE ENGINES

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ABSTRACT

Recent advances in flow control have the potential for significant impact on the design and performance of modern gas-turbine engines. Flow control has the potential to delay separation, enhance mixing of fluids, create "virtual" shapes, modify wake behavior, and reduce drag. Various opportunities for flow control throughout the engine are discussed in terms of their impact on the compressor, combustor, turbine, and inlet and nozzle. The impact that many of these could have is substantial; this is discussed in the context of key engine metrics, and the issues that must be overcome to realize this vision.

INTRODUCTION

Modern gas-turbine engines are complex systems that convert chemical potential energy into useful flow energy safely, reliably, and efficiently, with minimum life cycle cost and weight. As such, they move large quantities of air, and their ability to deliver depends on our ability to control that flow. The emerging field of flow control thus has the potential for significant impact on gas turbine engines, with opportunities throughout the engine to impact key product metrics.

The definition of flow control that we adopt here is the use of a small modification (e.g. fluid injection) to change the behavior of a much larger flow. This definition is intentionally sufficiently broad as to not preclude purely passive geometry modifications such as riblets or vortex generators, although the primary intent is to consider the impact of recent and future technology innovations. The key emphasis is on the ability to modify the behavior of the larger flow without having to act on the scale of that flow. The concept of flow control is not new, with boundary layer blowing or suction to delay separation known since Prandtl[1], and in use today in areas such as supersonic inlets. More recent results provide the promise of achieving similar benefits with much lower actuation levels. One of the more mature such technologies, for example, applies unsteady forcing of the boundary layer to enable separation control at much lower authority requirements by coupling into dynamics of the flow[2,3]. In addition to mitigating separation, flow control has the potential to enhance or modify mixing[4], create a controllable "virtual" shape[5], manage wakes[6,7], control boundary layer drag[8,9], etc.; an excellent review of flow control is given by Gad-el-Hak[10]. The purpose of this paper is not to describe the technology, but the applications of flow control to the gas-turbine engine, and the impact these might have on the system. The organization of this paper is first to briefly discuss the key metrics for the engine, then to describe possible opportunities for each component area, and finally to discuss some key issues and challenges that must be overcome.

The basic components of the propulsion system are the fan and compressor, the combustor, turbine, inlet and nacelle, and nozzle. A detailed description of engine components and design can be found in any of several textbooks. Typical P&W (tactical) military and commercial (or more generally subsonic transport) engines are shown in Figures 1 and 2. The commercial engine is shown integrated with the nacelle in Figure 4; the nacelle is an integral part of the propulsion system and has several significant opportunities for flow control.

There are several key differences between the military and commercial engines, most obviously the bypass ratio; the commercial engine generates most of its thrust from the large, low pressure ratio fan, and thus also has a much larger turbine to take more energy out of the core flow. The military engine shown here includes a large augmentor for short duration high thrust, and a vectoring nozzle. The difference between these two illustrates the difference between optimizing primarily for thrust-specific fuel consumption (TSFC), versus optimizing thrust/weight. Any discussion of the metrics must include an understanding of the difference in priorities for the different customers.

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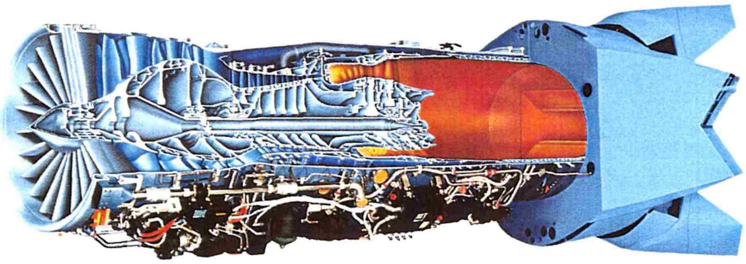
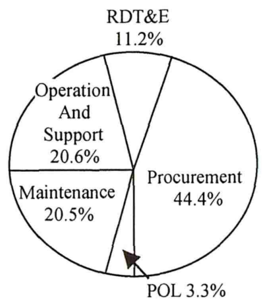


Figure 1. F119-PW-100 engine (used in F-22 Advanced Tactical Fighter). 3-stage fan, 6-stage compressor, single stage LPT and HPT, thrust vectoring nozzle.



Military Fighter LCC

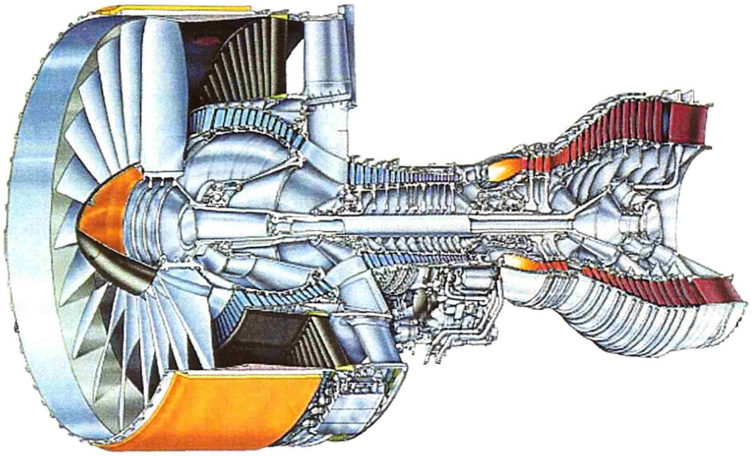
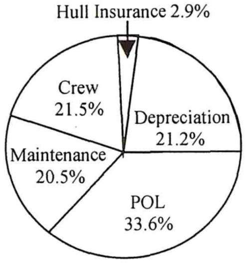


Figure 2. PW 4084 engine (used in 777 aircraft). Fan, 6-stage LPC, 11-stage HPC, 2-stage HPT, 7-stage LPT.



Commercial Transport DOC

Figure 3. Comparison of typical commercial direct operating cost (DOC) and military fighter life cycle cost (LCC) breakdown. POL (petroleum, oil and lubricant) is primarily fuel, RDT&E is development cost.

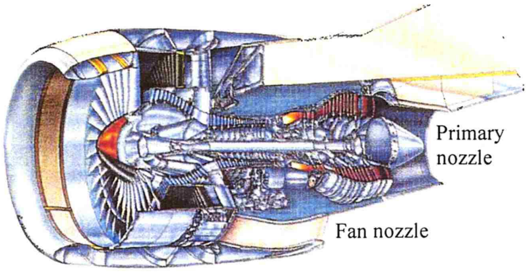


Figure 4. PW 4168 (100" fan) showing the nacelle for a separate flow configuration.

ENGINE CUSTOMER METRICS

The ultimate metric, of course, is providing maximum value to the engine customer, at minimum cost. There are a number of factors that are relevant:

- Thrust specific fuel consumption (TSFC)
- Weight
- Manufacturing cost
- Maintenance cost
- Reliability
- Noise
- Emissions
- Low-observability (IR and radar cross-section)
- Propulsion airframe integration (PAI)

Trade factors can be established between different metrics, these depend on the engine / airframe combination, mission (e.g. short vs. long range), price of fuel, and so forth. Defining a single number as typical is therefore not possible; for weight, for example, it can range from less than $500 of initial engine cost per pound to as high as $3000.

A primary contributor to operating or life-cycle cost is fuel consumption, but initial acquisition and maintenance costs are also significant. Thus one cannot add limitless cost or complexity to an engine in a relentless drive to reduce TSFC. Previous work on riblets was not adopted for commercial aircraft due to the maintenance cost[11], a similar situation exists for laminar flow control (also discussed in Ref. 11); the cost of fuel would have to increase for these technologies to be considered. Because the utilization of a military engine is much lower than for a commercial engine, the fuel consumption is much less critical than other factors, as shown in Figure 3. Weight is an issue for both military and commercial engines. Note that an extra pound of engine weight requires extra wing area for added lift, extra fuel, and thus ultimately translates into much more than the original pound in extra total system weight.

Noise and emissions are increasingly becoming important differentiators in the commercial engine business, driven by regulations. Many airports restrict access based on noise. Furthermore, for short-hop flights, noise-abatement flight profiles can add significant time to the total flight, and thus a noise reduction can translate directly into value for the airline. Emissions have been a concern for many years because of local air quality, primarily from NO_X, CO, smoke, and unburned hydrocarbons. Total NO_x emissions are subject to regulations that are becoming increasingly stringent, and several European countries (Sweden and Switzerland) have started imposing landing penalties based on NO_X emissions. A more recent concern is the impact of emissions on global climate change (GCC)[12]. The primary impact on GCC from aircraft engine emissions comes from CO_2, which is a major greenhouse gas, although the impact of other emissions such as NO_x can also be significant. Short of changing fuel, only improvements in fuel efficiency can impact CO_2 production.

Propulsion / airframe integration (PAI) is relevant to both military and commercial customers, although the issues differ. For commercial engines, nacelle diameter and length are important. Military engines also face low-observability (LO) requirements, both IR and radar cross-section, along with PAI issues with integrating vectoring and afterburning engines into LO-constrained aircraft designs. The engine must also operate reliably over its flight envelope, thus requiring potential compromises between take-off and cruise. Finally, and perhaps most important of all, is that both military and commercial customers are paying for (predictable) availability. An aircraft on the ground is not generating revenue or conducting missions, and particularly in the case of unscheduled maintenance, this can dramatically alter the cost equation. Key reliability metrics include non-recoverable in-flight shut-downs, unscheduled engine removals, and extended twin operations (ETOPS) capability.

If one plots performance on a key metric such as thrust to weight for tactical military engines against year of entry into service, as shown in Figure 5, it is clear that we are approaching a limit in our ability to improve performance with existing technology. A plot of TSFC vs. year of entry into service for commercial engines would show a similar trend; an initial rapid improvement in early development of gas turbine engines, with a more recent tendency towards more incremental improvements. Flow control is one set of possible technologies that may alter the game and enable us to provide significantly greater value to gas turbine engine customers.

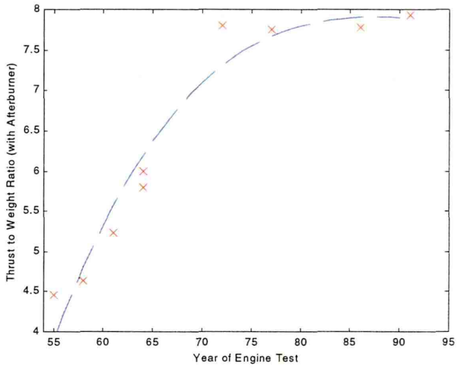


Figure 5. Trend of maximum thrust to weight ratio vs. year of engine test. Data are with afterburner if available. Performance on this metric has stayed roughly constant since ~1970. (Available data in the open literature from Reference 13.)

ENGINE CONTROL SYSTEMS

A brief discussion of engine control systems is given here, the objective being to characterize conventional control actions that are applied in today's engines.

Fuel flow control is the most fundamental control function in the aircraft gas turbine engine: set fuel flow to obtain desired thrust. The ratio of these two quantities is the fundamental performance parameter, TSFC = thrust specific fuel consumption = fuel flow ÷ thrust. However, we generally do not measure either of these quantities, fuel flow or thrust, in flight. What we measure in flight is some parameter, typically either engine pressure ratio (EPR) or low rotor rotational speed (N1), that correlates well with thrust. This correlation, EPR-thrust or N1-thrust, is established based on thrust measurements obtained in ground test facilities. Then in flight, fuel flow is adjusted via closed-loop control to obtain the value of EPR or N1 corresponding to the target thrust. In today's engines, this process is governed by the full authority digital electronic control, or FADEC (the FADEC is the box mounted external to the fan case at bottom center of Figure 2).

The FADEC has a number of additional control functions. In the compression section of the engine, both bleed flow extraction and variable-stagger stator vanes are used to provide adequate stall margin at each operating condition. Schedules for actuation of bleed valves and the unison rings that drive the variable stator vanes are developed based on both steady-state engine operating parameters and transient information such as rate of change of RPM. In the turbine section, turbine case cooling (TCC) is applied at cruise to obtain tighter clearances for higher efficiency. These control actions for compressor stability and TCC air are essentially open-loop controls. That is, in today's engines we do not actually measure compressor operating line or turbine tip clearances and feed that information back to the controller.

In military fighter engines, control of the variable-geometry exhaust nozzle is an important function. Control of the convergent section and throat area must be coordinated with not only the engine operating condition but also the augmentor operation. In the case of thrust-vectoring nozzles, control of the divergent flaps that set the thrust vector direction has to be integrated with the vehicle flight control system.

Future engine systems that may incorporate flow control technology will likely require distributed controls, as opposed to a single centralized FADEC. Because much of the engine environment is at high temperature, compact high-temperature electronics technology will be required to enable distributed controls. With the development of compact high-temperature sensors, controls, and actuators already underway[14,15,16] it may be possible to envision "micro-adaptive flow control" for engine applications on the scale of a single airfoil or an individual fuel nozzle. In the following sections, some possibilities for application of flow control technology in gas turbine components are outlined.

FAN AND COMPRESSOR

The compressor adds energy to the flow, achieving pressure ratios that can exceed 40:1 in current commercial engines, with expectations of increasing this further in the future so as to improve efficiency. Military engines tend towards lower pressure ratio, due to the optimization of thrust / weight, rather than TSFC. Pressure rise per stage is typically less than 1.5, resulting in many stages of compression (as shown in Figure 1, the F119 has 9 stages, while the PW4084 in Figure 2 has 18, including the fan). Compressor efficiencies are on the order of 90 percent. The primary issues with the compressor and fan are twofold. First, is the cost and weight associated with the number of airfoils. Second is stability, or operability; more of an issue here than in the turbine because the compressor is producing a pressure rise. The highest performance is typically reached close to the stall boundary, but adequate stall margin must be maintained at all conditions. Aeroelastic behavior such as flutter is also a design consideration, particularly for the fan. The flutter margin requirement can set blade aspect ratio in today's wide-chord shroudless fans. High cycle fatigue (HCF) in the compressor, generally generated by upstream stator row wakes, can lead to premature blade failure if resonant stresses are not correctly predicted, resulting in undesirable maintenance and availability impact. Compressor stall is currently avoided through scheduled bleeds and variable-stagger stator vanes, together with a stall margin that allows for effects of inlet distortion and tip clearance deterioration. Military engines also have variable geometry inlet guide vanes (IGV's) in front of the fan to enable optimum behavior at multiple points in the operating map.

One of the first flow control applications to receive considerable attention in gas turbine applications is active compressor stability control. If the compressor operated closer to the stall boundary, then additional work could be obtained per stage, and hence fewer stages would be required. The current approach avoids stall by scheduled bleed and stator vane actuation. This schedule is based on engine tests, and must therefore allow stall margin to account for engine to engine variability, wear (primarily tip clearances), thermal transients, and disturbances such as pressure or thermal distortion. This margin could be reduced if feedback were used; this requires some precursor to detect the imminent onset of stall. Furthermore, if one could use feedback to stabilize the unstable dynamics, one could potentially operate past the stall boundary, resulting in even greater work per stage. There are considerable references for this subject, see for example Reference 17 and the references therein. Actuation approaches include bleed[18] and air injection near the blade tips[19]. Note that in contrast to many of the other applications discussed, these flow control approaches treat the dynamics of the overall compressor system, rather than the dynamics on the scale of a shear layer.

Cost, weight, and length of the engine are driven to a great extent by the number of stages of compression (see Figures 1 and 2). The number of stages is set by work per stage, which is limited by blade separation. Aspiration on the blade can be used to delay separation, with the added benefit of removing high entropy fluid[20]. Design of a single-stage fan at 3.5 pressure ratio with 6% bleed, 3% each from stator and rotor, has been described by Kerrebrock et al[22]. A longer-term goal is to reach a 30:1 compression in 3 blade rows[21]. The pressure ratios that are predicted to be achievable with

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