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Identifying Optimal Fan Compressor Pressure Ratios for the Mixed-Stream Turbofan Engine

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This paper describes a heuristic approach for determining the optimal fan compressor pressure ratio for a fixed set of mixed-stream turbofan engine parameters. During the aircraft design process, it is important to select an engine design that minimizes fuel consumption while producing the thrust required by the various aircraft mission flight conditions. Although the most fuel-efficient values of such parameters as bypass ratio and high-pressure compressor (core) pressure ratio depend on the integrated effects of the various flight altitudes, Mach numbers, and thrusts required throughout the mission, it is possible to heuristically locate the most efficient fan compressor pressure ratio to complement other engine parameters independent of the mission. At this optimal value, thrust-specific fuel consumption is approximately minimized and specific thrust is approximately maximized at all flight conditions. Exploiting the observed engine performance characteristics, optimal fan compressor pressure ratios were successfully located for a wide range of bypass ratios and core compressor pressure ratios across a variety of on- and off-design flight conditions.

Nomenclature

F	= uninstalled engine thrust, lbf
f_0	= overall engine fuel-to-air ratio
M_0	= freestream Mach number
M_5	= core flow Mach number at turbine exit
$M_{5'}$	= bypass flow Mach number at mixer entry
m_0	= overall engine air mass flow, lbm/s
P_{t5}	= core flow total pressure at turbine exit
$P_{t5'}$	= bypass flow total pressure at mixer entry
S	= thrust-specific fuel consumption, lbf/lbm/s
T_{t4}	= core burner total temperature, °R
α	= bypass ratio (bypass mass flow/core mass flow)
π_c	= overall compressor pressure ratio
$\pi_{c'}$	= fan compressor pressure ratio

I. Introduction

NEW aircraft are designed to be capable of carrying out a prescribed nominal mission. To minimize the fuel required to perform this specified mission, it is desirable for the engine to operate as efficiently as possible at each of the flight altitudes and Mach numbers flown during the maneuvers within the mission. A more efficient engine requires a smaller fuel store to perform the design mission, which results in a lighter, more maneuverable aircraft with lower operating costs. Hence, a major interest at the preliminary design stage is selection of the best values for the basic engine design variables. In general, optimal values of variables such as bypass ratio α and overall compressor pressure ratio $\pi_c = \pi_{c'}$ times the high pressure compressor pressure ratio, depend on the specifics of the mission and its component maneuvers. This work shows, however, that it is possible to heuristically locate the most efficient fan compressor pressure ratio $\pi_{c'}$ to complement these other engine parameters independent of the mission requirements.

A. Background

At the heart of the heuristic method used to identify the optimal $\pi_{c'}$ value is a relationship first noticed by a graduate student¶ working in conceptual engine design. He noticed that, regardless of the reference flight condition and engine design variable values, there was always a single fan compressor pressure ratio at which on-design uninstalled thrust-specific fuel consumption S was minimized and on-design uninstalled engine specific thrust F/m_0 was maximized. Upon closer inspection, he found that this always happened when the bypass flow Mach number at the mixer $M_{5'}$ was slightly less than the core flow Mach number at the turbine exit M_5. Taking advantage of this relationship allowed him to quickly generate engine designs that always had near-optimal $\pi_{c'}$ values.

To see why the $\pi_{c'}$ value that minimizes S and maximizes F/m_0 is considered optimal, first recall that S is calculated using

$$S = f_0/F/m_0$$

where f_0 =(total engine fuel flow, lbm/s/engine inlet air flow, lbm/s).

For a given set of design-point parameters, including fixed π_c and α, f_0 is independent of $\pi_{c'}$. Mixer performance (and hence, specific thrust), however, is determined by $\pi_{c'}$. For a global variation in design-point parameters, there are then minimums in S at the maximum specific thrust for a fixed flight altitude and velocity. What was not clear prior to this paper was whether a minimization in mission fuel consumption would occur for only $\pi_{c'}$ values selected at the design-point minimum S locations.

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¶Richard Branam observed this during an engine design course. Although he did not investigate the phenomenon in depth, he deserves credit for noticing it and prompting the authors to look further.

B. Mission

As noted earlier, the primary design objective is to get the best performance over an entire mission rather than at a single design point. The graphs and numerical results in this paper are based on a high-performance fighter mission similar to the running example in Mattingly et al.[1] and to the mission used in Nadon et al.[2]

C. Engine Cycle Software

All engine performance evaluations in this research were made using the Turbine Engine Reverse Modeling Aid Program (TERMAP),[3] a robust, on-design and off-design engine evaluation code created for the U.S. Air Force Research Laboratory. TERMAP is a detailed, nonideal cycle analysis code that models the compressor and turbine maps to compute engine performance results for both choked and unchoked turbine conditions.

II. Understanding and Locating $\pi_{c'}$ for Optimal S

We now turn our attention to understanding why optimality of S (and $F/\dot{m}_0$) occurs at a certain $\pi_{c'}$, and how this optimal fan compressor pressure ratio can be identified.

A. On-Design Flight Conditions

Figure 1 shows specific fuel consumption S and thrust $F/\dot{m}_0$ vs fan compressor pressure ratio $\pi_{c'}$ for fixed values of overall pressure ratio π_c, burner total temperature T_{t4}, and freestream Mach number M_0, and various values of bypass ratio α. In this figure,

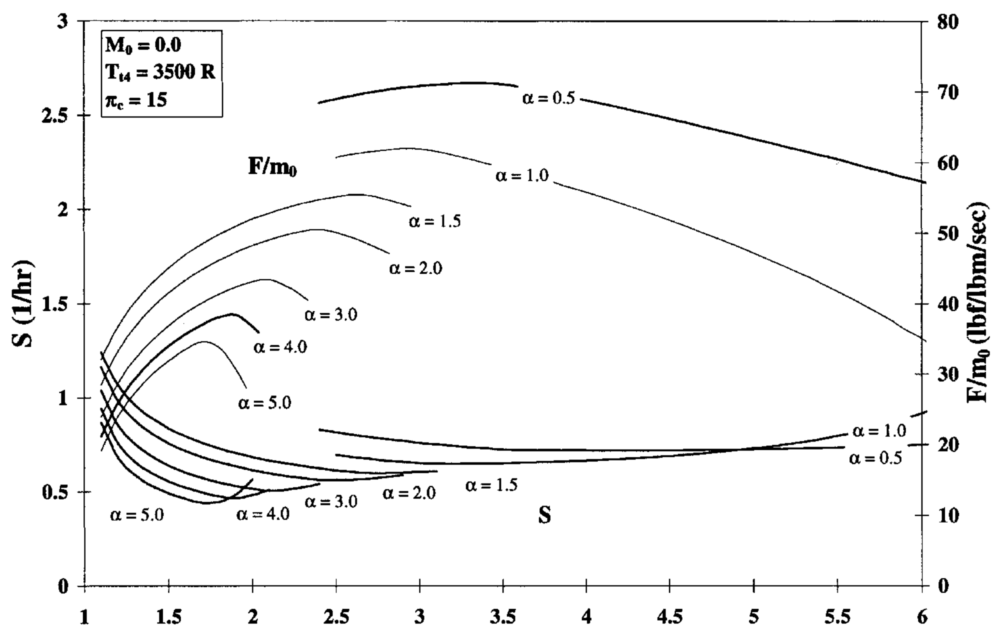

Fig. 1 Uninstalled S and specific thrust vs $\pi_{c'}$ with varying α at on-design condition 1.

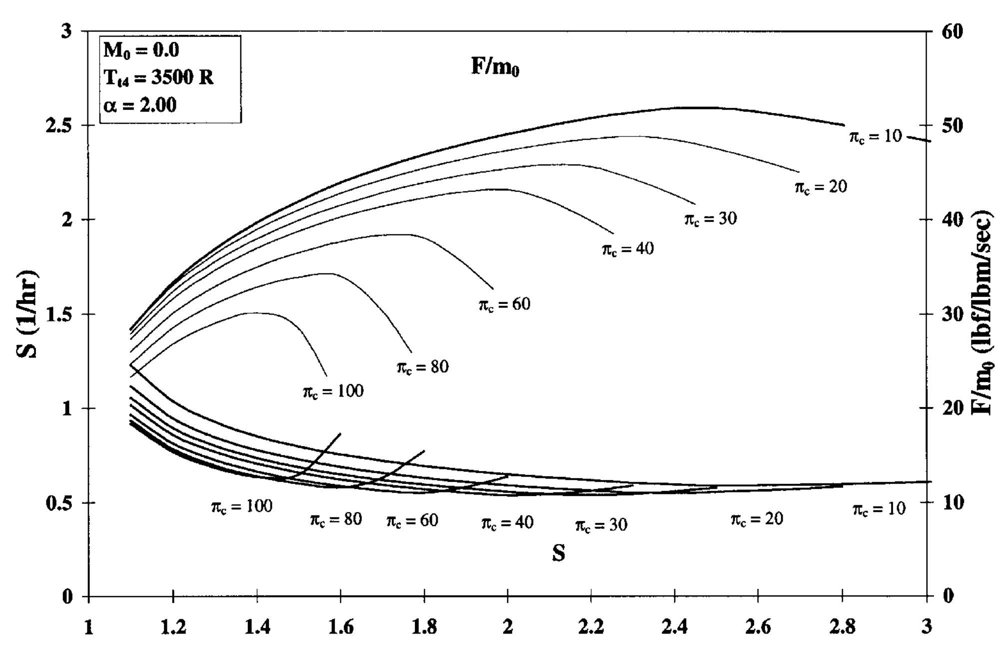

Fig. 2 Uninstalled S and specific thrust vs $\pi_{c'}$ with varying π_c at on-design condition 1.

as in other figures to follow, a dual set of vertical axes is used to allow both characteristics to appear on the same plot; F/m_0 is to be read from the right side, and S from the left. For any given set of engine parameters S is minimized (and F/m_0 maximized) at a single fan compressor pressure ratio, although this value changes with the parameter values. A similar relation occurs when the bypass ratio is fixed and the overall pressure ratio is varied, as in Fig. 2. Furthermore, this behavior does not appear to be dependent on the initial value of T_{t4}. A number of calculations with widely varying values produced very similar results, such as those shown in Fig. 3. No attempt was made in any case to enforce equality of mixer entrance stagnation pressure of the fan duct or turbine exit duct, and so some extreme cases may not be fully realizable.

Next we observe that the ratio of the bypass and core flow total pressures at mixer entry $P_{t5'}/P_{t5}$ is correlated to the minimum S point. It is clear from the plot of S and F/m_0 vs $P_{t5'}/P_{t5}$ (all of which are engine cycle outputs) in Fig. 4 that approximately optimal S and F/m_0 are obtained at a fixed $P_{t5'}/P_{t5}$ ratio of 1.00, regardless of the value of α. Fixing α and varying π_c produces similar results as shown in Fig. 5. Additional experiments have shown that this is also independent of other engine parameter values (T_{t4} and M_0).

In Figs. 4 and 5, only $\pi_{c'}$ was varied to generate the values of S and F/m_0, because the $P_{t5'}/P_{t5}$ ratio is only a function of the fan compressor pressure ratio combined with constant α and π_c values. Figure 6 shows the relation between $P_{t5'}/P_{t5}$ and $\pi_{c'}$ (all other engine

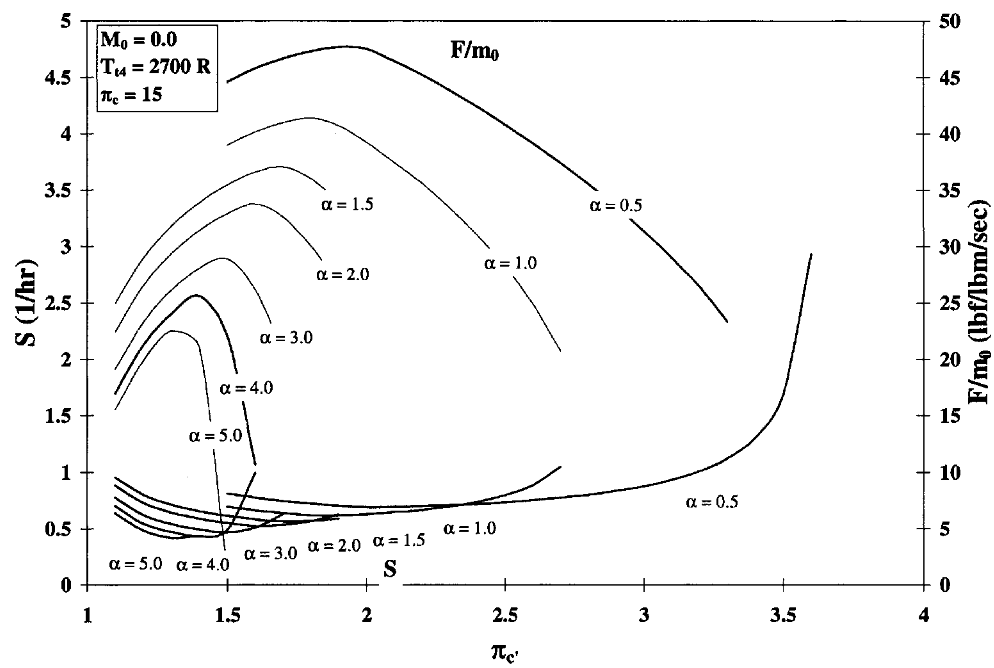

Fig. 3 Uninstalled S and specific thrust vs $\pi_{c'}$ with varying α at on-design condition 2.

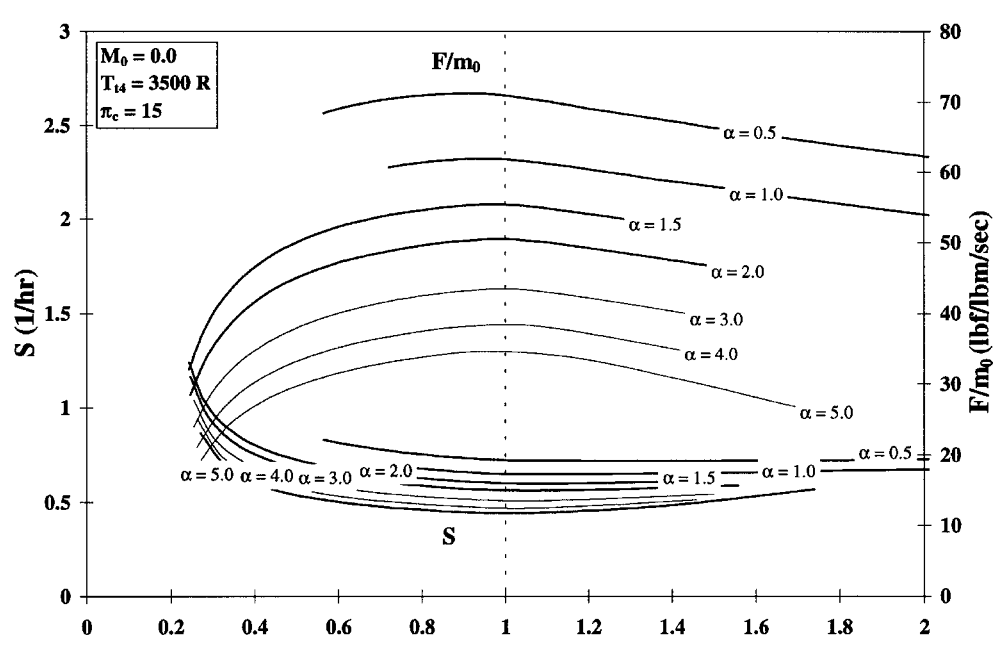

Fig. 4 On-design uninstalled S and specific thrust vs $P_{t5'}/P_{t5}$ for varying α.

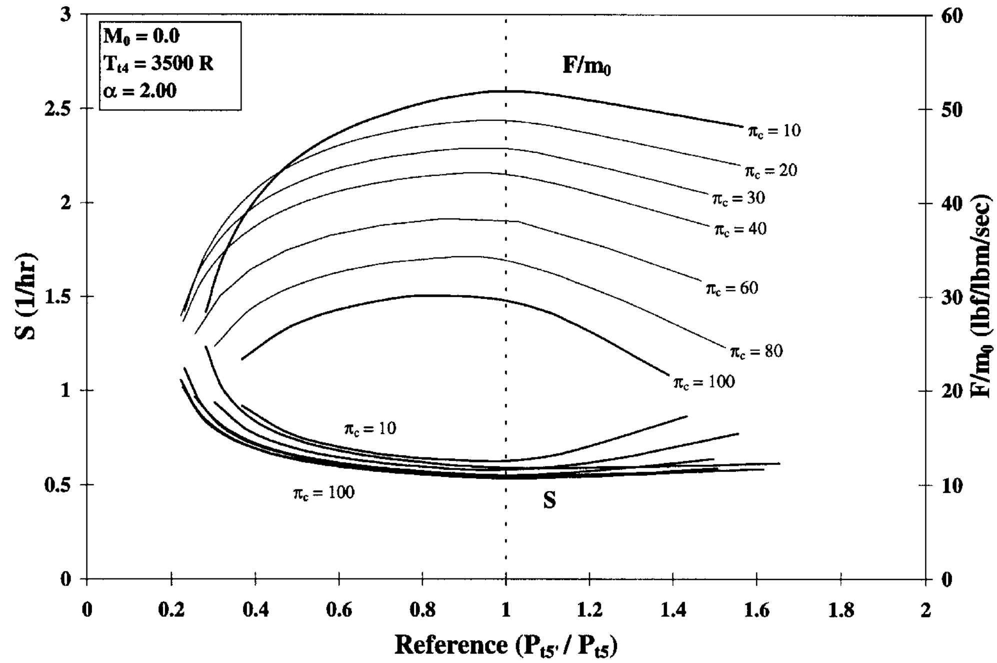

Fig. 5 On-design uninstalled S and specific thrust vs $P_{t5'}/P_{t5}$ for varying π_c.

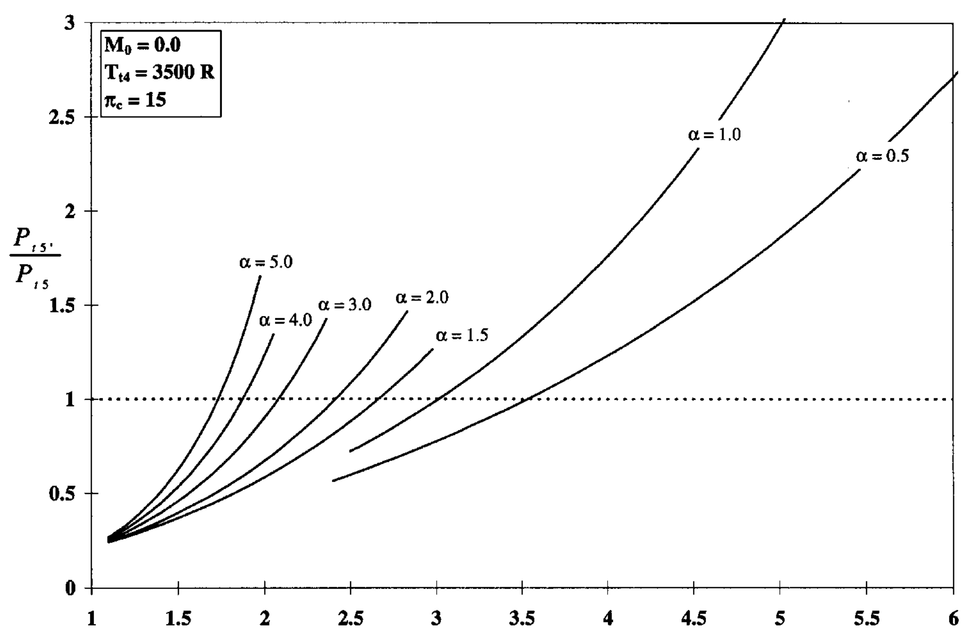

Fig. 6 $P_{t5'}/P_{t5}$ vs $\pi_{c'}$ at varying α.

parameters are held constant). Notice that $P_{t5'}/P_{t5}$ for each bypass ratio is monotonically increasing (a property that will be exploited in locating the $\pi_{c'}$ at which the optimal $P_{t5'}/P_{t5}$ is obtained). The dashed line near unity pressure ratio identifies the combination of $\pi_{c'}$ and α that minimizes S for the given flight condition.

Thus, for the on-design engine, instead of searching over all combinations of all the design variables, it is possible to reduce the design space by simply finding the value of $\pi_{c'}$ that causes $P_{t5'}/P_{t5}$ to reach its optimal value.

B. Application to Off-Design Flight Conditions

The on-design engine property noted earlier would not be useful if it applied exclusively to the on-design condition. Recall that in the context of engine optimization for a specified mission, we desire to identify an on-design set of engine parameters that minimizes fuel consumption over an entire mission while meeting the thrust requirements at the variety of flight altitudes and Mach numbers imposed by that mission. Hence, if the selection of an optimal $\pi_{c'}$ value only minimized S (maximized F/m_0) at reference conditions, this property would be of very limited use. However, extensive computer experiments showed that selecting an optimal $\pi_{c'}$ value for the reference engine also optimized S (and F/m_0) for all off-design flight conditions. For example, Figs. 7–9 show off-design S and F/m_0 values plotted against reference engine (on-design) $P_{t5'}/P_{t5}$ values for three off-design flight conditions. For each flight condition, S is minimum for reference $P_{t5'}/P_{t5}$ approximately equal to one.

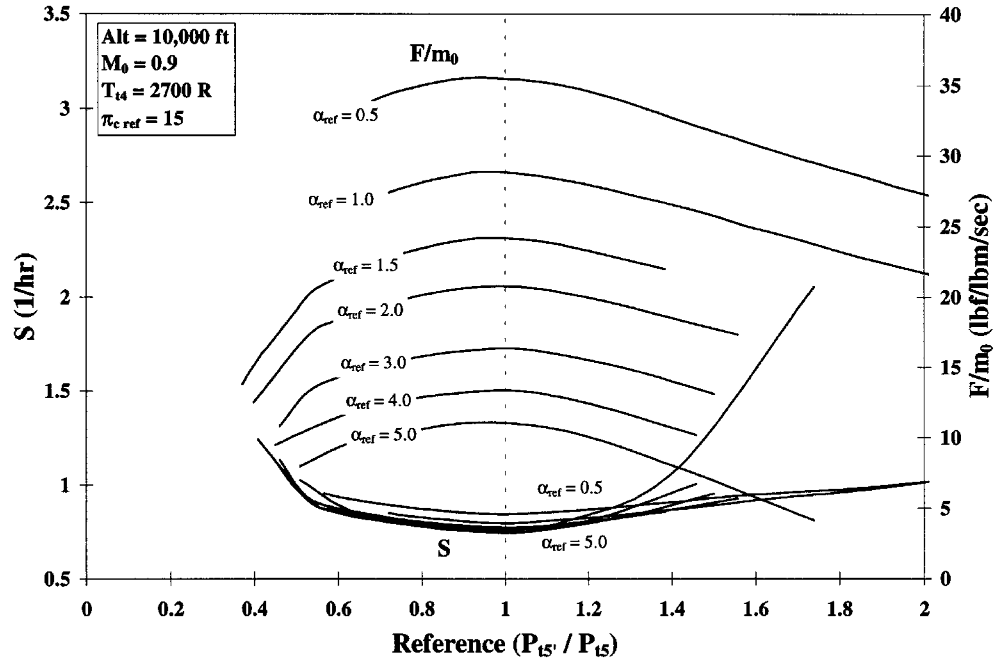

Fig. 7 Off-design uninstalled S and specific thrust vs reference engine $P_{t5'}/P_{t5}$ at off-design flight condition 1.

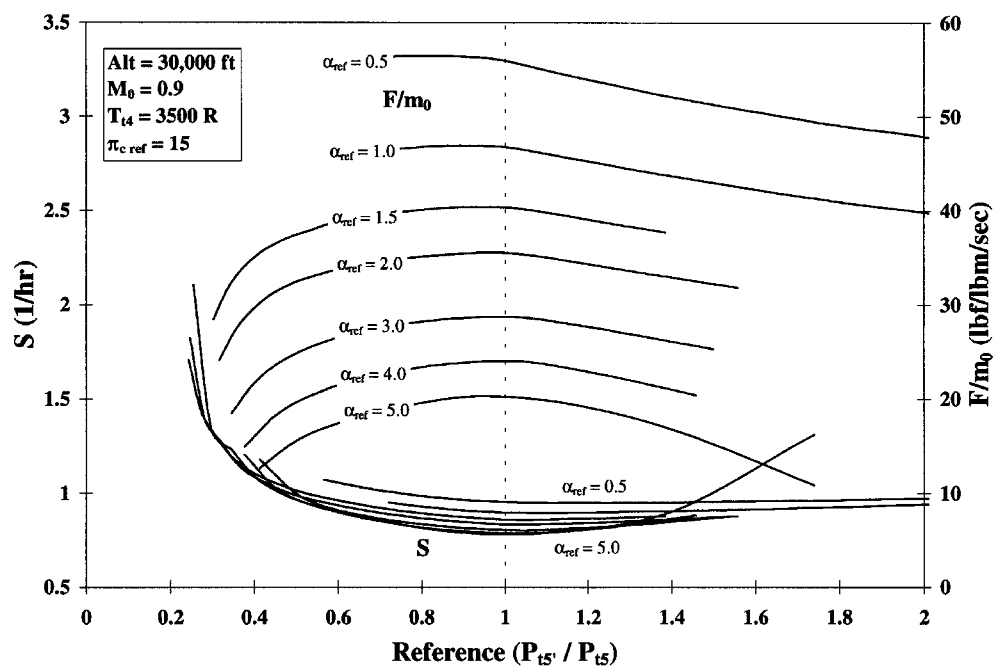

Fig. 8 Off-design uninstalled S and specific thrust vs reference engine $P_{t5'}/P_{t5}$ at off-design flight condition 2.

Consistent results using diverse off-design conditions and throttle settings demonstrate that off-design optimality is maintained over a wide range of flight conditions and burner temperatures.

As can be seen in some of the curves shown in Figs. 4 and 5, and Figs. 7–9, depending on flight condition, throttle setting, and reference engine α and π_c values, the optimal $P_{t5'}/P_{t5}$ ratio may be slightly different than 1.00. For this reason, it was sometimes possible to improve engine efficiency and performance by tweaking the on-design $\pi_{c'}$ value corresponding to $P_{t5'}/P_{t5}$ equal to one. The resulting improvement in mission fuel consumption was generally quite small, however. In cases where a unity ratio is slightly suboptimal, the engine corresponding with unity ratio will have performance (in terms of S and $F/\dot{m}_0$) that is only slightly less efficient than the true optimal engine, and will have a $\pi_{c'}$ that is quite near the true optimal fan compressor pressure ratio.

It should be noted that it is common to specify $P_{t5'}/P_{t5}$ equal to 1 on the grounds that this is a desirable mixer condition. Here, however, we have made no such assumption and instead have demonstrated that meeting this condition yields desirable engine performance characteristics.

III. Understanding Off-Design Optimality Using Reference Engine Optimization

It is important to understand why S and $F/\dot{m}_0$ optimality is maintained once a departure from reference engine flight conditions has occurred. One might expect that the off-design fan compressor

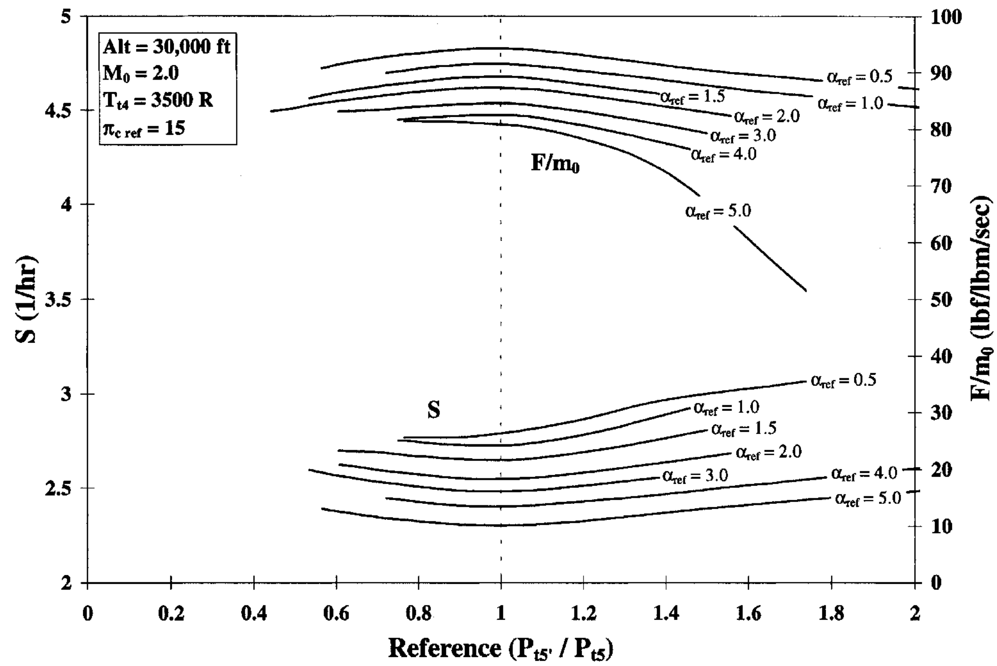

Fig. 9 Off-design uninstalled S and specific thrust vs reference engine $P_{t5'}/P_{t5}$ at off-design flight condition 3.

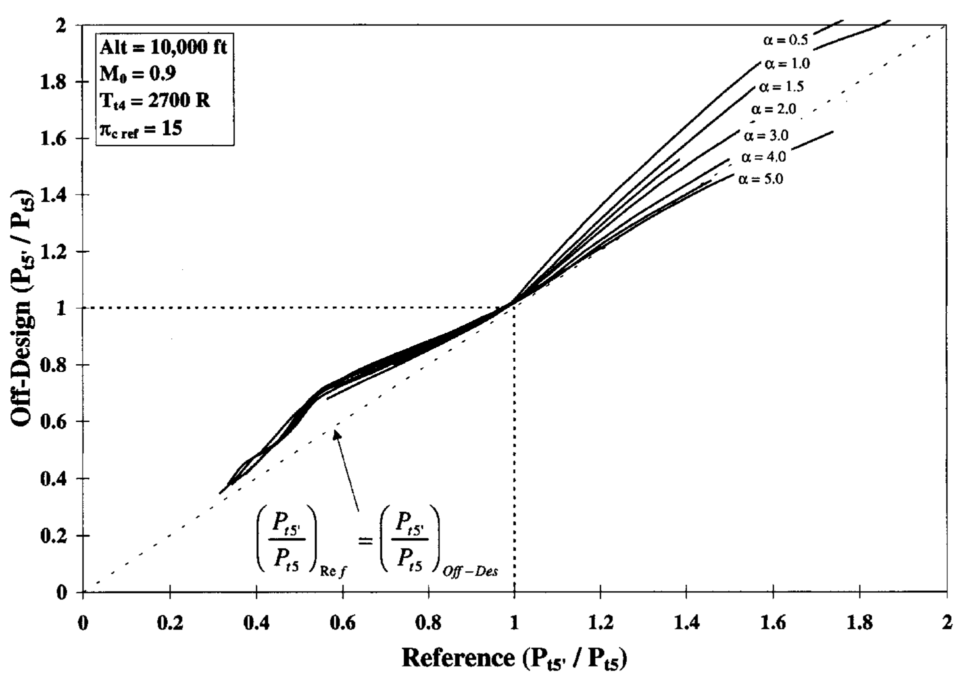

Fig. 10 Variation of off-design $P_{t5'}/P_{t5}$ ratio with changes in on-design $P_{t5'}/P_{t5}$ ratio for off-design condition 1.

pressure ratio that minimizes S and maximizes $F/\dot{m}_0$ at that operating condition would be the value that causes the off-design $P_{t5'}/P_{t5}$ ratio to be 1.00. For conditions other than reference engine flight, the off-design $\pi_{c'}$, π_c, and α can be significantly different from the reference $\pi_{c'}$, π_c, and α. This would seem to imply that the resulting off-design $P_{t5'}/P_{t5}$ ratio is likely to be very different as well.

However, in reality, the $P_{t5'}/P_{t5}$ ratio does not change significantly with changing flight conditions when it is first optimized for the reference engine. This is attributable to the fact that for most flight conditions, the engine spool rpm typically remains at 80–100% of the full-throttle reference engine rpm. Over this range of spool speeds, $M_{5'}$ and M_5 do not vary significantly from their full-throttle reference engine values.[4] Because P_{t5}' and P_{t5} are derived directly from these Mach numbers (via the isentropic compressible flow equations), it follows that the $P_{t5'}/P_{t5}$ ratio also remains relatively constant. This was confirmed by computation. For example, Figs. 10–12 show the relations for reference and off-design $P_{t5'}/P_{t5}$ ratios for three off-design conditions. Although there may be significant differences between $(P_{t5'}/P_{t5})_{\text{Ref}}$ and $(P_{t5'}/P_{t5})_{\text{Off-Des}}$, the curves converge at $(P_{t5'}/P_{t5})_{\text{Ref}} \approx 1.00$, so that $(P_{t5'}/P_{t5})_{\text{Ref}} \approx (P_{t5'}/P_{t5})_{\text{Off-Des}}$ for all flight conditions.

IV. Method for Locating Optimal $\pi_{c'}$

As shown in the previous section, near-optimal engines (in terms of S and $F/\dot{m}_0$) exist when a fan compressor pressure ratio is chosen,

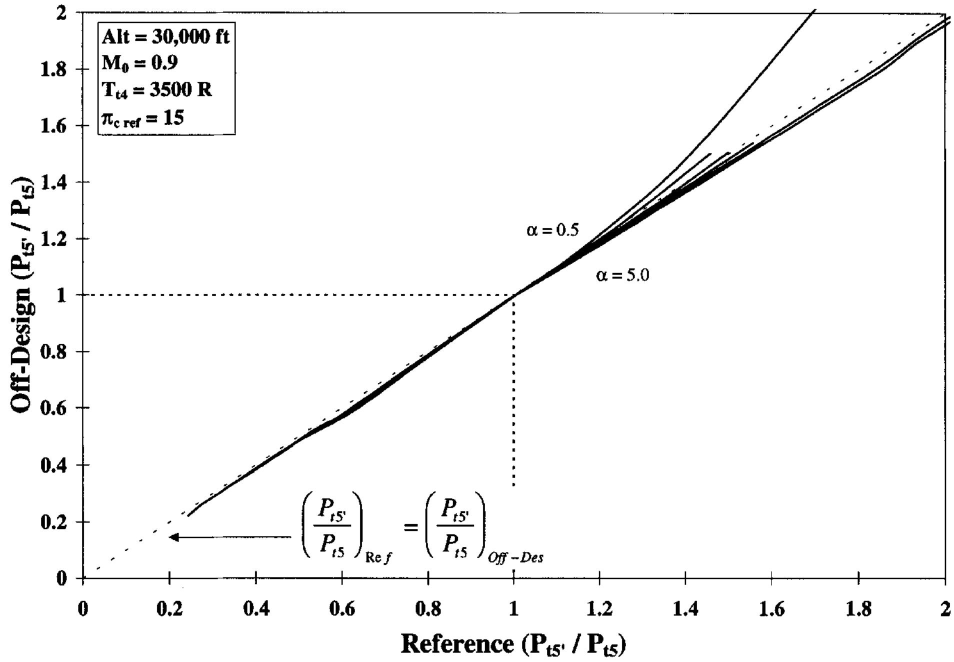

Fig. 11 **Variation of off-design $P_{t5'}/P_{t5}$ ratio with changes in on-design $P_{t5'}/P_{t5}$ ratio for off-design condition 2.**

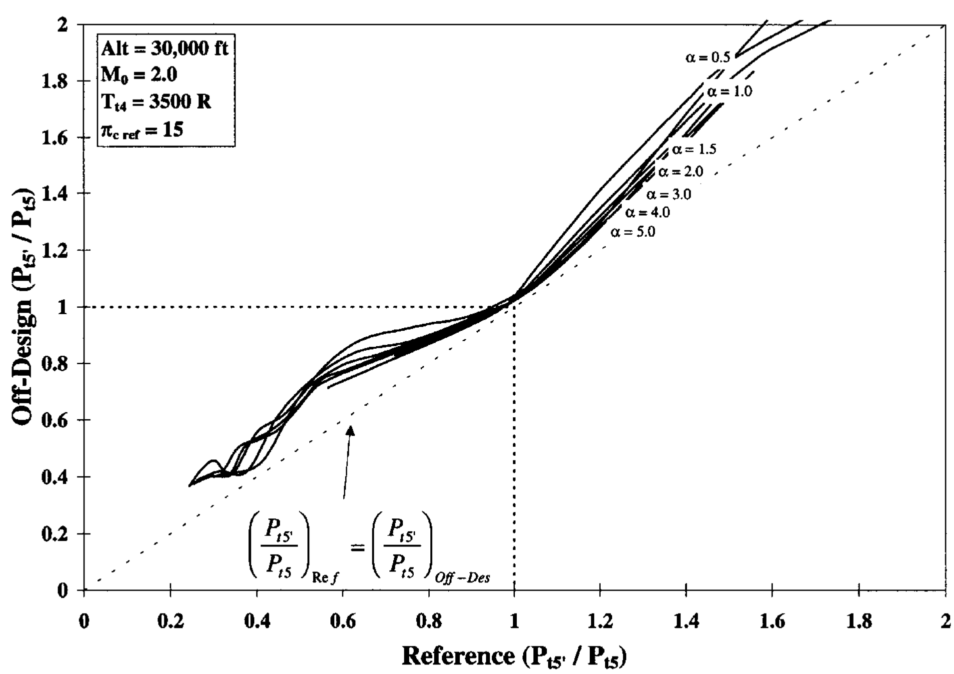

Fig. 12 **Variation of off-design $P_{t5'}/P_{t5}$ ratio with changes in on-design $P_{t5'}/P_{t5}$ ratio for off-design condition 3.**

which when combined with the other engine parameters, creates a reference engine $P_{t5'}/P_{t5}$ ratio of 1.00. Because the $P_{t5'}/P_{t5}$ ratio is a monotonically increasing function of $\pi_{c'}$ for any combination of α and π_c (Fig. 6), a simple root-finding algorithm, such as Newton–Raphson supplemented by a bisection algorithm,[5] can be employed to locate the optimal $\pi_{c'}$. This technique was successfully implemented in an engine design optimization program with excellent results.[6]

V. Conclusions

It appears to be possible to compute a fan compressor pressure ratio that will approximately minimize thrust-specific fuel consumption and maximize specific thrust independent of bypass ratio, overall compressor pressure ratio, and off-design flight condition. This optimization occurs when the ratio of bypass and core flow total pressures at mixer entry is near unity. This in turn results in a near-perfect dependency of bypass ratio on the fan compressor pressure ratio, thereby reducing the number of independent variables needed to specify the engine design. Although setting the ratio of bypass and core flow total pressures at mixer entry equal to one sometimes produced slightly suboptimal engines, using that value allowed consistent, automatic solution using simple numerical optimization techniques, and at worst, always produced a fan compressor pressure ratio that was very close to the optimal value.

Acknowledgments

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