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Simulation of Aircraft Gas Turbine Engines

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ABSTRACT

The paper describes a computer program to simulate aircraft gas turbine engines. The program has been written for IBM compatible micro computers and is modular in its approach. Either analytical equations or detailed performance characteristics of individual components are used to model the steady state operation of the complete engine.

NOMENCLATURE

C_s	=	velocity equivalent of isentropic enthalpy drop (m/s)
C_p	=	specific heat at constant pressure (kJ/kg °C)
d	=	rotor tip or rms diameter (m)
f	=	fuel/air ratio
LCV	=	lower calorific value (kJ/kg)
$\dot{m}$	=	mass flow rate (kg/s)
M	=	Mach number
N	=	rotational speed (rev/s)
P	=	pressure (bar or N/m²)
Q	=	heat release or transfer (kJ/kg)
S	=	entropy (kJ/kg.K)
T	=	temperature (K)
U	=	rotor tangential velocity (m/s)

Greek Symbols

γ	=	ratio of specific heats
δ	=	ratio ($P/P_{standard}$)
Δ	=	small increment
η	=	isentropic efficiency
η_{comb}	=	combustion efficiency
θ	=	ratio ($T/T_{standard}$)
τ	=	torque (N/m)

Sub/superscripts

a	=	actual
i	=	isentropic
O	=	total
∞	=	ambient conditions
1	=	compressor entry
2	=	compressor delivery/combustion chamber inlet
3	=	combustion chamber outlet/turbine entry
4	=	turbine outlet/propelling nozzle entry
5	=	propelling nozzle outlet

INTRODUCTION

An aircraft gas turbine engine represents a complex system comprising a number of rotating and stationary components, each with its own performance characteristics. The performance of the complete engine depends on the performance characteristics of the individual components or sub-systems and matching. Moreover, in service an engine operates over a wide range of flight conditions. Hence, testing a complete engine to explore its full performance envelope can be both very costly and extremely laborious. Therefore, simulating the operation of the aero gas turbine engine on a computer has obvious advantages. Consequently, a number of papers have been published on this subject in the open literature.

Broadly speaking, gas turbine simulation models that have been produced may be divided into three categories, namely:

(i) analog simulation models;
(ii) hybrid simulation models;
(iii) digital simulation models.

These models may be used to represent either the steady state or the dynamic operation of the engine.

A review of the available simulation models, both analog and non linear digital - the so called Dynasar, was given by Durand (1). Evans (2) described a method which graphically illustrated the fundamentals of matching the compressor, turbine, and primary nozzle components of a single spool turbojet engine. Saravanamuttoo and Fawke (3,4,5) used the compressor and turbine characteristics and applied the analyses to a range of engines including a twin spool engine which was then under development. Their approach essentially consisted of synthesising the thermodynamic relationships that described each engine component. Sufficient dynamic equations were introduced to describe transient behaviour between

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components. They claimed good agreement between test results and simulation. The method advanced by Saravanamuttoo was adopted by Cottington (6) who produced a computer code using DIGISIM, a standard simulation language at that time. The investigations of Schobeiri (7), Mats and Tunakov (8), Prokpof'ev (9) also cover various aspects of simulation.

From the brief review of the published work cited here, it would appear that there is still a need for a general simulation model which may be used to represent different engine configurations and to study, particularly at the conceptual design stage, the effect of component performances on the overall performance of the engine. Hence, it is important to ensure that the package is suitable for use by the design office staff.

The aim of this paper is to describe a micro computer based program that has been developed for digital simulation of the steady state performance of gas turbine engines.

DESIGN AIMS FOR SIMULATION PROGRAMS

A modern gas turbine engine for aircraft propulsion may be either a simple turbojet, a turboprop, a ducted turbofan or an unducted turbofan. It may have a single, twin or triple spool construction. A computer simulation program should permit the user to assemble the components in any desired configuration.

Each component has its own distinct performance characteristics which may be modelled either analytically or by experimentally obtained performance data. The program should allow the user to model the components in a preferred manner.

The program should be modular so that, if desired, individual modules may be used to study the performance of the components or sub systems comprising a particular engine configuration.

DESCRIPTION OF THE PROGRAM

The program can be divided into three main sections as follows:

(i) program control section;

(ii) components' description and modelling section, e.g. compressor, combustion chamber, turbine, etc.

(iii) processes section, e.g. diffusion, compression, combustion, etc.

The link between the three sections is shown in Table 1.

Table 1 Program Sections

Components	Program Control	Processes
Intake	System description, data entry and modelling	Diffusion
Compressor		Compression
Combustion Chamber	Execution	Combustion
Turbine, etc.	Output	Expansion, etc.

The control section provides the interface between the user and the program. Once all the sub systems that make up the engine have been defined, the control section then proceeds sequentially taking the necessary geometric data and/or performance data from the components' section and the relevant analytical expressions or experimental data from the processes section. Finally, the results are presented to the user by the program control section.

The program is modular in its approach and has been written in Fortran 77 for the IBM and compatible micro computers. A flow diagram showing the program logic is given in Fig. 1.

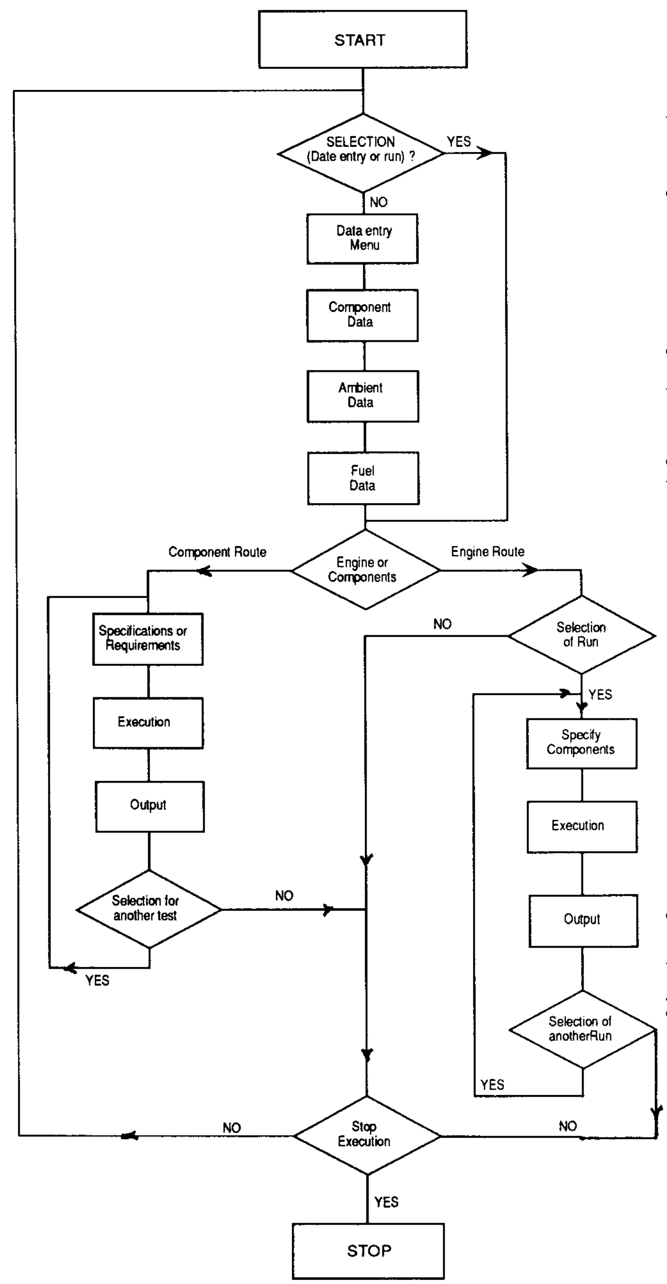

Fig. 1 FLOW DIAGRAM - {GAS TURBINE SIMULATION}

THEORETICAL BACKGROUND

The main components of a turbojet engine and the corresponding thermodynamic cycle are shown in Figs. 2(a) and 2(b) respectively.

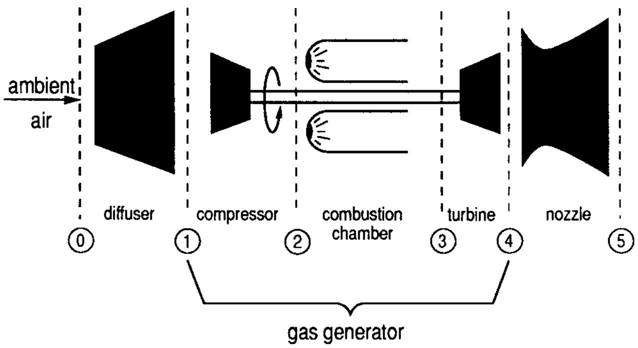

FIG. 2(a) SCHEMATIC DIAGRAM FOR TURBOJET ENGINE

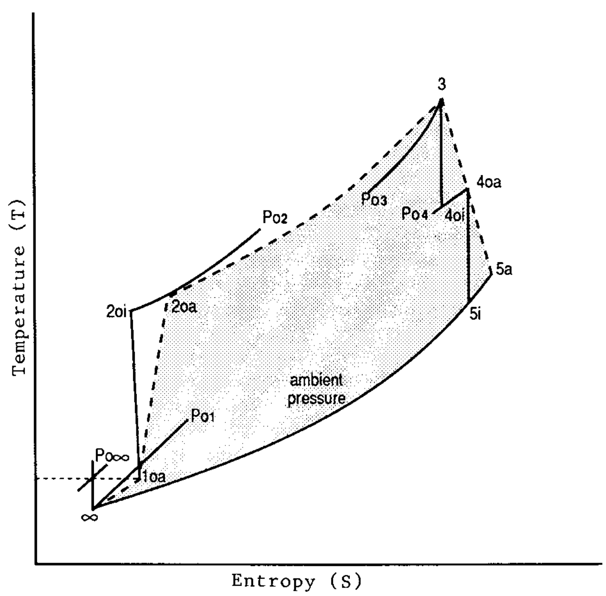

FIG. 2(b) TEMPERATURE-ENTROPY DIAGRAM FOR TURBOJET ENGINE

The modelling of each component is described in the following.

Air Intake

Air entering the engine intake at approximately the flight Mach number must be decelerated to satisfy the compressor entry velocity triangle. The intake process which produces pressure rise due to the ram effect is shown in Fig. 3. The governing equations are given below:

$$T_{01} = T_{\infty} + \frac{(V_f - V_1)^2}{2\,C_p} \qquad (1)$$

$$P_{01}' = P_{\infty}\left(\frac{T_{01}}{T_{\infty}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (2)$$

$$P_{01} = P_{01}' - \Delta P_{0-intake} \qquad (3)$$

$$\Delta P_{0-intake} = \sum_{1}^{n} \delta P_0 \qquad (3a)$$

$$T_{01}' = T_{\infty}\left(\frac{P_{01}}{P_{\infty}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (4)$$

$$\eta_{intake} = \left\{\frac{T_{01}' - T_{\infty}}{T_{01} - T_{\infty}}\right\} \qquad (5)$$

where: δP_0 = the loss of stagnation pressure in an elemental length (1)

n = number of elemental steps in the intake

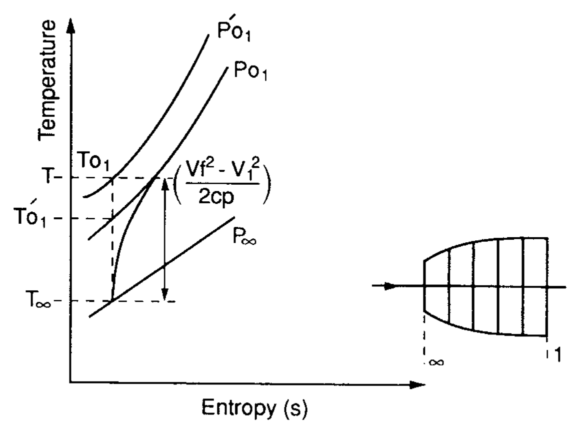

FIG. 3 INTAKE PROCESS

The overall loss of stagnation pressure can be calculated in a step by step manner by using the Darcy formula for friction and at the same time satisfying the well established diffuser performance criteria.

Compressor

The performance of a compressor is fully described by a number of either dimensionless or normalised parameters as given below:

$$\frac{\tau}{d_2^2\,P_{01}} = \frac{1}{2\pi}\cdot\frac{1}{\eta_c}\left(\frac{d_2\,N}{\sqrt{C_p T_{01}}}\right)^{-1}\cdot$$

$$\cdot\,\frac{\dot{m}\sqrt{C_p T_{01}}}{d_2^2\,P_{01}}\cdot\left\{\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right\} \qquad (6)$$

$$\frac{\tau}{\delta} = f\left(\eta_c, \frac{N}{\sqrt{\theta}}, \frac{\dot{m}\sqrt{\theta}}{\delta}, \frac{P_{02}}{P_{01}}\right) \quad (7)$$

Where $\delta = \left(P_{01}/ P_{0\ ref}\right)$

$$\theta = \left(T_{01}/ T_{0\ ref.}\right)$$

The performance characteristics are usually plotted as shown in Fig. 4. In order to use the performance characteristics in a simulation program it is necessary to consider one of the following two options:

(i) determine the coefficients for equation (7) and then use the equation to calculate the parameters for an arbitrarily selected point on the performance map;

(ii) store the characteristics in look-up tables and then use an interpolation technique to determine the values of the performance parameters for any arbitrarily selected point on the performance maps.

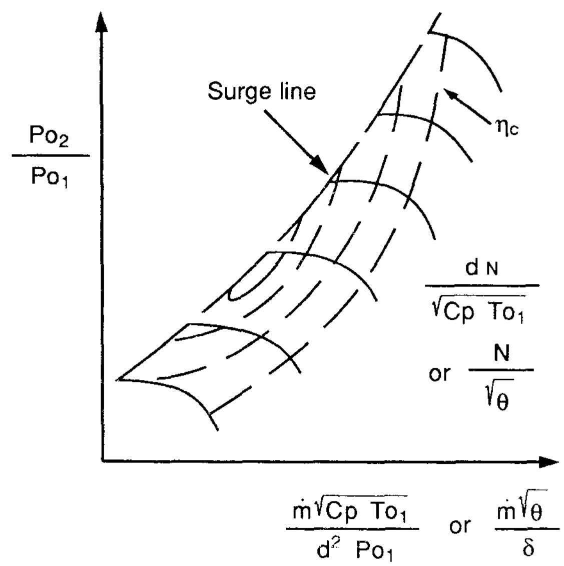

FIG. 4 COMPRESSOR PERFORMANCE CHARACTERISTICS

In the present program the second option was chosen because it produced a more reliable estimate of the performance parameters at any point on the performance map. The format of the look-up tables used in the program is shown in the following.

Table 2a Mass Flow vs Pressure Ratio Characteristics

Pr \ N	→
↓	mass flow rate

Table 2b Compressor Efficiency vs Pressure Ratio

Pr \ N	→
↓	compressor efficiency

If the values of two parameters are specified, the program searches for the other two from these look up tables. Langrangian interpolation is used to estimate the values lying at intermediate points.

Combustion Chamber

The combustion chamber entry conditions are assumed to be those given by the compressor discharge. The routine handling the combustion chamber calculates the following:

(i) the loss of stagnation pressure during combustion;

(ii) the temperature of gas at the outlet of the combustion chamber.

The loss of stagnation pressure is, quite often, assumed to be a constant percentage of the compressor delivery pressure. In this program the loss of pressure is calculated. The governing equations are given below.

$$Q_{gas} = Q_{theoretical} - Q_{lost} \quad (8)$$

$$m_a (1+f)\, C_{pg} \left(T_{03}' - T_{0e}\right) = f\, m_a\, LCV - Q_{lost} \quad (9)$$

$$\eta_{comb} = \frac{Q_{gas}}{Q_{theoretical}} \quad (10)$$

$$\Delta P_{0\text{-}total} = \Delta P_{0\text{-}momentum} + \Delta P_{0\text{-}friction} \quad (11)$$

$$\Delta P_{0\text{-}momentum} = P_{02} - P_{03} \quad (11a)$$

$$\frac{P_{03}}{P_{02}} = \frac{\gamma_{av}}{\gamma_{av}+1}\left[1 - \frac{\gamma_2}{\gamma_{av}} M_2^2\right] \left\{\left[\frac{\gamma_{av}}{\gamma_3+1}\left(1 - \frac{\gamma_2}{\gamma_{av}} M_3^2\right)\right]^2 - 2\,\frac{\gamma_2^2}{\gamma_2-1}\,\frac{\gamma_{av}-1}{\gamma_{av}+1} M_3^2 \left(1+\frac{\gamma_2-1}{2} M_2^2\right)\frac{Q_{gas}}{C_{p2}T_{02}}\right\}^{1/2} \quad (12)$$

$$\Delta P_{0\text{-friction}} = \int \frac{dP_0}{P_0}$$

$$= \left(\frac{\gamma M_2^2/2}{1+\frac{\gamma-1}{2} M_2^2} - \frac{1+\frac{\gamma-1}{2} M_2^2}{2\left(1+\frac{\gamma-1}{2} M_2^2\right)}\right)$$

$$\int \frac{dM^2}{M} \quad (13)$$

Turbine

The performance of a turbine, like that of a compressor, is also fully described by a number of either fully dimensionless or normalised parameters as given below:

$$\frac{\tau}{d_2^2\,P_{03}} = \frac{1}{2\pi}\cdot\eta_t\left(\frac{d_2\,N}{\sqrt{C_pT_{03}}}\right)^{-1}\cdot$$

$$\cdot\frac{\dot{m}\sqrt{C_pT_{03}}}{d_2^2\quad P_{03}}\cdot\left\{1-\left(\frac{P_{04}}{P_{03}}\right)^{\frac{\gamma-1}{\gamma}}\right\} \quad (14)$$

$$\frac{\tau}{\delta} = f\left(\eta_t,\ \frac{N}{\sqrt{\theta}},\ \frac{\dot{m}\sqrt{\theta}}{\delta},\ \frac{P_{04}}{P_{03}}\right) \quad (15)$$

$$\text{Where } \delta = \left(P_{03}\,/\,P_{0\ ref}\right)$$

$$\theta = \left(T_{03}/\ T_{0\ ref}\right)$$

The performance characteristics are usually plotted as shown in Fig. 5. It can be seen from Fig. 5b that turbine efficiency is a function of the velocity ratio (U_2/C_s) and the speed paramter. The relationship between velocity ratio, pressure ratio and speed parameter is of the form:

$$\frac{U_2}{C_s} = \frac{\pi}{\sqrt{2}}\left(\frac{d_2\,N}{\sqrt{C_pT_{03}}}\right)\left\{1-\left(\frac{P_{04}}{P_{03}}\right)^{\frac{\gamma-1}{\gamma}}\right\}^{-1} \quad (16)$$

As in the case of the compressor, the performance characteristics of the turbine also are stored in two dimensional look-up tables.

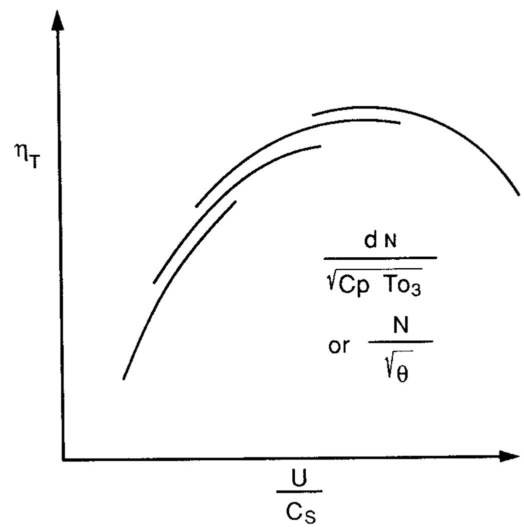

FIG. 5(a) TURBINE FLOW CHARACTERISTICS

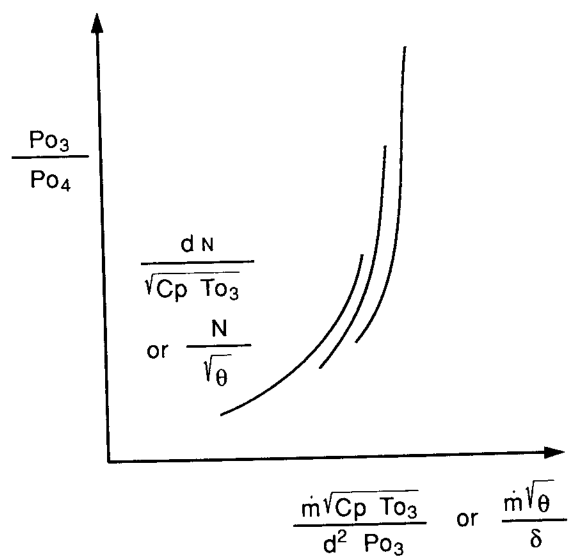

FIG. 5(b) TURBINE EFFICIENCY VS VELOCITY RATIO

Propelling Nozzle

The propelling nozzle is intended to accelerate the exhaust gas leaving the turbine exit to the velocity of the jet. The expansion process is shown in Fig. 6. The pressure at the nozzle outlet may be greater than, equal to or less than the prevailing free stream pressure. The equations governing the nozzle flow are given below:

$$T_5 = T_{04} - \frac{V_j^2}{2\,C_p} \qquad (17)$$

$$P_{05} = P_{04} - \Delta P_0 \qquad (18)$$

where: $\Delta P_0 = \sum_1^n \delta P_0$

and δP_0 = the loss of stagnation pressure in elemental length (1)

n = number of elemental steps in the nozzle.

$$P_5 = P_{05} \left(\frac{T_5}{T_{04}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (19)$$

$$T_5' = T_{04} \left(\frac{P_5}{P_{04}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (20)$$

$$\eta_{nozzle} = \left\{\frac{T_{04} - T_5}{T_{04} - T_5'}\right\} \qquad (21)$$

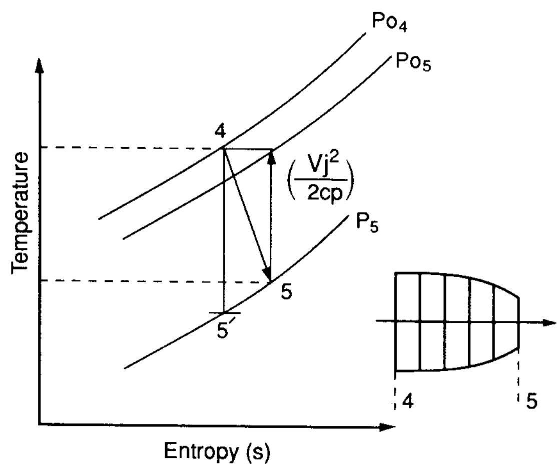

FIG. 6 PROPELLING NOZZLE PROCESS

HARDWARE AND SOFTWARE REQUIREMENTS

The program has been written for the IBM-AT or compatible micro computers with at least 1 Mega byte RAM, 40 Mega byte hard disk and Maths coprocessor. It should also run on PS/2- 50 or higher systems.

The code uses Fortran 77 language. The output is saved in ASCII files, therefore the results as well as the input data can be plotted in the graphical form by using a suitable graphics package such as Microsoft CHART or any other advanced graphics package.

RESULTS

The programme was used to calculate specific thrust and fuel consumption for a set of data from a proprietary engine. The results are shown in Fig. 7. The calculations were performed by increasing the flight Mach number in small increments. It has not been possible to compare the results with measured data for a variety of reasons, however the trends shown in the diagrams appear to be acceptable.

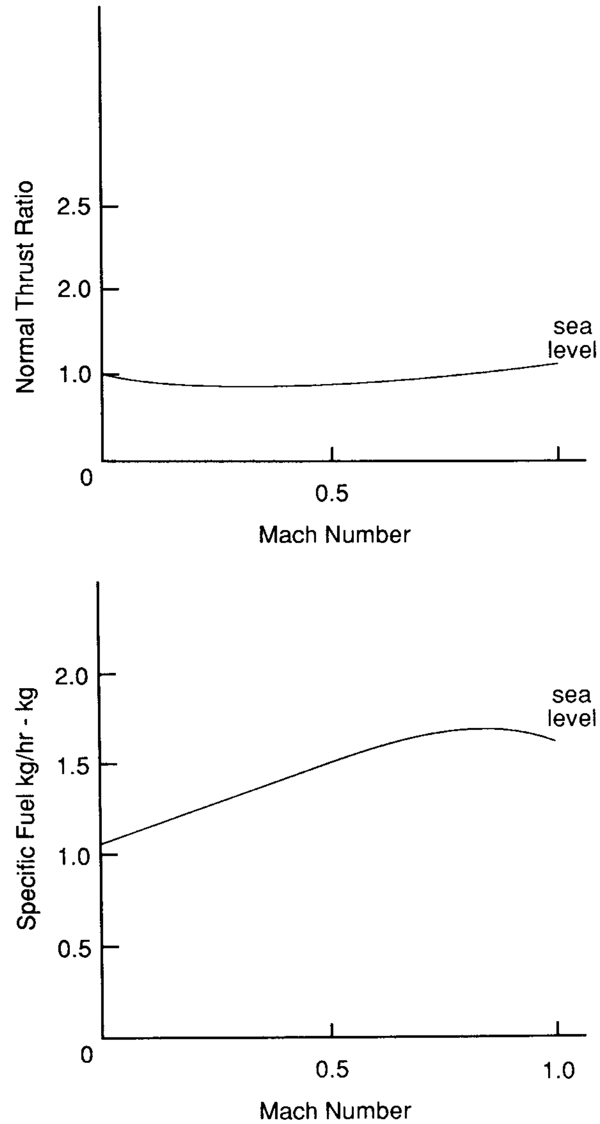

FIG. 7 CALCULATED PERFORMANCE

CONCLUSIONS

(1) The paper describes a procedure which has been used to develop a program for simulating gas turbine engines. The program has been written in Fortran 77 for IBM AT or compatible micro computers.

(2) The main feature of the procedure is that

components can be assembled to represent different engine configurations, therefore it should prove to be useful for exploratory studies at the design stage.

(3) Although it has not been possible to compare the results, obtained by calculations, the trends shown appear to be acceptable.

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