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VATEMP
The Variable Area Turbine Engine Matching Program

J. E. A. ROY-AIKINS[1]
J. R. PALMER[2]

School of Mechanical Engineering
Cranfield Institute of Technology
Cranfield, Bedford MK43 0AL
United Kingdom

ABSTRACT

Variable geometry in key gas turbine components offers the advantage of either improving the internal performance of a component or of re-matching the engine cycle to alter the flow-temperature-pressure relationships. Future gas turbines are expected to use variable geometry components extensively if they are to overcome some of the problems encountered by present day engines at off-design conditions in order to give much more advanced performance. Greater attention is also being paid to the impact of installation losses on the performance of aircraft engines.

A computer program called VATEMP, herein described, has been developed capable of simulating the steady-state performance of arbitrary gas turbines with or without variable geometry in almost any gas path component. Results obtained from the program led to the conclusion that variable geometry components have the potential to improve significantly the off-design performance of gas turbines.

NOMENCLATURE

A	area, m^2
A_c	inlet capture area, m^2
BD	brick data
CN	corrected speed ($N/\sqrt{\theta}$) relative to design
CV	nozzle velocity coefficient
C_D	drag coefficient
C_{FG}	nozzle gross thrust coefficient
C_{FGR}	flight nozzle gross thrust coefficient
C_{FGT}	test nozzle gross thrust coefficient
D	drag, N
d	a change
E	balance error variable
F	thrust, N
H	specific enthalpy, J kg^{-1}
M	Mach number
N	rotational speed, rev min^{-1}
n	number of errors or variables
P	total pressure, atm
PR	pressure ratio
p	static pressure, atm
Q	corrected gas flow, $W\sqrt{T}/AP$
q	free stream dynamic pressure, $\rho V_o^2/2$, N m^{-2}
SV	station vector
sfc	specific fuel consumption, mg $N^{-1}s^{-1}$ or μg J^{-1}
T	total temperature, K
TF	turbine flow function, $W\sqrt{T}/P$
TIT	turbine inlet temperature, K
V	independent variable
W	gas mass flow, kg s^{-1}
WAC	compressor corrected airflow, $W\sqrt{T}/P$
Δ	a change
δ	pressure corrected to standard day
η	efficiency
θ	temperature corrected to standard day
μ	bypass ratio

Subscripts

AE	aft-end
a	ambient
b	base
c	compressor
cc	combustor
des	design
G	uninstalled gross
I	installed net
INL	inlet component
i	ith error
in	inlet to a component
j	jth variable
min	minimum
n	nth error or variable
POW	power off-take (work and air bleed)
R	ram
Rec	recovery
TRIM	trim
t	turbine
th	throat
2	compressor or fan inlet
8	nozzle throat

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[1] Formerly, Postgraduate Student
[2] Formerly, Senior Lecturer

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9	nozzle exit
9max	maximum nozzle exit
10	maximum fuselage
11	engine connection point

INTRODUCTION

The physics of operation of all gas turbine engines involves satisfying the various conditions of compatibility between the components. At the design point, the primary cycle performance variables and component losses are judiciously chosen such that for the required duty, cycle performance is optimized to produce the desired output. The components are then all well matched and the engine is probably operating most efficiently.

When the engine is operating away from the design point, that is at off-design, one or more components may be badly matched which could lead to poor engine performance. Variable geometry in the relevant components can offer the opportunity of improving component performance or of varying the thermodynamic cycle significantly, with the advantage that cycle performance can be re-optimized or controlled in sympathy with changing operating conditions.

Gas turbine performance simulation work with the aid of digital computers has been going on at Cranfield for over two decades, and was initiated by Palmer (1967) who developed TURBOCODE for programming cycle calculations on a digital computer. Research efforts at Cranfield have culminated in the development of a series of computer programs which can handle nearly all facets of performance simulation. The backbone of all of these programs is the TURBOMATCH program developed by Palmer (1983).

Though each of these programs looks into certain aspects of performance simulation, one thing they all have in common is that they can be used only for engines with fixed or simple variable geometry components, and also they all neglect the effects of the losses associated with aircraft installations. It is envisaged that future gas turbines will employ variable geometry components extensively, if they are to give much improved performance at off-design over those of the present day. With this point in mind, the VATEMP program was developed which is capable of simulating both the uninstalled and installed design point and steady-state off-design performance of arbitrary gas turbines with or without variable geometry components.

MECHANICS OF PROGRAM DESIGN AND OPERATION

The philosophy on which VATEMP is structured is that a gas turbine engine is composed of only a few different types of component, with each component handling a distinct thermodynamic process. Because of the steady flow nature of the gas turbine, any engine type can be considered as a combination of some of these basic processes in series, for one or more streams. Mathematical models representing the various possible thermodynamic processes are programmed in "bricks" which can be called upon at any time to evaluate the conditions of the gas at exit from a component, knowing the conditions at inlet and the characteristics of the component. If an engine is considered to be constructed in modular form, any engine type can be simuated, therefore, by assembling the relevant bricks in sequence, in accordance with the "Codewords".

The inputs to the program include the data which define the various component characteristics, and the data (such as pressure ratio and rotational speed) which define each design point on the component maps. The latter are held as Brick Data (BD) for the respective components. The condition of the air at inlet to the intake component is required to start the calculations, and this is given by specifying the altitude, Mach number, and airflow rate. The thrust of the engine is evaluated, and if a particular design thrust is specified, the calculated areas and gas flow rates are all scaled appropriately. The design point calculations yield scale factors (if necessary) which are applied to the various component maps during off-design calculations. The outputs from the program are the data for each component operating point, the data defining the state of the gas at each engine station, and the performance parameters for the engine, such as net thrust, specific fuel consumption (sfc), and specific thrust.

In order to satisfy the compatibility requirements of

(1) mass flow,
(2) work
(3) rotational speed, and
(4) static pressure (mixer)

at off-design, the primary performance variables, that is

(1) airflow,
(2) turbine inlet temperature, TIT,
(3) overall pressure ratio, and
(4) non-dimensional speed,

will all take unique values at any specified power, for any given intake conditions and component geometries. (Bypass ratio, μ, of turbofans is also an important variable, but once this has been chosen at the design point, it only determines the overall level of performance that can be attained by the engine). The idea from which VATEMP emerged is that the performance engineer should have access to tools which he can use to control or specify one or more of these performance variables (including μ) at off-design, in an attempt to re-optimize or improve cycle performance of his engine. This flexibility of operation can be provided by variable geometry.

VATEMP allows the user to vary the geometry of the following gas path components;

(1) Intake,
(2) Compressor,
(3) Turbine,
(4) Nozzle,
(5) Mixer, and
(6) Bypass splitter.

The various geometries can either be specified (with the exception of the intake) or allowed to float (bypass splitter excepted) to take up a unique value of area which will satisfy the matching constraints. In the former case, the geometry can be given as off-design data or as a scheduled function of either one or two variables. The functions are given either mathematically or graphically, the variables being simple combinations of Station Vectors (SV), Brick Data, and constants. With graphical representations, there is provision for each curve in the relationship to have up to a maximum of five discontinuities.

The variables which measure geometry change are either a physical area somewhere in the component or a parameter which denotes the position of the mechanism which effects an area change. For the inlet, the variable involved is the throat area, whereas IGV/stator angle measures the geometry setting of a fan or compressor. The inlet area relative to the minimum, A/Amin, indicates turbine geometry position while for a convergent nozzle, the exit area is the variable involved. Convergent-divergent nozzles have two areas which come into play, at the throat and at the exit. Either can be evaluated or specified as desired.

With a variable area mixer, mixing is assumed to take place at constant final area, therefore, "hot" and "cold" areas are traded-off for each other. As for as the bypass splitter is concerned, it is used essentially as a two-position valve which is either open or closed to allow flow or not. It may be necessary to regulate this area to control the Mach number of the flow pasing through. The idea of specifying the splitter area is to have a means by which the level of bypass ratio can be measured and against which the relevant geometries affecting μ can be scheduled.

As with all computer programs, there are limitations on the use of the VATEMP program. The program cannot be used to simulate the performance of an engine using any type of hydrocarbon fuel, nor does it allow for chemical dissociation of the gas, and for the effect of air humidity. The model used to evaluate installed performance is quite basic as the pertinent data that are required to evaluate all the installation loss components were not readily available. The results give only a feel for the effects of engine installation, and only engines buried in the fuselage can be simulated, such as with military installations. No provision is made for the evaluation of duct pressure loss due to Raleigh heat addition for duct/afterburning engines.

Codewords and Component Perfromance Representation

As was mentioned earlier, the thermodynamic processes taking place in a particular component are simulated in a "brick" which can be called upon at any time to perform the calculations for that component; so, if arbitrary gas turbines are to be simulated, then whenever a brick is called, the program will not "know" the relative position of the component in the engine configuration. This is made possible by the use of codewords, each codeword comprising a brick name which is a six letter word, and one or more addresses describing the codeword. Each address comprises a codeword descriptor letter followed by an address list.

A typical codeword is

```
COMPRE S3-4 D19-30 R62 V4,2,19 W5,2,20 A31-51 L2
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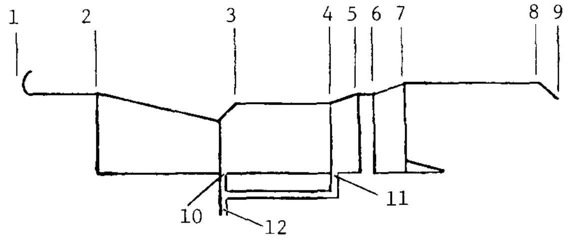
COMPRE is a brick name and it is followed by the Station, Brick Data, Result, 1st Variable, 2nd Variable, Scheduled Data, and Label addresses, respectively.

The above codeword simply says that the component is a compressor (or fan) situated between engine stations 3 and 4, with the necessary data to facilitate the calculations of the conditions of the gas at exit (station 4), knowing those at inlet (station 3), being placed in BD(19) to BD(30) inclusive. The execution of the brick calculations also results in the calculation of BD(62), in this case, compressor work, which is a brick data for the relevant driving turbine. The independent variables that are perturbed when an off-design equilibrium point is being sought are BD(19) and BD (20), pressure ratio and rotational speed, respectively. The variables for the associated scheduling function (IGV angle against non-dimensional speed, say) are given in BD(31) to BD(51) inclusive. The label address permits looping on a variable, in series or parallel. An example of the codeword hierarchy for a single spool free turbine engine is given in Fig. 1 and a brief description of the function of the bricks is given below.

ARITHY	performs arithmetic functions
BURNER	evaluates combustor performance
CODEND	psuedo-codeword denoting end of codeword input
COMPRE	evaluates compressor or fan performance
DUCTER	performs duct flow calculations with or without burning
HETCOL	performs cold stream calculations for heat exchangers
HETHOT	performs hot stream calculations for heat exchangers
INTAKE	performs intake calcuations
MIXEES	performs simple mixing where one flow is small relative to the other
MIXFUL	performs complete mixing, with solutions of the relevant momentum equations
NOZCON	performs calculations for a convergent propelling nozzle or bypass stream in a variable area mixer
NOZDIV	evaluates performance of a convergent-divergent nozzle
PERFOR	performs engine performance calculations
PREMAS	performs splitter and other simple flow calculations
TURBIN	evaluates turbine performance



A Free Turbine Engine

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INTAKE S1      D1-5,78
COMPRE S2-3    D6-17      R36 V1,2,6  W2,2,7  A86-106
PREMAS S3-10,3 D18-23                         A107-127
PREMAS S10-12  D80-85                         A128-148
BURNER S3-4    D24-27     R69                         L1
MIXEES S4,11,5
TURBIN S5-6    D28-42         V3,2,38
TURBIN S6-7    D43-57         V4,2,44 W5,2,43
DUCTER S7-8    D58-62
NOZCON S8-9,1  D63,79
PERFOR S1,0,0  D43,64-77
CODEND
```

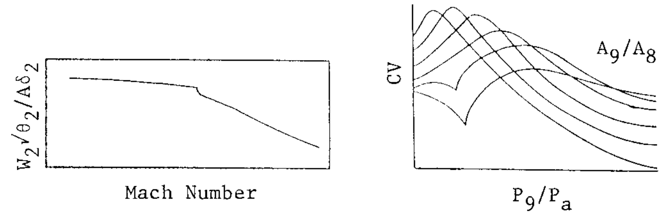
Fig. 1 Codeword Hierarchy for a Free Turbine Engine

The station vector is a list of items, five of which (suitably chosen) completely describe the state of the gas at any engine station in accordance with the gas law. The elements that make up the station vector are,

(1) fuel-air mass ratio
(2) gas mass flow
(3) static pressure
(4) total pressure
(5) static temperature
(6) total temperature
(7) velocity
(8) area.

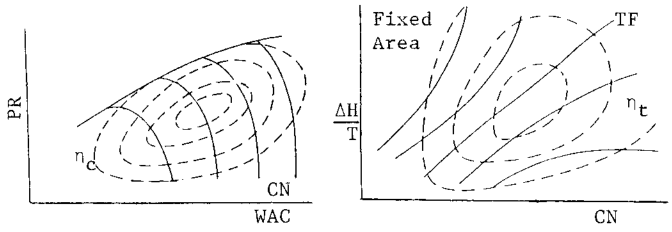
The brick data items for each brick include all the data that define a current operating point on the component performance map and those data that facilitate brick operation. Such data include efficiency, pressure ratio, and map number. These are given for each component at the design point and may change at off-design either by being specified by the user or as a result of perturbations of the specified independent variables. Once the conditions of the gas at outlet are known, the inlet conditions to the component immediately downstream are obtained and the procedure is repeated for the relevant component or brick.

The performance of each component is obtained from maps representing the characteristics of the component or from simple equations describing certain processes. Typical performance maps are shown in Fig. 2. A suitable chice is made in accordance with the desired simulation. Some maps are included in the program which can be scaled to represent the performance of the components of any engine whose performance the user wishes to simulate. Optionally, the user may input his own maps.



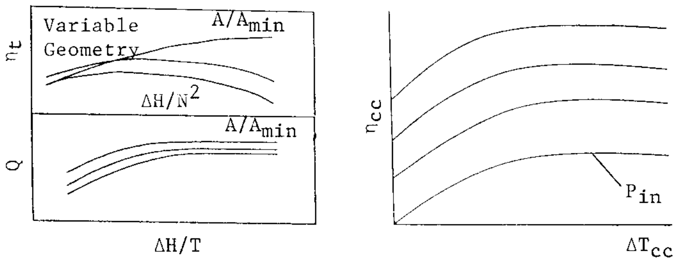
Inlet Max. Flow Map

Nozzle Map



Compressor (Fan) Map

Turbine Map



Turbine Map

Combustor Map

Fig. 2 Component Performance Maps

The Balancing Technique

The component matching procedure used is not too different from that described by Cohen et al. (1987) for predicting the off-design performance of gas turbines. The "guesses" and "checks" that are made at various stages as suggested are replaced by "variables" and "errors"; however, in this case, the errors are used to change all the variables simultaneously in a manner that realistically describes the actual engine behaviour. The balancing technique reduces all the errors to zero at the equalibrium point.

An iterative method employing the multi-dimensional Newton-Raphson method (described by McKinney, 1967) is used to solve the governing simultaneous non-linear equations of the form,

$$E_i = f(V_j) \quad \begin{array}{l} i = 1,2,.....,n \\ j = 1,2,.....,n \end{array} \qquad (1)$$

When an off-design point is given, a pass is made around the engine and matching errors are generated as base errors, E_{bi}, while the independent variables take values equal to V_{bj}. Thereafter, each independent variable is perturbed and the changes in errors caused by a change in each variable, $\partial E_i/\partial V_j$, are noted during each loop. After all the variables have been perturbed, the equation

$$dE_i = \sum_{j=1}^{n} \frac{\partial E_i}{\partial V_j} dV_j \qquad (2)$$

can be written for the total change in each error, $E_i - E_{bi}$.

When the engine is balanced, all matching conditions are satisfied and all errors vanish, yielding the required solution for the variables. A matrix equation can therefore be set up from Eq. (2) for n errors to give, for small changes in the variables,

$$\begin{bmatrix} \frac{\Delta E_1}{\Delta V_1} \cdots\cdots \frac{\Delta E_1}{\Delta V_n} \\ \vdots \\ \frac{\Delta E_n}{\Delta V_1} \cdots\cdots \frac{\Delta E_n}{\Delta V_n} \end{bmatrix} \begin{bmatrix} dV_1 \\ \vdots \\ dV_n \end{bmatrix} = - \begin{bmatrix} E_{b_1} \\ \vdots \\ E_{b_n} \end{bmatrix} \qquad (3)$$

The new values for the variables can thus be obtained from

$$V_j = V_{bj} + dV_j \qquad j = 1,2,....,n \qquad (4)$$

Since the governing equations are non-linear, it is unlikely that after the first try, the V_j's obtained from Eq. (4) will balance the engine. It may be necessary to repeat the iterative process a number of times until all the errors are within the specified tolerance of half a percent, when a solution is obtained.

Choice and Change of Variables

The matrix equation given in Eq. (3) requires that the number of independent variables be equal to the number of errors. The rules for choosing the types of variable and error for any engine configuration are given by Palmer (1983) and by Roy-Aikins (1988b). Unlike its predecessor, VATEMP is capable of changing the types and altering the numbers of variables and errors before or during an off-design run. In the case where an area is allowed to float, that is when area is an independent variable, it is possible that under certain operating conditions one or more constraints may be violated and this may cause the program to abandon variable geometry operation of one or more components. For example, a minimum or maximum area constraint may be reached on a component.

Under these circumstances, the program will perturb the specified power control parameter until a value is obtained at which the components in question operate in the variable geometry mode at the limiting value of the constraints. This power setting is taken as the critical power for the given intake conditions with which future specified powers will be compared to predetermine whether or not the affected components will operate in the variable geometry mode. This exercise may reduce execution time. In the fixed geometry mode, the relevant areas are held fixed at the value obtained at the critical power.

It is clear that in the fixed geometry mode, the area in question can no longer be a variable so, therefore, another variable should be introduced or an error deleted. The course of action will depend on engine configuration and control. There are other constraints such as limit loading on a turbine and minimum surge margin on a compressor that may prevent variable geometry operation of a component or of the engine as a whole.

The changes of variables and/or errors under these circumstances are made internally and the program requires no assistance from the user. However, there are instances where the user may desire to alter the constitution of the set of variables. For example, fan speed may be the initial parameter that controls engine power while TIT varies. Subsequently, the user may wish to let fan speed vary while TIT is specified. This is possible in VATEMP, which is an added advantage avoiding the need to change codewords and to re-run the program.

Installed Performance

More attention is being paid to engine installation losses with respect to magnitude and relative importance as aircraft flight envelopes have grown wider. In the past, fighter aircraft in particular have suffered in performance due to poor prediction of these losses and poor integration of the engine with the airframe. If future aircraft are to attain their planned performance goals, then the effect of installation losses will have to be considered quite early in the development of an engine.

Installed performance analyses are usually carried out by airframe manufacturers and if this is to be covered in detail, then a program which may even be larger than VATEMP will have to be written. VATEMP however contains a simplified model which can be used to estimate installation losses for engines that are buried in the fuselage, as is typical of fighter installations.

The throttle-dependent installed propulsive thrust can be written as

$$F_I = F_G - D_R - \Delta F_{Rec} - F_G(1 - C_{FGR}/C_{FGT}) - \Delta D_{INL} - \Delta D_{AE} - \Delta D_{TRIM} - \Delta F_{POW} \qquad (5)$$

The throttle-dependent trim drag is usually small and is, therefore, neglected. As the thrust loss due to air and power off-take is installation dependent and may therefore be quite difficult to quantify, it is neglected, thereby leaving the first six terms on the right hand side of Eq. (5) to define the net installed thrust. From the definition of gross thrust coefficient, C_{FG}, the fifth term in Eq. (5) reduces to the difference in installed and uninstalled gross thrusts thereby accounting for the change in thrust due to internal performance of both test and flight nozzles.

If the switch to indicate that installed performance is required happens to be on, then only the second and third terms in Eq. (5) define the net uninstalled thrust, otherwise, the first four terms on the right hand side are used, with C_{FGT} set equal to unity. The uninstalled gross thrust is not necessarily the ideal gross thrust, but the gross thrust of the test nozzle.

To obtain the uninstalled thrust, the engine is balanced on the assumption that both pressure recovery and C_{FGT} are unity, that is, the inlet and nozzle are both removed. Pressure recovery is then introduced, obtained from one of five maps such as that shown in Fig. 3, and the engine is balanced once again with the nozzle in place. Since the program incorporates only one nozzle performance map, it is not possible to simulate engine performance with different flight and test nozzles, so it is assumed that the test nozzle is an ideal one with C_{FGT} equal to 1 and therefore, the uninstalled net thrust calculated is the ideal net thrust. After the engine is balanced a second time, the net thrust obtained is the sum of the first four terms on the right hand side of Eq. (5). Upon substracting the ideal net thrust and the fifth term in Eq. (5) from the value of thrust obtained, the thrust loss due to pressure recovery is found.

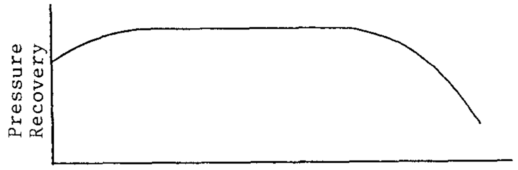


Fig. 3 Inlet Pressure Recovery

The throttle-dependent inlet drag is defined as,

$$\Delta D_{INL} = qA_c \Delta C_{DINL} \qquad (6)$$

The inlet drag coefficient is obtained from a map such as that in Fig. 4. Four such maps are incorporated in the program. Since the reference drag coefficient, giving the reference drag which is to be added to the aircraft drag polar, is included in Fig. 4, the reference drag is first to be evaluated whenever the flight conditions change, by evaluating the maximum power condition, since by definition the reference drag is the drag obtained when the airflow is a maximum. The throttle-dependent drag is thus zero at this flight condition.

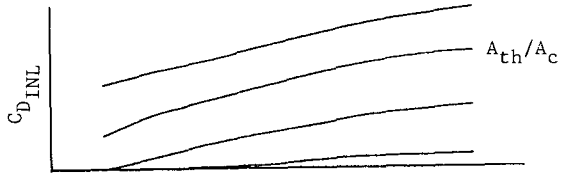


Fig. 4 Intake Drag Representation

To obtain the inlet capture area, A_c, the flight and power conditions for which the inlet is sized are given as off-design data immediately after the design point has been evaluated. The reduced airflow at exit from the inlet is evaluated and using the inlet maximum flow characteristic such as that shown in Fig. 2, the inlet capture area is obtained.

The throttle-dependent aft-end drag is defined as

$$\Delta D_{AE} = qA_{10} \Delta C_{DAE} \qquad (7)$$

The afterbody nomenclature adopted by May and Zavatkay (1973), and which is reproduced schematically as Fig. 5, is used here. To obtain A_{10}, a value of A_{9max}/A_{10} is given at the design point and since it is assumed that the maximum area to which the nozzle exit can expand is equal to the area at nozzle inlet, A_{9max} is obtained by specifying a Mach number for the exhaust flow at the jet pipe exit at the design point.

The aft-end drag coefficient is obtained from maps such as that in Fig. 6. The program has one such map built in, for flight at Mach 0.9. The reference aft-end drag is defined as the drag obtained for a fully expanded nozzle with exit area equal to A_{11}. Therefore, by taking an abscissa value of unity in Fig. 6 and with A_9 equal to A_{9max}, the reference aft-end drag coefficient is obtained for the given flight conditions, which is subtracted from the drag coefficient evaluated

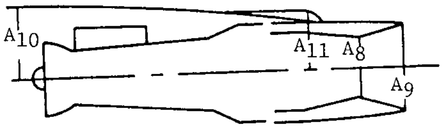


Fig. 5 Afterbody Nomenclature Adopted

at any power setting to give the change in aft-end drag coefficient.

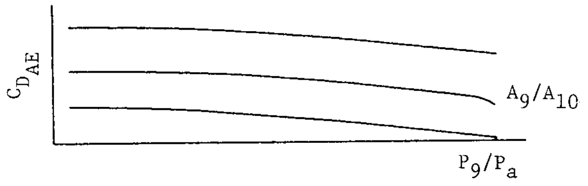


Fig. 6 Aft-End Performance Map

There is no provision for the user to input his own inlet and aft-end drag maps. However, the program can be slightly modified without much difficulty to include this capability.

Graphical Output

A graphics package written using the UNIRAS library routines is included in VATEMP and this gives the user great flexibility in the manner in which he can graphically present the off-design performance of his engines. Any two of twenty variables can be plotted against each other using the plotting codes.

The performances of a maximum of six engines or an engine with up to a maximum of six different intake operating conditions can be compared in one graph, and a maximum of six different graphs can be plotted on a page, in "portrait" or "landscape" format. Each graph is automatically labelled and titled.

PROGRAM CAPABILITIES

The program was used to study the performance of certain engine types with unconventional controls. The results of some of the investigations were reported by Roy-Aikins (1988a and 1990). The results of two examples are presented here.

Fig. 7 compares the performance of a single spool free turbine turboshaft for helicopter application for two different types of control, at hovering flight at sea level. In one case, a variable geometry compressor was used to control engine airflow while power was modulated at constant rotational speed to improve engine response rates. The other was a conventional control where both airflow and speed decreased with decreasing power.

Though it was possible to use a variable geometry compressor to modulate power at constant rotational speed down to very low power settings (minimum of 28 percent power), it was decided to revert to conventional control at about 60 percent power as the compressor operated at unacceptable levels of both efficiency and surge margin at low powers, which resulted in very high TITs and, hence, very high sfc's. As seen in Fig. 7, both sfc and TIT for the rapid response engine compare well with those for the conventional engine down to a power setting of about 70 percent, after which a recourse to conventional control was sought, for the reasons mentioned above.

The propelling nozzle of the variable geometry engine could have been closed gradually, in addition, as thrust was attenuated at constant speed. However, the gradient of nozzle area change with power was found to be low even though acceptable sfc's were obtained. Therefore, this method of power control was excluded to avoid having a complex control system.

It was shown by Roy-Aikins (1988a) that variable geometry could be used in both turbines of the rapid response engine to obtain idle power at an sfc level compared to that of the conventional engine. Such an engine will, however, be unreliable.

The performance of a twin-spool mixing turbofan controlled such that fan and compressor operating points are held fixed as thrust is modulated is presented in Fig. 8. For the reasons discussed by Roy-Aikins (1988a), turbofans are not suitable for this type of control as do turbojets, simply because for the unmixed flow turbofan only the "hot" thrust can be modulated, whereas the mixed flow engine requires a means of reducing the pressure in the bypass flow to ensure mixing of the bypass and core streams, which becomes more difficult as altitude increases and as thrust decreases. However, a mixing turbofan is considered here due to the many variable area components involved.

As the engine is throttled back, the static pressure in the mixer decreases; this results in an increase in mixer cold stream Mach number since the total pressure in the bypass stream remains constant as the fan operating point remains fixed. Therefore, the cold stream area in the mixer reduces as thrust decreases, and since mixing is assumed to occur at constant mixer total area, the hot stream area increases proportionaly. The HP turbine area decreases with a reduction in thrust (TIT) to maintain choked throat conditions, since both gas mass flow and total pressure are constant at HP turbine inlet. The inter-turbine total pressure, however, decreases with a reduction in thrust at a faster rate than does the corresponding total temperature, with the result that the LP turbine area increases as thrust decreases.

Since each turbine does a fixed amount of work continuously at a reduced inlet temperature as thrust decreases, the pressure ratio across each turbine increases as thrust decreases; therefore, the pressure ratio across the nozzle decreases with reduction in thrust for fixed pressure ratio across the expansion system. A bigger nozzle throat area is, therefore, required to reduce the back pressure to permit the turbines to operate at higher pressure ratios as thrust decreases. Meanwhile, the nozzle exit area increases to attain full expansion as thrust is reduced.

As is clearly seen in the figure, both the uninstalled and installed sfc's are lower for the varibale geometry engine than the corresponding values for the fixed geometry engine. As was expected, the installation losses cause the installed performance of each engine to be poorer than the corresponding uninstalled performance.

CONCLUSION

VATEMP, a component-matching thermodynamic analysis computer program which uses component performance maps to evaluate the gas conditions at the various engine stations of a gas turbine, is a powerful and flexible analytical tool for the evaluation of the steady-state uninstalled and installed performance of arbitrary gas turbines with variable and invariable

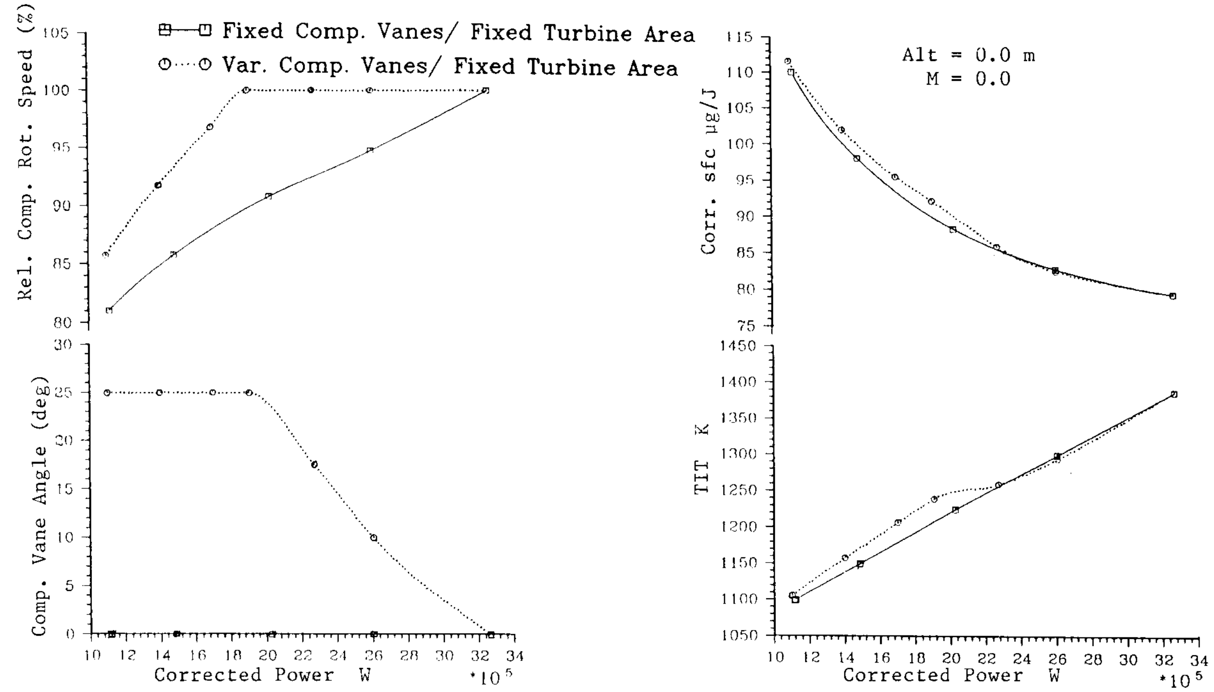


Fig. 7 Performance of a Rapid Response Free Turbine Engine

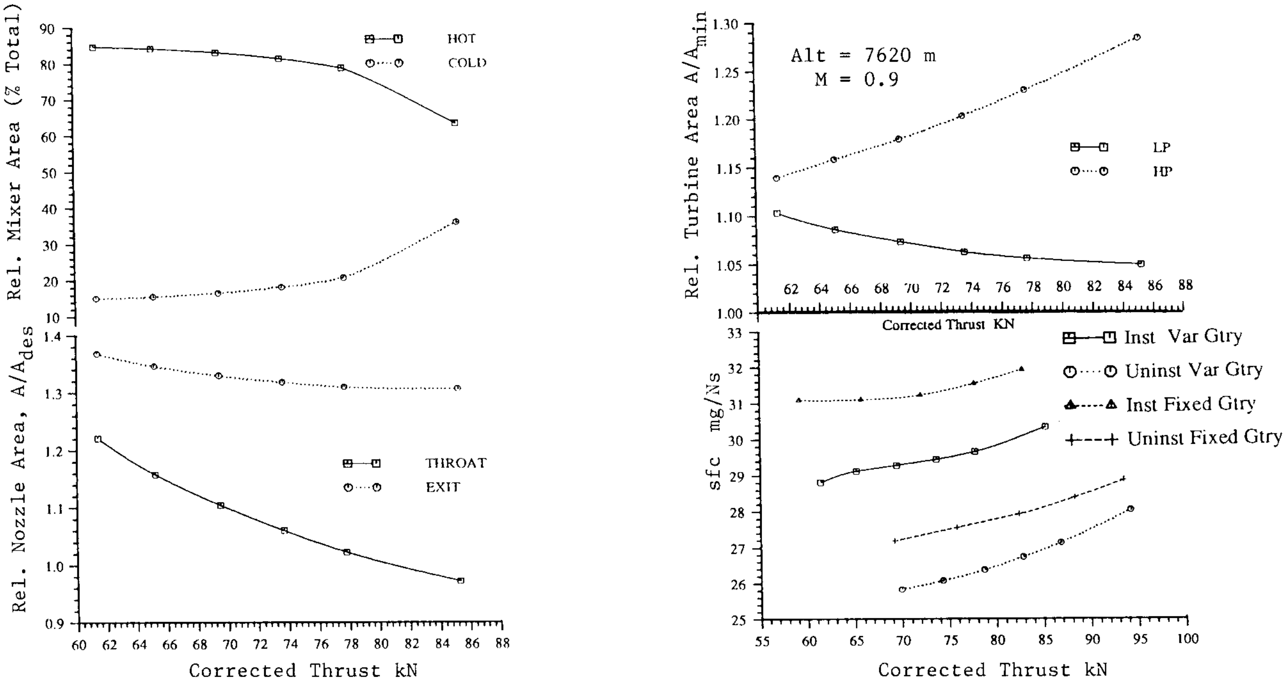


Fig. 8 Variable Geometry Turbofan Performance

geometry gas path components. The geometry of nearly all components can be scheduled or allowed to vary to satisfy the matching constraints. Its advanced graphics capability is an attractive feature which reduces the time for off-design cycle analyses.

Results obtained from the program compares satisfactorily with published results and investigation of some of the off-design problems encountered by present day engines indicates that there may be widespread use of variable geometry components in future gas turbines as significant improvements in engine performance can be obtained by the use of such components.

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