Considerations for the Use of Variable Geometry in Gas Turbines

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ABSTRACT

The loss of performance of a gas turbine at off-design is primarily due to the rapid drop of the major cycle performance variables with decrease in output, and this may be aggravated by poor component performance. Postulated propulsion demands require that future engines attain performances much more advanced than those of the present day. The specific nature of the improvement in performance will depend on engine duty, but it is expected that the improvement will include higher power loadings and better response, in addition to better fuel burn characteristics.

Innovative design and advanced materials and structures will play key roles in bringing about a revolution in gas turbine technology, but these will have to be accompanied by novel control methods which can influence the position of the engine operating point. The latter may require the use of variable geometry in one or more gas path components to improve the internal matching of a component or to re-match the engine cycle such that the component operating point and/or the primary cycle performance variables are re-optimized or controlled with changing operating conditions. This paper examines how variable geometry could be used to improve the off-design performance of gas turbines.

NOMENCLATURE

A turbine inlet area, m²
CN corrected speed (N/√θ) relative to design
F thrust, N
FPR fan pressure ratio
HP high pressure
I rotor inertia, kg m²
k constant
LP low pressure
M flight Mach number
N rotor speed, rev min⁻¹
P excess power, Watts
Q calorific value of fuel, 43100 kJ kg⁻¹
r compressor pressure ratio

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INTRODUCTION

The gas turbine is put to use in quite a wide variety of applications to satisfy the propulsion requirements of many mechanical systems, in the air, at sea, and on land. Regardless of the final form of the output, the physics of operation of the gas turbine as dictated by the requirements of matching of the gas path components may cause a loss of engine performance when operating away from the design point, that is at off-design, which may result in reduced economy and/or safety of operation.

Loss of performance at off-design is primarily due to the rapid drop of the major cycle performance variables with decrease in power. There is also the possibility that one or more components may be operating with efficiency markedly reduced from the maximum, resulting in a deterioration in component
performance. Therefore, if the engine can be operated or controlled so that component operating points fall in regions of the performance maps where efficiency is high or (at least) acceptable, or the lapse rate of the major cycle performance variables with decrease in power is reduced, then an improvement in overall performance can be expected.

The factors which are of primary importance when the off-design performance of a gas turbine is being investigated include the specific fuel consumption (sfc), the maximum power capability, and response. Both sfc and maximum power are related to economy of operation, while response can be viewed as the very control conditions. Depending on the application, one or more of these factors may be more important than the others, and it may be necessary to obtain acceptable levels for them at all operating conditions, at the expense of the others.

A performance variable which is of the utmost importance to gas turbines classified as jet engines is the bypass ratio, \( u \). This does not strongly impact the matching conditions at off-design, but rather it determines the overall level of performance which the engine can obtain. The propulsion requirements demanded by aircraft at supersonic flight conditions conflict with those for subsonic flight, and since aircraft capable of supersonic flight also fly at subsonic speeds, the design of supersonic propulsion systems is normally compromised so that the engine does not perform poorly in any one flight leg. A suitable engine for such applications would be one whose cycle can be changed or varied with operating conditions to give characteristics or a performance that is well tailored to the propulsion demands in any flight leg.

With regards to installation losses which are associated with aircraft gas turbine inlet and exhaust systems, it is known that these mean that it is not always possible to predict these losses more accurately but also to reduce them substantially, if future high performance aircraft are to attain their planned performance goals fully.

The internal matching of a gas turbine component or the relative matching of the components can be altered by varying the geometry of the appropriate components passively or actively, respectively. This has the effect of changing flow areas, thereby altering the flow-temperature-pressure relationship at some engine stations. It is envisaged that future gas turbines will employ variable geometry components extensively in an attempt to overcome some of the problems encountered by present day engines at off-design. Ray-Aikins (1988) developed a computer program called VATEMP which is capable of simulating the steady-state off-design performance of arbitrary gas turbines with or without variable geometry components. This was used to investigate the performance of engines incorporating such components in the light of some of the problems encountered at off-design, as mentioned above.

This paper discusses briefly some of these problems for both shaft power and jet engine cycles. Results obtained with the VATEMP program are also presented to show potential performance gains of cycles employing variable geometry\(^2\) components.

**SPECIFIC FUEL CONSUMPTION**

**Shaft Power Cycles**

The sfc of a shaft power cycle is related to the thermal efficiency \( \eta_{th} \) by the expression

\[
sfc = \frac{1}{\eta_{th}}
\]

where \( \eta_{th} \) is a function of some cycle performance variables, component efficiencies, and the type of working fluid. For a single shaft turboshaft cycle of the simple or regenerative type, the general relation,

\[
\eta_{th} = f(U, T, \gamma_c, \gamma_t, \gamma_p, \gamma_e)
\]

can be written. sfc can be plotted against pressure ratio for a series of values of the ratio \( U \) of turbine inlet temperature to engine inlet temperature, keeping component efficiencies and specific heats fixed, as shown in Figure 1. The curves clearly show that for the simple cycle, sfc is dependent on both turbine inlet temperature, TIT, and compressor pressure ratio, whereas for the regenerative cycle, sfc strongly depends on TIT while the effect of pressure ratio may be insignificant, if TIT is high enough. For a real cycle, both pressure ratio and TIT decrease as power decreases; component efficiencies may also change. The net effect is that there is a gradual rise of sfc as power is reduced. Curves for real cycles with component efficiencies at the design point as those given in Figure 1 are shown dashed in the figure.

![Fig. 1 Typical sfc curves for turboshfts](http://appliedmechanics.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1990/79085/V005T15A005/2400106/v005t15a005-90-gt-271.pdf)

The ideal way of operating an engine is to hold both TIT and compressor pressure ratio constant as power changes. This is possible but will require a complex control system which may introduce problems. However, improved performance can be obtained if either TIT or pressure ratio is held fixed at the design value as power is reduced. An examination of the non-dimensional flow at turbine inlet shows that TIT or pressure can be maintained constant as power varies, if the area at turbine inlet is made to vary. The question arises which of constant pressure ratio and constant TIT operation gives a better improvement in performance; alternatively, would it be better to schedule turbine areas so that both TIT and compressor pressure ratio vary but are held at higher levels than those for a conventional fixed geometry engine? Results will be shown later on in an attempt to answer this question.

**The Jet Engine Cycle**

Unlike the shaft power cycle, the sfc of a jet engine cycle is inversely proportional to the product of the thermal and propulsive efficiencies, that is,

\[
sfc = \frac{1}{\eta_{th} \eta_p}
\]

For fixed flight conditions, as TIT is reduced to decrease power, \( \eta_{th} \) decreases whereas \( \eta_p \) increases, as illustrated in Figure 2. Therefore, one cannot say for

\(^2\) The term 'variable geometry' refers to variable area compressors, turbines, and exit nozzles.
sure whether sfc will increase or decrease as thrust changes; what is to be achieved is that the rate at which sfc increases with a change in thrust should be kept to a minimum. This implies that in general, both $n_{th}$ and $\eta_p$ should be held as high as possible at any given thrust level. A simple analysis for a single-spool turbojet (shown schematically in Fig. 3) for compatibility of flow and energy will throw some light on how this can be accomplished.

It was said earlier that both airflow and compressor pressure ratio should be maintained at the highest possible values at any thrust setting, if sfc is to be kept as low as possible. It is clearly seen from Eq. (6) that this is possible only if the turbine throat area is made to vary with TIT. It may not be desirable to maintain constancy of pressure ratio and airflow with changes in thrust, but there is scope for performance improvement by the use of a variable area turbine. A mass flow balance for the propelling nozzle shows that a variable area nozzle is also needed if the compressor operating point is to be held fixed as the engine is throttled.

The losses associated with the installation of an engine in the airframe principally stem from the reduction of airflow with a decrease in thrust. A higher airflow reduces inlet drag due to less spillage of the captured airflow and it also reduces aft-end drag as a larger nozzle exit area is required to pass a higher mass flow, resulting in a smaller aft-end base area. Therefore, maintaining maximum airflow is also beneficial from the point of view of installation effects.

**Maximum Power Capability**

The power developed by a gas turbine is related to the airflow swallowed and the maximum cycle temperature (commonly called TIT), so therefore the power is a maximum at the point where both airflow and TIT are highest. For any given operating conditions, the maximum power is limited by either TIT or rotor speed(s), or both. Active control re-matches the components to maintain constancy of pressure ratio and airflow and a choked turbine, whereas passive control affects the internal performance of the entire cycle, whereas passive control affects the internal performance of the component only.

**Power Limited by Spool Speed**

When the maximum power is limited by spool speed, power can be increased further by increasing TIT by either active or passive control of the cycle, or by both. Active control re-matches the components to affect the performance of the entire cycle, whereas passive control affects the internal performance of the component only.
A possible running line (AB) is also shown. The broken nominal vane settings is represented by the solid lines vane angles. A change of vane angle. In Fig. 5, the same characteristic is also shown, and once again, the solid lines are representative of that for the LP compressor of a twin-spool engine. The changes caused by cycle modification are those for the original characteristic at the nominal spool engine. The changes caused by cycle modification which can only be effected by active control. Therefore, one or more components at the "back" end of the engine need to have their area varied to accomplish this. A possible extension of the operating line is marked BD in Fig. 5. It may be necessary to use variable geometry in other compressors to accommodate the increase in airflow or to keep rotor speed within limits.

ENGINE RESPONSE

Prediction of the transient performance of gas turbines is a well established art. This exercise is quite valuable to development engineers as it provides an insight of the behaviour of an engine, and also helps control engineers in the development of a suitable control system which can drive the engine close to its limits safely. In general, engine response is considered from the point of view of engine handling and contingency operation, with more emphasis being put on the former. However, the quest for high performance gas turbines, especially those for military application, is causing performance engineers to approach the subject from a different viewpoint; as a result, response rate is being given more consideration nowadays.

Gas turbines generally operate in such a way that a change in gas generator rotor speed(s) is required to effect a power change. A common exception is found in applications for electrical power generation (to maintain constant frequency) where a single shaft turboshaft may be utilized. Due to the fact that the working fluid has a finite mass, and rotors have inertia, there is a time lag between fuel flow change and power change. There are cases where an instantaneous power change is desirable such as in emergencies and terrain contour flying; in such cases, power change with little or no speed change may be beneficial. Various methods have been proposed for increasing the response rates of gas turbines, and research in this area is being actively pursued.

If a single spool turboshaft is considered, engine response time is given by,

$$\Delta t = k I \int \frac{N}{P} \frac{M \Delta N}{P} \, \, \, (7)$$

When a variable geometry compressor is used to increase power, the working line is extended towards a higher mass flow and pressure ratio as temperature increases. This is shown in Fig. 4 where power is increased from point B on the nominal characteristic by opening the vanes to a position (point C) where maximum TIT is reached, provided that an adequate surge margin is maintained throughout.

With the deployment of a nozzle, the situation is much different. If it is assumed that the low pressure (LP) rotor has reached maximum speed, then as temperature increases, the operating point on the LP compressor map will remain on a constant speed line.

In this example, it is assumed that the operating point on the compressor map does not change as power is increased, that is point B on Fig. 5 remains fixed. The constant TIT lines can be envisaged as rotating anti-clockwise as power is increased. In general, the component whose geometry is varied is either the fan nozzle, or the nozzle immediately downstream of the relevant driving turbine. A combination of these may be appropriate. If maximum power is limited by either intermediate or high pressure (HP) rotor speed, the operating line may not necessarily lie on a constant speed line as power increases, due to the fact that a re-matching of the components may cause the temperature at inlet to the compressor to change.

Maximum Power Limited by TIT

When maximum power is limited by TIT, spool speeds should increase to increase airflow to produce more power. On a compressor characteristic, the operating point moves along a line of constant relative TIT as power is increased further. Since the operating line is controlled, a re-matching of the component occurs which can only be effected by active control. Therefore, one or more components at the "back" end of the engine need to have their area varied to accomplish this. A possible extension of the operating line is marked BD in Fig. 5. It may be necessary to use variable geometry in other compressors to accommodate the increase in airflow or to keep rotor speed within limits.

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3 Unless otherwise specified, 'nozzles' refers to turbines and propelling nozzles.
Therefore, for minimum response time, the speed range over which a power change occurs should be a minimum, and the excess power at each transient speed, a maximum. The former can be accomplished by the use of variable geometry, and the latter, by improved fuel scheduling which can be brought about by a variable nozzle.

To date, variable geometry in compressors is chiefly used for surge control. Its potential for controlling the flow through a compressor has been realized and it is now a "hot" contender for use in rapid response engines. Variable vanes make it possible to control airflow at constant rotor speed, resulting in a significant improvement in engine response rates. If it is undesirable to operate the engine at constant speed, a variable geometry compressor can still be used to reduce the speed range over which a given power change occurs. Since the operating line hardly changes when variable geometry in a compressor is deployed, the speed change during an increase of power can be reduced, for example, by raising the initial speed and lowering the final speed on the steady-state operating line. This is illustrated in Fig. 6 (line AB) where positive preswirl (vanes closed) is used at the lower speed end, and negative preswirl (vanes open), at the upper speed end. Note also the changes in surge margin. As was discussed by MacIsaac and Saravanamuttoo (1975), the choice depends on the type of engine and on the number of spools.

Variable geometry in a turbine or propelling nozzle can also be used to reduce speed change. As was discussed by MacIsaac and Saravanamuttoo (1975), the choice depends on the type of engine and on the number of spools.

The rate at which excess fuel can be added is limited by compressor surge and materials (temperature), and it may depend also on the rate at which airflow can be increased. Not much can be done about temperature limitation except that overtemperature can be used to increase the amount of fuel supplied, which shortens blade life. Variable geometry turbines and nozzles can be used also to increase the excess torque on a rotor to provide faster acceleration. An improvement arises from a redistribution of the pressure ratio across the turbines, or turbines and nozzle, to provide more power to the driving turbine, or from lowering the operating line on the driven compressor thereby increasing the available surge margin. As with the control of speed change, the choice of whether a turbine and/or nozzle is used depends on the type of engine and on the number of spools.

No results will be presented here to show that variable geometry improves engine response rates. Work that was carried out at Cranfield (under contract) on a single spool free turbine engine for military helicopter application has, however, verified this. The findings of an investigation on the use of variable geometry to improve engine response rates were reported by MacIsaac and Saravanamuttoo (1975).

SUPersonic PROPULSION

The turbojet and the turbofan are the two types of jet engine used for aircraft propulsion. The latter falls into two categories, with mixed and with unmixed flows. The turbojet, with its high operability, shortens blade life. Variable geometry turbines and nozzles can be used also to increase the excess torque. As was discussed by MacIsaac and Saravanamuttoo (1975), the choice depends on the type of engine and on the number of spools.

To date, both the turbofan and the turbojet are used to meet the conflicting propulsion requirements of supersonic flight and economy of operation of commercial transports, and range and survivability of fighters have greatly led to the concept of "supercruise", and the turbofan may well be chosen to meet these diverse propulsion requirements. Bypass ratio is one of the important cycle variables of the turbofan and its choice at the design point greatly determines the level of performance attained by an engine. The duty to which an engine is put dictates a particular level of \( \mu \) for optimum performance. For given design-point values of the primary cycle performance variables, higher levels of thrust require higher levels of nozzle pressure ratio which in turn can be obtained from having higher fan pressure ratios, FPR. If one considers a mixing turbofan, the requirement of confluence in the mixer dictates that \( \mu \) decreases as FPR goes up, as shown in Fig. 7. Therefore, to obtain the high specific thrusts required for supersonic propulsion, medium to low levels of \( \mu \) should be used; this is supported by fuel burn considerations as can be seen in Fig. 6. However, the lower \( \mu \) is the more the engine is to be throttled back to produce the required subsonic cruise thrusts. Therefore, subsonic sfc increases with reduction in \( \mu \) due to increased losses, as illustrated in Fig. 8.

From engine weight considerations, for a given airflow, core power (and hence size) goes down as \( \mu \) goes up, and since the core is the heavier part of the engine, engine weight decreases with an increase in \( \mu \), see Fig. 8. Jet noise levels can also be related to specific thrust, and since a low specific thrust is required to keep jet noise down, high bypass ratios are desirable. So in general, a high bypass ratio is
required for good performance of a turbofan with the exception of supersonic cruise engines. This calls for a compromise in the choice of \( \mu \) when the cycle performance variables are being selected for engines capable of supersonic propulsion. It is logical to say that if such engines are to give much more advanced performance in the future, then a cycle whose bypass ratio can be varied with flight conditions will be most suitable. Nowadays, such variable cycle engines are being given intensive consideration in the gas turbine propulsion world.

### PROGRAM RESULTS

The following examples are intended to illustrate some possible uses of variable geometry components in gas turbines. Optimization of the cycle for a particular duty was not considered and only extreme cases were taken into account. Therefore, no attempt was made to use variable geometry in other components, if it can be avoided. It should be borne in mind that it may not be possible to limit variable geometry to the appropriate component only in order to accomplish a given result. For example, as fan vanes are opened to increase TIT at constant fan speed, compressor speed increases; it may be necessary to use variable geometry in the compressor as well to prevent overspeeding of the HP rotor before maximum TIT is reached.

#### sfc Improvement

**Shaft Power Cycles.** Variable geometry was used in the appropriate turbine to keep either TIT or pressure ratio fixed at the design value as the power of a single spool free turbine engine was modulated. Both the simple and the regenerative types of cycle were considered, both being optimized for maximum specific power at the same design power.

The performance characteristics obtained with the constant pressure ratio control are quite dissimilar to those obtained with the constant TIT control, and the trends in performance for both the simple and regenerative types of cycle are similar in all respects, with the exception of the sfc curves. The performance curves shown in Fig. 9 are those for the regenerative cycle in which the performance obtained with both constant TIT and constant pressure ratio operation is compared with that obtained for the conventional control where speed, pressure ratio and TIT are all allowed to vary with power. Variable geometry was used in the gas generator turbine to effect constant pressure ratio operation, whereas for constant TIT operation a variable area power turbine was employed. The appropriate turbine area decreased as power was reduced. When the minimum area or surge margin constraint was encountered, turbine area was held fixed and the engine was in a conventional manner as power was reduced further. Compared with the conventional engine, the other two engines operate at a higher pressure ratio at each speed. The sfc curves show that for the simple cycle, both the constant pressure ratio and the constant TIT engines give an improvement in performance over the conventional engine at all power settings, the constant pressure ratio engine being more efficient. For the regenerative cycle, holding the pressure ratio fixed results in a poorer performance when compared with the conventional operation due to the high compressor delivery temperatures obtained.

It can be concluded that the biggest improvement in sfc occurs for the regenerative cycle controlled so that TIT remains constant as power is modulated. The response of such an engine is, however, sluggish.

Roy-Aikins (1988) discusses in detail the physical explanation of the causes for the difference in performance of the two unconventional types of control.

#### Jet Engine Cycles

The compressor operating points of a two-spool turbojet for fighter application were held fixed as thrust was modulated by using variable nozzles, right down to a thrust setting at which a constraint was encountered (about 50 kN).

Thereafter, the engine was controlled in a conventional manner as thrust was reduced further. The performance of the engine thus controlled is compared in Fig. 10 with that of the conventional engine.

An examination of the HP turbine flow function shows that when the engine is in the variable geometry mode, turbine area decreases as temperature decreases, whereas matching analysis of two turbines in series shows that both the LP turbine and exit nozzle areas increase with a reduction in thrust, as shown in Fig. 10. There is an improvement in both the installed and uninstalled sfc's over those for the conventional engine. The higher airflow reduces spillage drag whilst a larger nozzle exit area reduces aft-end losses. A bigger saving in sfc was observed at supersonic flight Mach numbers, at all thrust settings. As discussed by Roy-Aikins (1988), turbofans are not suitable for this type of operation chiefly because only the "hot" thrust of the unmixed flow type can be modulated and the TIT conditions of the gas in the bypass stream remains almost constant if duct heating is not employed, whereas the requirement of mixing the bypass and core streams of the mixed flow type dictates that some means of reducing the pressure in the bypass duct is required at certain operating conditions and power settings.

#### Extended Power

The case where maximum power is limited by rotor speed is considered here, for a twin-spool mixed flow turbofan. Fig. 11 shows some performance curves for the
variable geometry in any other component. An increase in variable geometry was used to change component loading and spool speed, in another, should be appreciated. A variable pass ratio of 0.26. At subsonic flight conditions, the condition was reached first. The increase in thrust amounted to 7 percent as noted in Fig. 12. A variable area LP turbine could be used in addition to hold fan operating point fixed, if this is desired. The difficulty of designing a control system which can control the appropriate geometries to increase thrust further when it is limited by TIT in one case, and spool speed, in another, should be appreciated. The Variable Bypass Ratio Cycle

A low bypass ratio mixed flow turbofan was considered in this case. The engine was designed for cruise at an altitude of 9144 m at Mach 0.9, with a bypass ratio of 0.26. At subsonic flight conditions, the components were all assumed to be at their nominal settings, whilst at supersonic flight conditions variable geometry was used to change component loading so that a bypass ratio change was effected. The extreme case is considered here, which is that of a bypass ratio of zero; that is, the engine is assumed to be operating as a turbojet at the supersonic flight conditions considered.

In general, variable geometry is required in the mixer to facilitate matching of the components in order that the required level of $\beta$ be attained at any given operating conditions. The compressor also requires variable geometry for proper flow matching with the fan, whereas the nozzle and LP turbine require variable geometry to control the loading on the LP and HP turbines respectively, and hence, fan and compressor work. Variable geometry is required in the HP turbine to control HP rotor speed. The fan may incorporate variable geometry to control fan surge margin, and it may be necessary for the bypass splitter to have variable geometry in order to control the Mach number of the flows passing through.

The changes required in some performance variables in switching from the turbofan at the maximum dry thrust conditions (limited by TIT) to the same conditions for the turbojet are shown in Fig. 13. The maximum dry thrust of the turbojet was obtained at LP spool speed and TIT limits. The maximum afterburning thrust was obtained at reheat temperature of 360 K less than that required by the turbofan to produce the same thrust. With sufficient variable geometry, the variable cycle engine could produce the maximum afterburning thrust of the turbofan, at dry power and at a reduced bypass ratio, with significant savings in fuel consumption. At a typical cruise power setting, the saving in sfc amounted to 16 percent. Steinmetz and Hines (1987) discuss how variable geometry is used in
various flight phases to control the bypass ratio of a variable cycle engine for supersonic propulsion.

CONCLUSION
Variable geometry can be used in key components to improve the off-design performance of gas turbines, significantly. The improvements stem from the fact that the internal performance of a component can be improved or that the cycle can be re-matched to give favourable operating points on the component performance maps, with the result that the major cycle performance variables can be controlled or re-optimized as engine operating conditions change.

The improvement in performance may occur as a saving in fuel consumption, an increase in output, better handling qualities, or a combination of these, but the magnitude of performance improvement will be dictated strongly by engine reliability and safety factors.

REFERENCES