Performance Cycle Analysis of Turbofan Engine with Interstage Turbine Burner

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This paper presents the performance-cycle analysis of a dual-spool, separate-exhaust turbofan engine, with an interstage turbine burner (ITB) serving as a secondary combustor. The ITB, which is located at the transition duct between the high- and the low-pressure turbines, is a relatively new concept for increasing specific thrust and lowering pollutant emissions in modern jet engine propulsion. A detailed performance analysis of this engine has been conducted for steady-state engine performance prediction. A code is written and is capable of predicting engine performances (i.e., thrust and thrust specific fuel consumption) at varying flight conditions and throttle settings. Two design-point engines were studied to reveal trends in performance at both full and partial throttle operations. A mission analysis is also presented to ensure the advantage of saving fuel by adding ITB.

Nomenclature

\[ A = \text{cross-sectional area} \]
\[ a = \text{sound speed} \]
\[ F = \text{uninstalled thrust} \]
\[ f = \text{fuel/air ratio, or function} \]
\[ g_r = \text{Newton’s constant} \]
\[ h_{lb} = \text{low heating value of fuel} \]
\[ M = \text{Mach number} \]
\[ m = \text{mass flow rate} \]
\[ P = \text{static pressure} \]
\[ P_t = \text{total pressure} \]
\[ R = \text{universal gas constant} \]
\[ S = \text{uninstalled thrust specific fuel consumption} \]
\[ T_0 = \text{total temperature} \]
\[ V = \text{absolute velocity} \]
\[ \alpha = \text{bypass ratio} \]
\[ \gamma = \text{specific heat ratio,} \ c_p/c_v \]
\[ \eta = \text{efficiency} \]
\[ \pi = \text{total pressure ratio} \]
\[ \pi_t = \text{ratio between total pressure and static pressure because of the ram effect,} \ P_t/P_0 \]
\[ \tau = \text{total temperature ratio} \]
\[ \tau_o = \text{ratio of total temperature and static temperature because of the ram effect,} \ T_o/T_0 \]

\[ \tau_d = \text{ratio of burner exit total enthalpy to enthalpy at ambient condition} \]

Subscripts

\[ b = \text{main burner} \]
\[ c = \text{engine core, compressor, or properties at upstream of main burner} \]
\[ cL = \text{low-pressure compressor} \]
\[ cH = \text{high-pressure compressor} \]
\[ d = \text{diffuser} \]
\[ f = \text{fan} \]
\[ itb = \text{ITB, or properties at downstream of ITB} \]
\[ m = \text{mechanical or constant value} \]
\[ n = \text{constant value} \]
\[ o = \text{total} \]
\[ R = \text{reference conditions} \]
\[ t = \text{properties between main burner exit and downstream, or total/stagnation values of properties} \]
\[ tH = \text{high pressure turbine} \]
\[ tL = \text{low pressure turbine} \]
\[ 0 = \text{engine inlet} \]

Introduction

TURBOFAN engine, a modern variation of the basic gas turbine engine, has gained popularity in most new jet-powered aircrafts, including military and civilian types. Basically, it is a turbojet engine with a fan. The fan causes more air to bypass the engine core and exit at higher speeds, resulting in greater thrust, lower specific fuel consumption, and reduced noise level. Usually, the fan and low-pressure compressor (LPC) are connected on the same shaft to a low-pressure turbine (LPT). This type of arrangement is called a two-spool engine.

Interstage turbine burner (ITB) is a relatively new concept in modern jet engine propulsion. Most commercial turbofan engines have a transition duct between the high-pressure turbine (HPT) and the LPT. The ITB considered in this study is the placement of flameholders inside the transition duct. ITB is also known as a reheat cycle, in which the expanded gas from each expansion process in a turbine is reheated before the next expansion process, as shown in Fig. 1. In ITB, fuel is burned at a higher pressure than a conventional afterburner, leading to a better thermal efficiency. The major
advantages associated with the use of ITB are an increase in thrust and potential reduction in NOx emission. Recent studies on the turbine burners can be found in the literature (for example, see Liew et al., Liu and Sirignano, Sirignano and Liu, and Vogeler). However, these studies are only limited to parametric cycle analysis, which is also known as on-design analysis.

The work presented here is a systematic performance-cycle analysis of a dual-spool, separate-exhaust turbofan engine with an ITB. Performance-cycle analysis is also known as off-design analysis. It is an extension work for the previous study, that is, on-design cycle analysis, in which we showed how the performance of a family of engines was determined by design choices, design limitations, or environmental conditions.

In general, off-design analysis differs significantly from on-design analysis. In on-design analysis, the primary purpose is to examine the variations of specific engine performance at a flight condition with changes in design parameters, including design variables for engine components. Then, it is possible to narrow the desirable range for each design parameter. Once the design choice is made, it gives a so-called reference-point (or design-point) engine for a particular application. Off-design analysis is then performed to estimate how this specific reference-point engine will behave at conditions other than those for which it was designed. Furthermore, the performance of several reference-point engines can be compared to find the most promising engine that has the best balanced performance over the entire flight envelope.

**Approach**

The station numbering for the turbofan cycle analysis with ITB is in accordance with APR 755A (Ref. 8) and is given in Fig. 2. The ITB (the transition duct) is located between stations 4.4 and 4.5.

The resulting analysis gives a system of 18 nonlinear algebraic equations that are solved for 18 dependent variables. Table 1 gives the variables and constants in this analysis. As will be shown, specific values of the independent variables \( m \) and \( n \) are desirable for the computations of \( A_{4.5} \) and \( A_8 \).

**Off-Design Cycle Analysis**

The following assumptions are employed:
1. The air and products of combustion behave as perfect gases.
2. All component efficiencies are constant.
3. The area at each engine station is constant, except the areas at stations 4.5 and 8.
4. The flow is choked at the HPT entrance nozzles (station 4), at LPT entrance nozzles (station 4.5), and at the throat of the exhaust nozzles (stations 8 and 18).
5. At this preliminary design phase, turbine cooling is not included.

An off-design cycle analysis is used to calculate the uninstalled engine performance. The methodology is similar to those described in Mattingly and Mattingly et al. Two important concepts are mentioned here to help explaining the analytical method. The first is called referencing, in which the conservation of mass, momentum, and energy are applied to the one-dimensional flow of a perfect gas at an engine steady-state operating point. This leads to a relationship between the total temperatures \( T \) and pressure ratios \( P \) at a steady-state operating point, which can be written as \( f(T, P) \) equal to a constant. The reference-point values (subscript \( R \)) from the on-design analysis can be used to give value to the constant and allow one to calculate the off-design parameters, as described next:

\[
f(T, P) = f(T_R, P_R) = \text{constant} \tag{1}
\]

The second concept is the mass flow parameter (MFP), where the one-dimensional mass flow property per unit area can be written in the following functional form:

\[
\text{MFP} = \dot{m} \sqrt{T_i}/P_i A
\]

\[
\text{MFP} = M \sqrt{\gamma R T / R_0 [1 + (\gamma - 1)/2]} M_2^{(\gamma+1)/2(\gamma-1)} \tag{2}
\]

This relation is useful in calculating flow areas, or in finding any single flow quantity, provided the other four quantities are known at that station.

**Component Modeling**

In off-design analysis, there are two classes of predicting individual component performance. First, actual component characteristics can be obtained from component hardware performance data, which give a better estimate. However, in the absence of actual component hardware in a preliminary engine design phase, simple models of component performance in terms of operating conditions are used.

**High-Pressure Turbine**

Writing mass flow rate equation at stations 4 and 4.5 in terms of the flow properties and MFP gives

\[
\dot{m}_4 = (P_4 / \sqrt{T_4}) A_{4} \text{MFP}(M_4) = \dot{m}_3 (1 + f_b) \tag{3}
\]

and

\[
\dot{m}_{4.5} = (P_{4.5} / \sqrt{T_{4.5}}) A_{4.5} \text{MFP}(M_{4.5}) = \dot{m}_3 (1 + f_b + f_{tib}) \tag{4}
\]
Rearranging Eqs. (3) and (4) and equating \( \dot{m}_3 \) yield

\[
\frac{P_{t4.4} \sqrt{T_{t4.4}}}{P_{t4}} A_{4.5} = A_4 \frac{MFP(M_{4.5})}{MFP(M_{4.5})} \left( \frac{1 + f_b + f_{ab}}{1 + f_b} \right) P_{t4.4} \frac{T_{t4.4}}{T_{t4.5}}
\]

(5)

The right-hand side of the preceding equation is considered constant because of the following assumptions: the flow is choked at stations 4 and 4.5, the flow area at station 4 is constant, variation of fuel-air ratios \( f \) is ignored compared to unity, and the total pressure ratio of ITB is constant. Using referencing, it yields

\[
\frac{P_{t4.4} \sqrt{T_{t4.4}}}{P_{t4}} A_{4.5} = \left( \frac{P_{t4.4} \sqrt{T_{t4.4}}}{P_{t4.5}} A_{4.5} \right) \frac{MFP(M_{4.5})}{MFP(M_{4.5})}
\]

(6)

Rearranging and solving for \( \pi_{itb} = P_{t4.4}/P_{t4} \) yields

\[
\pi_{itb} = \frac{\sqrt{\pi_{t4.5} T_{t4.5} A_{4.5}}}{\sqrt{\pi_{t4.5} T_{t4.5}}} \frac{A_{1.5}}{A_{4.5}} \pi_{itbR}
\]

(7)

The equation relating \( \pi_{itb} \) and \( \tau_{itb} \) comes from HPT efficiency equation:

\[
\tau_{itb} = 1 - \eta_{itb} \left[ 1 - \pi_{itb}^{(\gamma_b - 1)/\gamma_b} \right]
\]

(8)

\( A_{4.5}/A_{4.5R} \) is related to the total temperature ratio of the ITB raised to the power of a value \( n \):

\[
A_{4.5}/A_{4.5R} = (\tau_{itb}/\tau_{itbR})^n
\]

(9)

From Eq. (9), if \( n \) is set equal to \( \frac{1}{2} \), then Eq. (7) reduces to

\[
\pi_{itb}/\sqrt{\tau_{itb}} = (\pi_{itb}/\sqrt{\tau_{itb}})_{R}
\]

(10)

For this reason, \( \frac{1}{2} \) is used for \( n \) in this study. Accordingly, the LPT entrance area \( A_{4.5} \) is controlled such that the HPT exit conditions (i.e., \( P_{t4.4} \) and \( T_{t4.4} \)) are unaffected by the ITB operation.

Low-Pressure Turbine

Writing the mass conservation at stations 4.5 and 8 using MFP and flow properties gives

\[
\pi_{itb} = \pi_{itbR} \left[ \frac{A_{4.5}}{A_{4.5R}} \frac{MFP(M_{4.5R})}{MFP(M_{4.5R})} \right]
\]

(11)

Similarly, the LPT efficiency equation gives

\[
\tau_{itb} = 1 - \eta_{itb} \left[ 1 - \pi_{itb}^{(\gamma_b - 1)/\gamma_b} \right]
\]

(12)

One relationship for \( A_8/A_{8R} \) is similar to \( A_{4.5}/A_{4.5R} \) except that it is raised to the power of a value \( m \):

\[
A_8/A_{8R} = (\tau_{itb}/\tau_{itbR})^m
\]

(13)

For the same reason as for \( n \), when \( m \) is set equal to \( \frac{1}{2} \) in Eq. (13) and \( M_8 = M_{4.5R} \), Eq. (11) reduces to

\[
\pi_{itb}/\sqrt{\tau_{itb}} = (\pi_{itb}/\sqrt{\tau_{itb}})_{R}
\]

(14)

Accordingly, the engine’s low-pressure-turbine performance in Eq. (11) will vary the same as the turbofan engine without the ITB when the ITB is turned off.

Engine Bypass Ratio

An expression for the engine bypass ratio is expressed by

\[
\alpha = \frac{\dot{m}_3}{\dot{m}_e}
\]

(15)

In terms of MFP and flow properties, the bypass ratio can be rewritten using referencing as

\[
\alpha = \alpha_R \frac{\pi_{itbR} \tau_{itbR}/\tau_{itbR}}{\pi_{itbR} \tau_{itbR}/\tau_{itb}} \left[ \frac{T_{t4.4}}{T_{t4.5}} \right] \left[ \frac{MFP(M_{4.5R})}{MFP(M_{4.5R})} \right]
\]

(16)

Fan and Low-Pressure Compressor

The equation for the total temperature ratio of the fan, which can be derived directly from the power balance of the low-pressure spool, is written as

\[
\tau_f = 1 + (\tau_{itb} - 1) \left[ \frac{\tau_{itb}}{\tau_{itbR}} - 1 \right] - \frac{\tau_{itb}}{\tau_{itbR}} - 1 + \alpha (\tau_{itb} - 1)
\]

(17)

Fan total pressure ratio is given by

\[
\pi_f = [1 + \eta_f (\tau_f - 1)]^{\gamma/\gamma - 1}
\]

(18)

Because the LPC and the fan are on the same shaft, it is reasonable to approximate that the total enthalpy rise of LPC is proportional to that of the fan. The use of referencing thus gives

\[
\tau_{itb} = 1 + (\tau_f - 1) \left[ \frac{\tau_{itb}}{\tau_{itbR}} - 1 \right]
\]

(19)

Equation (19) is rewritten to give the LPC total temperature ratio:

\[
\tau_{itb} = 1 + (\tau_f - 1) \left[ \frac{\tau_{itb}}{\tau_{itbR}} - 1 \right]
\]

(20)

The LPC total pressure ratio is expressed as

\[
\pi_{itb} = [1 + \eta_{itb} (\tau_{itb} - 1)]^{\gamma/\gamma_b - 1}
\]

(21)

High-Pressure Compressor

From the power balance of the high-pressure spool, solving for the total temperature ratio across HPC gives

\[
\tau_{itb} = 1 + \eta_{itb} \left[ 1 + \frac{f_b}{(1 - \tau_{itb})} \right] - \frac{T_{t4.4}}{T_{t4.5}}
\]

(22)

HPC total pressure ratio is then given by

\[
\pi_{itb} = [1 + \eta_{itb} (\tau_{itb} - 1)]^{\gamma/\gamma_b - 1}
\]

(23)

Exhaust Nozzles

The Mach number at both core (stations 8 and 9) and fan exhaust nozzles (stations 18 and 19) follows directly using

\[
M_8 = \sqrt{\frac{2}{\gamma_c - 1} \left[ 1 - \frac{P_{190}}{P_{190}} \right] - \frac{1}{\gamma_c - 1}}
\]

(24)

If \( M_8 > 1 \), then \( M_8 = 1 \), else \( M_8 = M_9 \)

(25)

\[
M_{19} = \sqrt{\frac{2}{\gamma_c - 1} \left[ 1 - \frac{P_{190}}{P_{190}} \right] - \frac{1}{\gamma_b - 1}}
\]

(26)

If \( M_{19} > 1 \), then \( M_{19} = 1 \), else \( M_{19} = M_{18} \)

(27)

Engine Mass Flow Rate

An expression for the overall engine mass flow rate follows by using MFP at station 4, giving

\[
\dot{m}_0 = \dot{m}_{0R} \frac{1 + \alpha R}{1 + \alpha R} \left[ \frac{T_{t4.4}}{T_{t4.5}} \right] \sqrt{\frac{MFP(M_{18R})}{MFP(M_{18R})}}
\]

(28)

Fuel-Air Ratios

The constant specific heat model13 is used to compute the fuel-air ratios for main burner and ITB.
Engine Performance Parameters

After the operating conditions for each engine component are determined, it is then possible to calculate the engine performance parameters. Whereas specific thrust is often used in on-design cycle analysis, thrust is commonly used in off-design cycle analysis. Accordingly, uninstalled thrust produced by the engine is

\[ F = \dot{m}_0 \left( \frac{F}{\dot{m}_0} \right) \]  

(29)

As shown in Eq. (29), thrust accounts for the variation in both specific thrust \( \frac{F}{\dot{m}_0} \) and mass flow rate \( \dot{m}_0 \).

Uninstalled thrust-specific fuel consumption \( S \) is simply obtained by

\[ S = \frac{f_o}{(F/\dot{m}_0)} \]  

(30)

Thermal efficiency \( \eta_{th} \), which is defined as the net rate of the kinetic energy gain out of the engine divided by the rate of thermal energy available from the fuel, is

\[ \eta_{th} = \frac{E_{\text{kinetic gain}}}{m_f \cdot h_{PR}} \]  

(31)

Engine Controls

A model for engine control system presented in Mattingly and Mattingly et al. is included into off-design analysis. It is necessary because it avoids compressor stalls or surges and also ensures that maximum limits on internal pressures and turbine entry temperatures are not exceeded.

Engine Configurations

Two sets of reference-point engine data at sea-level-static (SLS) condition are selected, that is, cases A and B, as provided in Table 2. For each case, a conventional engine is considered as a baseline engine while a similar engine operating with an addition of ITB is termed as ITB engine. In addition, the component performance parameters, listed in Table 3, are kept the same for both cases.

### Table 2 Design-point engine reference data

<table>
<thead>
<tr>
<th>Reference conditions</th>
<th>Case A</th>
<th>Case B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mach number ( M_{0R} )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Altitude ( h_R )</td>
<td>SLS</td>
<td>SLS</td>
</tr>
<tr>
<td>Main burner exit total temperature ( T_{t4,R} ), K</td>
<td>1450</td>
<td>1550</td>
</tr>
<tr>
<td>ITB exit temperature ( T_{t4,ITB} ), K</td>
<td>1350</td>
<td>1450</td>
</tr>
<tr>
<td>Compressor pressure ratio ( \pi_{CR} )</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Fan pressure ratio ( \pi_{FR} )</td>
<td>2.43</td>
<td>2.2</td>
</tr>
<tr>
<td>Fan bypass ratio ( \alpha_R )</td>
<td>0.73</td>
<td>4.0</td>
</tr>
<tr>
<td>Mass flow rate ( \dot{m}_{0R} ), kg/s</td>
<td>118</td>
<td>540</td>
</tr>
</tbody>
</table>

### Table 3 Engine component parameters

<table>
<thead>
<tr>
<th>Component parameters</th>
<th>Input value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pressure ratios</td>
<td></td>
</tr>
<tr>
<td>Inlet ( \pi_{d,\text{max}} )</td>
<td>0.99</td>
</tr>
<tr>
<td>Main burner ( \pi_b )</td>
<td>0.95</td>
</tr>
<tr>
<td>ITB ( \pi_{ITB} )</td>
<td>0.99</td>
</tr>
<tr>
<td>Nozzle ( \pi_n )</td>
<td>0.99</td>
</tr>
<tr>
<td>Fan nozzle ( \pi_{fn} )</td>
<td>0.98</td>
</tr>
<tr>
<td>Efficiencies</td>
<td></td>
</tr>
<tr>
<td>Main burner ( \eta_{b} )</td>
<td>0.99</td>
</tr>
<tr>
<td>ITB ( \eta_{ITB} )</td>
<td>0.99</td>
</tr>
<tr>
<td>HP spool ( \eta_{s,HP} )</td>
<td>0.92</td>
</tr>
<tr>
<td>LP spool ( \eta_{s,LP} )</td>
<td>0.93</td>
</tr>
<tr>
<td>Polytropic efficiencies</td>
<td></td>
</tr>
<tr>
<td>Fan ( e_f )</td>
<td>0.93</td>
</tr>
<tr>
<td>LP compressor ( e_{cL} )</td>
<td>0.8738</td>
</tr>
<tr>
<td>HP compressor ( e_{cH} )</td>
<td>0.9085</td>
</tr>
<tr>
<td>HP turbine ( e_{tH} )</td>
<td>0.8999</td>
</tr>
<tr>
<td>LP turbine ( e_{tL} )</td>
<td>0.9204</td>
</tr>
<tr>
<td>Fuel low heating value ( h_{PR} )</td>
<td>43,124 kJ/kg</td>
</tr>
</tbody>
</table>

For full throttle operation, the maximum inlet HPT total temperature \( (T_{t3} \text{ or main burner exit total temperature}) \) and the LPT inlet total temperature \( (T_{t1,5.5} \text{ or ITB exit total temperature}) \) are set to the values as listed in Table 2. For partial throttle operation, the minimum thrust is set to 20% of the maximum thrust.

A program was written in combination among Microsoft Excel spreadsheet neuron cells, VisualBasic, and macrocode to provide user-friendly interface so that the compilation and preprocessing are not needed.

### Predicted Performance Results

#### Full Throttle Performance

Figures 3a–3c present the uninstalled performance of the turbofan engines operating at full throttle settings for case A. These figures show the variations of thrust, thrust specific fuel consumption \( S \), and thermal efficiency with flight Mach number \( M_0 \) and altitude, respectively. Two different altitudes are SLS condition and 10 km. The solid lines represent ITB engine performance while the dashed lines represent baseline engine performance.
In Fig. 3a, ITB engines at two different altitudes exhibit an increase in thrust over the baseline engine as $M_0$ increases. Because of more fuel injected into ITB in addition to the main burner, ITB engines do have slightly higher fuel consumption than the baseline engine. Nevertheless, adding ITB is still beneficial because the improvement in thermal efficiency (Fig. 3c) reflects that the gain in thrust offsets the slight increase in $S$. In addition, ITB engines perform even better at supersonic flight because there is no increase in $S$ at all as $M_0$ is greater than 1.1.

In Figs. 3a and 3c, both thrust and thermal efficiency curves at 10 km exhibit a slope change at a $M_0$ of 1.2. The engine control system takes place at that operating point in order to limit the main burner exit temperature from exceeding the maximum inlet turbine temperature limit.

Figures 4a–4c present the uninstalled performance of the turbofan engines operating at full throttle settings for case B. It is found that both engines have similar performance trends over the flight spectrum as in case A. While gaining higher thrust, ITB engine at 10 km starts consuming less fuel at $M_0$ greater than 0.7.

According to Figs. 5a and 6a, it is clearly noticed that adding ITB further extends the engine operational range by producing higher thrust levels than that of a baseline engine. Within these higher thrust levels, the fuel consumption increases linearly with increasing thrust until it reaches a local maximum point, which represents the full throttle operation point. Depending on the engine configuration and flight conditions, this maximum point might or might not be higher than the $S$ level of a baseline engine at its full throttle operation. For example, the local maximum points for the case A ITB engine with $M_0$ of 0.8 and 1.0 (Fig. 5a) have always higher $S$ levels than that of baseline engine. This can be shown in Fig. 3b, where the case A ITB engine’s full throttle operations at $M_0$ lower than 1.2 yield slightly higher fuel consumption. Nevertheless, Fig. 6a shows that case B ITB engine operating at full throttle condition exhibits lower $S$ values at three different $M_0$. Therefore, for some applications (e.g., case A) it might be better to operate the ITB engine at partial throttle settings (i.e., lower $T_{t4,5R}$) to avoid burning extra fuel while still achieving modest thrust augmentations. This will certainly provide fuel saving to many aircraft engines, which normally run at partial throttle settings during cruise operations at high altitude.

As shown in Figs. 5b and 6b, the thermal efficiency of ITB engine is greatly improved over the baseline engine when ITB is on. However, its variation within the extended operational range is relatively small.


Table 4 Summary of results for mission analysis (24,000 lbf of takeoff weight)

<table>
<thead>
<tr>
<th>Mission phases and segments</th>
<th>$M_0$</th>
<th>Alt. (kft)</th>
<th>Fuel used, lbf</th>
<th>Fuel saved, lbf</th>
<th>Fuel saved, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2: A, warm up</td>
<td>0.0</td>
<td>2</td>
<td>380</td>
<td>347</td>
<td>8.7</td>
</tr>
<tr>
<td>2-3: E, climb/acceleration</td>
<td>0.875</td>
<td>23</td>
<td>484</td>
<td>475</td>
<td>1.9</td>
</tr>
<tr>
<td>3-4: Subsonic cruise climb</td>
<td>0.9</td>
<td>42</td>
<td>510</td>
<td>501</td>
<td>1.7</td>
</tr>
<tr>
<td>5-6: Combat air patrol</td>
<td>0.697</td>
<td>30</td>
<td>715</td>
<td>703</td>
<td>1.8</td>
</tr>
<tr>
<td>6-7: F, acceleration</td>
<td>1.09</td>
<td>30</td>
<td>248</td>
<td>244</td>
<td>1.6</td>
</tr>
<tr>
<td>6-7: G, supersonic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-8: I, 1.6M/5-g turn</td>
<td>1.6</td>
<td>30</td>
<td>415</td>
<td>401</td>
<td>3.3</td>
</tr>
<tr>
<td>7-8: J, 0.9M/5-g turn</td>
<td>0.9</td>
<td>30</td>
<td>297</td>
<td>292</td>
<td>1.8</td>
</tr>
<tr>
<td>7-8: K, acceleration</td>
<td>1.2</td>
<td>30</td>
<td>226</td>
<td>225</td>
<td>1.0</td>
</tr>
<tr>
<td>8-9: Escape dash</td>
<td>1.5</td>
<td>30</td>
<td>520</td>
<td>503</td>
<td>16.0</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11: Subsonic cruise climb</td>
<td>0.9</td>
<td>48</td>
<td>462</td>
<td>458</td>
<td>4.0</td>
</tr>
<tr>
<td>12</td>
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For the following mission study, only case A is considered. For simplicity, only critical mission phases and segments are selected. Each selected mission leg is judged to be critical because it has a high fuel consumption and is an extreme operating condition. In each mission leg, the ITB engine is operating at partial throttle settings to avoid burning extra fuel as previously discussed.

Table 4 contains a summary of the mission performance of ITB engine (case A) as compared to baseline engine in term of fuel consumption. Each aircraft has an initial takeoff weight of 24,000 lbf. It is found that ITB engine uses less fuel in all phases. Particularly, the fuel consumption in the warm-up (1-2) phase is significantly less. This calculation also shows that ITB engine consumes about 2.6% less fuel for all of those selected critical mission legs, which ensure the fuel efficiency of an ITB engine over the baseline engine. To get an even better fuel consumption, one might want to return to the on-design cycle analysis and choose other reference-point engines for further investigation.

Conclusions

A performance-cycle analysis of a separate-flow and two-spool turbofan with ITB has been presented. The mathematical modeling of each engine component (e.g., compressors, burners, turbines, and exhaust nozzles), in terms of its operating condition, has been systematically described. Results of this study can be summarized as follows:

1) ITB engine at full throttle setting has enhanced performance over baseline engine.
2) ITB operating at partial throttle settings will exhibit higher thrust at lower $S$ and improved thermal efficiency over the baseline engine.
3) Mission study ensures the ITB engine’s advantage of saving fuel over the baseline engine.

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References