INFLUENCE OF INLET PROFILE ON HIGH-BPR TURBOFAN PERFORMANCE USING A RADIAL PROFILE MAP

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Abstract

A radial-profile based high-bypass ratio turbofan performance model was developed in order to predict civil aircraft engine performance accurately. In this model, the fan of the high bypass ratio engine has been represented using a radial-profile performance characteristic map. It describes with accuracy the strong radial profiles of all thermodynamic variables very well. It is common to average these profiles so that the fan can be represented by one or two one-dimensional characteristics. In this study, a simple intake model was developed in order to obtain inlet radial profiles for fan rotors. The inlet radial profiles are dependent on the fan mass flow and intake geometry as well as flight condition. The aim is to study the influence of inlet radial profiles on a high-bypass turbofan engine performance. The results are compared with and without using inlet profiles. The results show a reduction in thrust and increase in specific fuel consumption.

1 General Introduction

In a high-bypass-ratio turbofan engine, the fan exhibits significant radial variations in thermodynamic variables [1,2].

In gas turbine performance modeling, it is common practice [3,4,5,6,7] to represent the fan as a one-dimensional component or two separate compressors with one-dimensional flow characteristics, a bypass fan and a core fan, where the core fan delivers the core flow and the bypass fan delivers the bypass air.

Recognizing that the flow is not uniform, researchers tried to simulate the gas turbine by developing a component zooming modeling capability [8, 9]. The main difficulty in implementing the zooming concept is to resolve high-fidelity flow fields accurately from a single value as supplied from one-dimensional component simulation. These solutions are dependent on the accuracy of the CFD model and require a very large computing resource.

Recently, a radial-profile based fan characteristic model has been developed and applied to investigate steady-state and transient performance of high-bypass ratio turbofan engine [10, 11]. The advantages of the new model are to represent the fan performance radially, allowing local influence of the fan to be considered individually. For example, the intake boundary layer thickness and the intake radial profiles could be investigated in the area close to the intake wall.

The current aim is to study the influence of inlet radial profiles on a high-bypass turbofan engine performance.

2 Description of the fan models and intake model

2.1 Model 1: Radial-Profile Based Fan Model

To give a preliminary understanding of the influence of fan inlet profile on engine performance, radial-profile based fan map model is used.

Realistic notional fan inlet radial profiles (not applied to any particular fan) were generated. Fan works directly in proportion to the rotor speed and the change in absolute swirl velocity across the rotor. The majority of losses can be divided into those related to Mach number (shock waves), and viscous losses related diffusion acting on boundary layers. The bigger the rotor speed, the larger the pressure ratio. The pressure ratio at rotor hub is much smaller than that at rotor tip. Due to the influence of tip clearance and second flows, the pressure ratio near the tip reduces. These profiles are shown in figure 1. These different fan models were then incorporated in the model of a high bypass ratio turbofan so a comparison could be carried out.

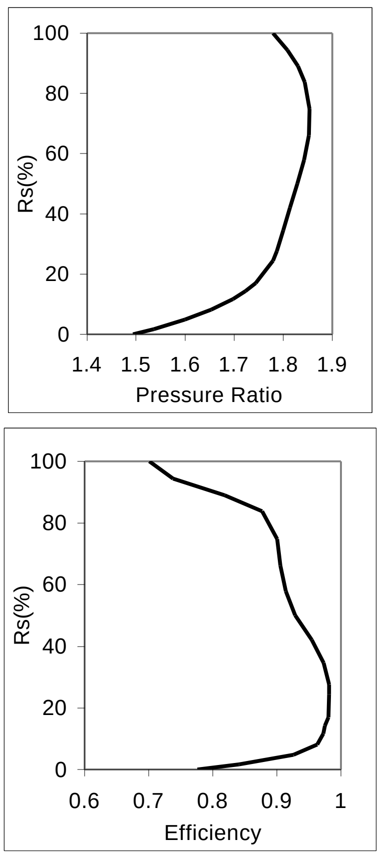

Figure 1. Fan Radial Profiles

The radial-profile based fan model uses directly the profiled flow information. The new radial-profile based fan model is based on several assumptions:

(1) When integrating over the radius, the averaged parameters such as pressure ratio and fan work for the radial-profile based fan model remain the same as those of the single-fan-map model.

(2) In addition, radial profiles at the fan rotor inlet are used as an input condition.

(3) Using a radial-profile based whole fan map, for a given non-dimensional speed $N/\sqrt{T}$ and β, the whole exit non-dimensional mass flow and pressure ratio can be calculated. At the same time, the radial profiles of pressure ratio, isentropic efficiency and non-dimensional mass flow at the trailing edge of the fan rotor blades are calculated and remain the same, i.e., they are independent of how the flow will split downstream. Figure 2 presents the concept of the radial-profile based fan model. Figure 3 gives the whole fan characteristic map.

2.2 Intake Models

Two Intake models are used here
Intake Model 1: Radial inlet profile
Intake Model 2: Uniform inlet profile

Model 2 represents no loss in intake total pressure recovery.
Model 1 represents the influence of intake wall boundary layer.

2.2 1 Intake Model 1

The intake model is used to obtain fan-inlet radial profile of total pressure, as shown in figure 4. The profile is dependent on several factors:

- Ambient condition
- Flight Mach Number
- Boundary-layer development on the intake wall.

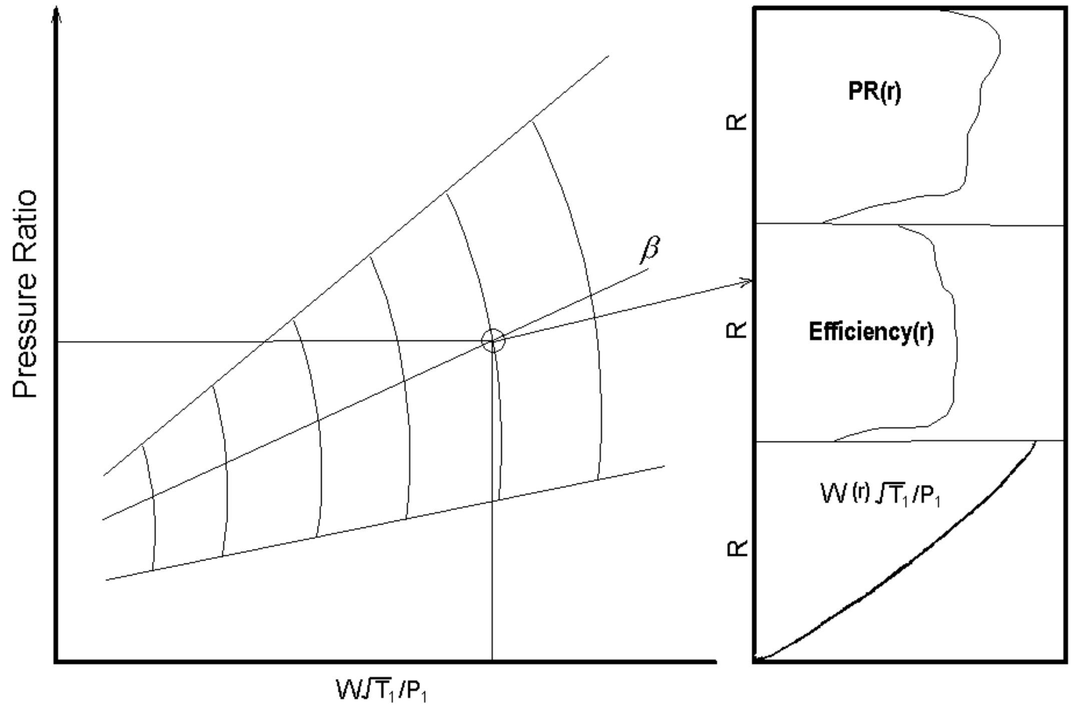

Figure 2. Concept of radial-profile based fan model

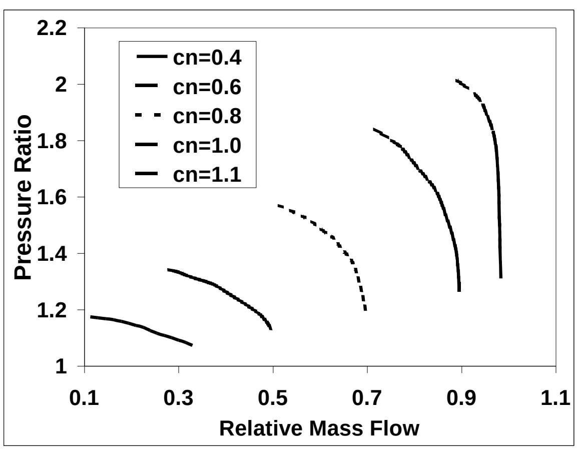

Figure 3. Whole Fan map

Using Ambient condition and flight Mach number, the fan inlet peak total pressure $P_{t,peak}$ and fan inlet total temperature T_t can be determined.

$$P_{t,peak} = p_a\left(1+\frac{g-1}{2}M_\infty^2\right)^{\frac{g}{g-1}} \tag{1}$$

$$T_t = T_a\left(1+\frac{g-1}{2}M_\infty^2\right) \tag{2}$$

Where p_a and T_a are the ambient pressure and temperature; M_∞ is the flight Mach number.
Then the profile $P_t/P_{t,peak}$ is the fan-entry total pressure recovery profile. It is dependent on the fan-entry boundary-layer velocity profile. It is influenced by the fan-entry Reynolds number and intake inner-wall pressure distribution, which affects the boundary layer growth rate. The fan-entry Reynolds number is a function of fan mass flow as follows:

$$R_e = \frac{\dot{m}_{FAN} L_{REF}}{m A_{REF}} \tag{3}$$

Where $\dot{m}_{FAN}$ is the fan mass flow rate; L_{REF} is the intake reference length; A_{REF} is the intake outlet area.
The boundary-layer thickness can be determined as follows:

$$d = C_d \frac{L_{REF}}{R_E^{0.2}} \tag{4}$$

$$C_d = 0.4$$

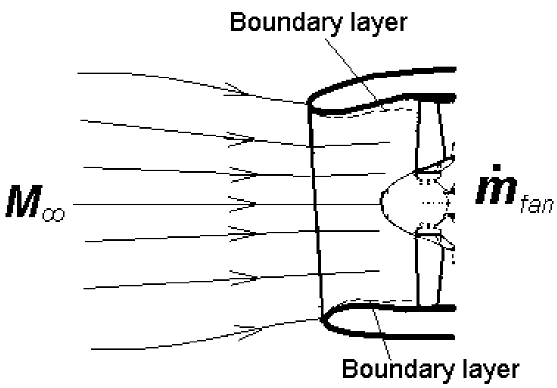

Figure 4. Boundary layer in an intake

Assume the velocity profile in the boundary layer is

$$\frac{u}{U} = \left(\frac{y}{d}\right)^{\frac{1}{7}} \qquad (5)$$

Where u is the air speed in the boundary layer; U is the air speed at the edge of the boundary layer. Therefore using equation (5), the profile $P_t/P_{t,peak}$ can be obtained. Figure 4 gives a typical profile at 100% non-dimensional fan speed.

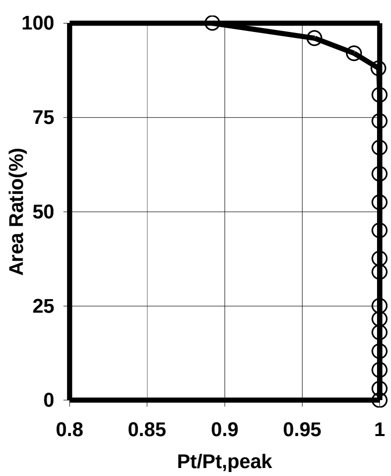

Figure 5. Profile $P_t/P_{t,peak}$ at 100% speed

There is the decrease in total pressure near the fan tip. That influence causes the decrease in mass flow rate and significant variation in engine performance.

3 Off Design Performance Calculation

The aero-engine selected for this investigation is a typical 2-shaft turbofan with separate exhausts. The main cycle characteristics are shown in Table 1. For all the models examined here, the representation of high-pressure compressor, turbines, combustor and nozzles is the same. The other details of the performance model employed are also the same.

Table 1. The Turbofan Cycle Investigated

Bypass Ratio	5.7
Fan Pressure Ratio	1.7

3.1 Fan Model

The input parameters are:
(1) Fan inlet total temperature T_t
(2) Fan inlet peak total pressure $P_{t,peak}$
(3) Fan Shaft Speed N_{fan}
(4) b
(5) Fan inlet profile: $P_t/P_{t,peak}$

The output conditions are
(1) Cumulative mass flow
(2) Radial pressure ratio profile
(3) Radial efficiency profile

To guess a fan bypass ratio and split the profile into bypass and core stream, the average pressure ratio and efficiency in the bypass and core streams can be obtained by using mass flow averaging. The bypass average parameters are different from the core parameters.

3.2 Calculation in Intake Model 1

In Intake Model 1, a fan mass flow rate is required and has to be calculated in the fan model. Therefore an additional iteration is required in order to determine a correct fan mass flow.

Figure 6 summarizes the iteration calculation procedure.

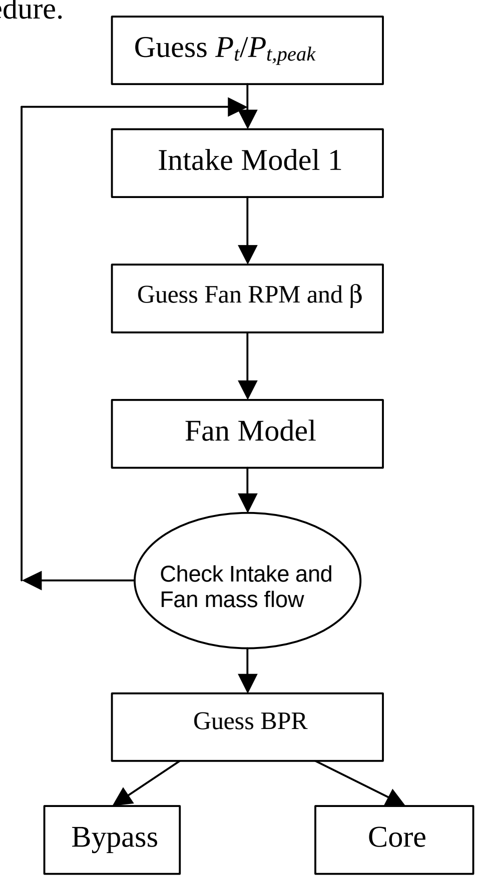

Figure 6. Iteration calculation procedure

3.3 Results and Analysis

Figures 7 to 9 presents the results from Model 1 and Model 2. The results clearly indicate the difference between the two intake models.

Intake Model 2 shows higher thrust, lower SFC and higher bypass ratio. Because the bypass stream has no reduction in mass flow and total pressure, the higher the mass flow, the bigger the thrust.

For Intake Model 1, the radial inlet total pressure profile has been implemented. The loss in total pressure and mass flow has been considered. Mass flow rate decreases near the fan tip. The bypass ratio decreases, the thrust decreases and SFC rises.

The reduction in fan inlet total pressure affects the turbofan engine performance considerably. A radial-profile based high-bypass ratio turbofan performance model can give reasonable and accurate representation and it can be used to estimate the fan and engine performance. Table 2 represents the relative variation.

Pt	Thrust	BPR	SFC
-1.00%	-1.11%	-1.027%	1.066%

Summary

A radial-profile based high-bypass ratio turbofan performance model was developed and an intake model was developed in order to obtain the fan inlet total pressure profiles

The results are compared with those using one-fan map model. The results show reduction losses in thrust and an increase in specific fuel consumption

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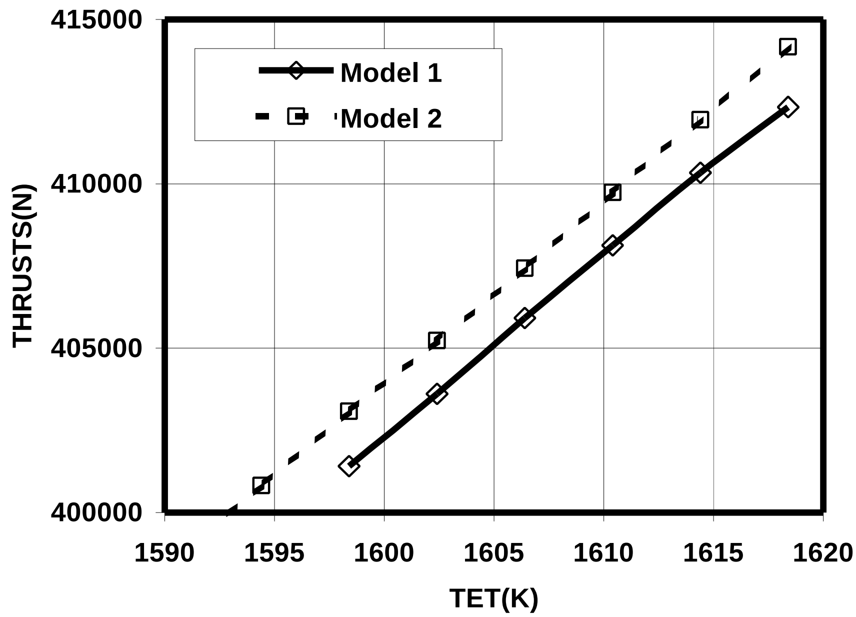

Figure 7. Thrust

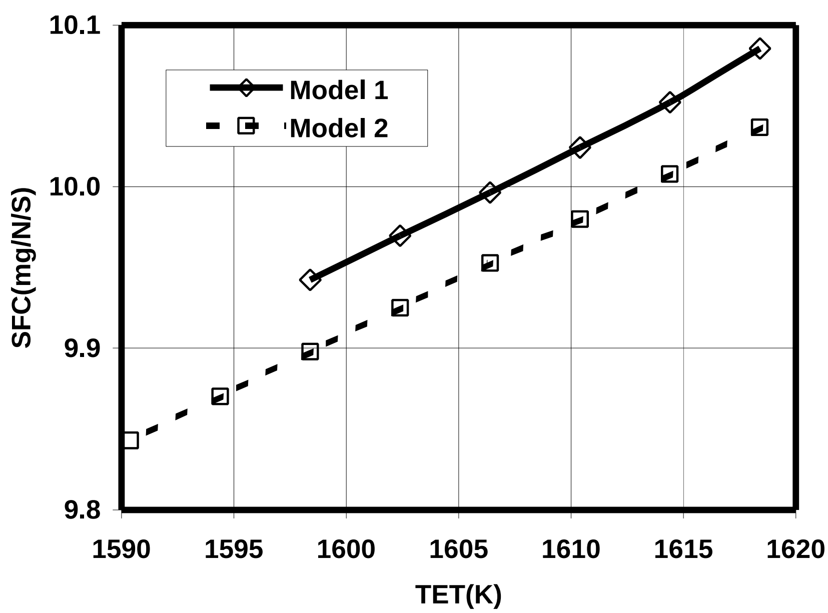

Figure 8. SFC

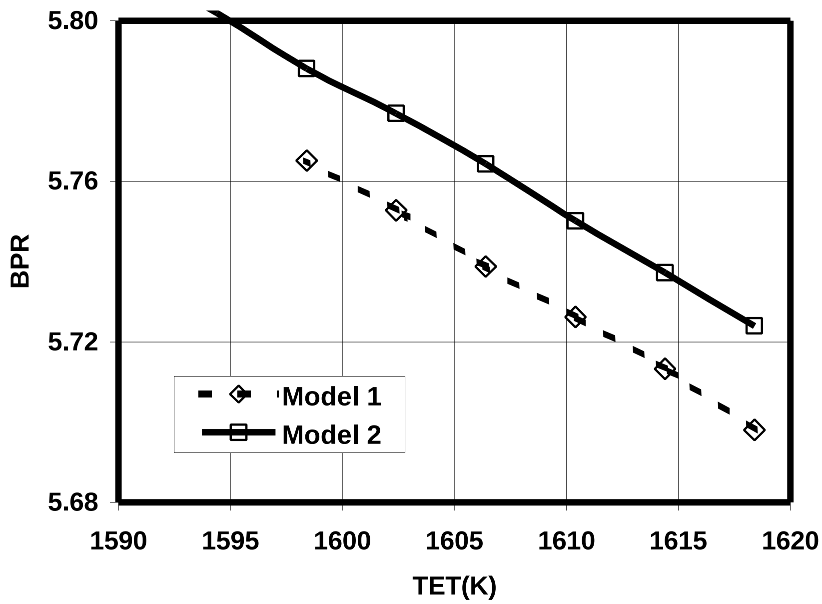

Figure 9. Bypass ratio