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EXPERIMENTS IN ACTIVE CONTROL OF STALL ON AN AEROENGINE GAS TURBINE

Christopher Freeman,
Rolls-Royce plc,
Derby, England

Alexander G Wilson
Rolls-Royce plc,
Derby, England

Ivor J Day
Whittle Laboratory,
Cambridge University,
Cambridge, England

Malcolm A Swinbanks
MAS Research Ltd,
8 Pentlands Court,
Pentlands Close,
Cambridge, England

ABSTRACT

This paper describes work carried out between 1989 and 1994 to investigate the application of 'Active Stall Control' to a Rolls-Royce Viper turbojet. The results demonstrate that stall control is feasible and can increase the stable operating range by up to 25% of pressure rise. Stall disturbances were detected using rings of high response pressure transducers positioned at different axial planes along the compressor, and processed using a PC-based data acquisition and control system. Actuation was provided by six hydraulically operated sleeve valves positioned to recirculate air over all or part of the compressor.

Stall was artificially induced using combinations of inbleed into the combustor outer casing, fuel spiking, hot gas ingestion and inlet pressure spoiling, thus replicating many of the transient conditions commonly observed to make a compressor prone to stall. Results are compared from a number of stall control strategies including those demonstrated at low speed by Paduano et al [1993] and Day [1993]. Best results were obtained with detection of non-axisymmetric disturbances coupled with axisymmetric control action. A control system of this type is demonstrated to be capable of extending the stable engine operating range at all speeds and with each method of inducing stall.

INTRODUCTION

Adequate surge margin is a primary requirement of every aeroengine compressor design. Conventional methods of ensuring sufficient margin (increasing blade numbers, variable guide vanes, handling bleed) all carry implicit penalties in terms of compressor weight, cost, complexity and/or efficiency. The search for an alternative means of achieving sufficient margin is as old as the gas turbine. Condition monitoring and subsequent bleed valve opening was studied in the 1960's. Stall cell triggered blowing [Ludwig and Nenni, 1978], and feedback control of surge in centrifugal compressors [Ffowcs Williams and Huang, 1989] were examined in the 1970's and 1980's. The most important advance since the 1960's has been the advent of microprocessors, which enable many detectors to be monitored simultaneously and rapid actuator movements to be accurately controlled. In the early 1990's control of rotating stall has been theoretically examined and demonstrated on low speed compressors by Paduano et al [1993] and by Day [1993]. Over the last decade many studies have been made too of stall inception in axial flow compressors at low and high speed.

The objective of the work described in this paper was to apply active stall control directly to an aeroengine. The intention was not to produce a flightworthy active control system, but rather to explore what gains could be achieved with current technology, what new technology might be needed in the future, and what the potential benefits might be.

Aeroengines in service experience a number of conditions that can make them prone to stall. These can be categorised as follows;

1. **Raised Working Line.** The working line can be raised by throttle transients, non-equilibrium clearance changes, non-equilibrium heat transfer and unsteady inlet flow. These are all transient conditions and typically last for a few seconds. Rubs, erosion, corrosion, foreign object damage, and bill of material damage also raise the working line and are irreversible without a shop visit.
2. **Lowered Surge Line.** The Surge Line can be lowered transiently by inlet distortion, non-equilibrium clearance changes and unsteady gas ingestion. Irreversible changes are produced by shaft out of balance, foreign object damage, bill of material damage and rubs.

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Any successful stall control system has to be capable nf dealing with short duration movements in both the working line and the stall line: monitoring the working line alone is not sufficient. Similarly any experimental investigation nf active contrnl techniques must allow both types of surge margin deterioration to be investigated.

EQUIPMENT

The Viper Engine

The VIPER was originally designed in the late 1940's as an expendable engine for unmanned air vehicles. Since that time it has been progressively developed and uprated, and is now used on a number of aircraft types. The research vehicle has an 8 stage axial flow compressor, a single stage turbine, an annular vaporiser combustor and a single shaft with 3 bearings. The overall design pressure ratio is 5.25, with a mass flow of 23kg/s and a turbine entry temperature of 1200K. Early designs had a 7 stage compressor. Later versions were upflowed with a '0' stage; the stages are therefore numbered from 0 to 7. The compressor has fixed inlet guide vanes and a stage 4 bleed through the stator outlet platforms into a bleed manifold. This is used for starting and low speed handling. At exit from the compressor there is a 2 row outlet guide vane arrangement and a diffuser split into 6 segments by the centre bearing support structure. For these tests the fuel flow rate was controlled manually. The VIPER was chosen as it is both simple and robust, whilst sharing many of the aerodynamic characteristics of more complex engines. The particular engine used for the experiments is an old mark, being time-expired after several thousand hours of flight.

The engine is shown in figure 1, with the stall control equipment fitted.

Control Bleed Recirculation

The actuation system adopted for most of the experiments described in this paper was bleed air recirculation. High pressure air was taken from a downstream position and reinjected through the compressor casing. The control mechanism thus had the combined effect of upstream injected flow such as used by Day [1993] and downstream bleed-off. The recirculated air was ducted forward through six pipes positinned around the annulus. These pipes were not symmetrically spaced around the engine because of the inevitable complexity of a real engine geometry (fig 1).

The axial position at which control actinn is required can move with engine speed as a result of changes in stage matching [Wilson and Freeman, 1994, Day and Freeman, 1994]. In order to accommodate this, a flexible arrangement was devised whereby air could be recirculated frnm the exit of the compressor to stage 4, from stage 4 to compressor inlet, or around the whole compressor from exit to inlet. Provision was thus made for 6 bleeds from stage 4 by segmenting the bleed manifnld, and fnr a similar number from the exit diffusers. Reinjection at inlet was through discrete adjustable area injectnr nozzles upstream of the inlet guide vanes, and at stage 4 through stator outer wall bleed holes. In each case nozzles were designed to inject the flow broadly parallel to the freestream directinn. The nozzles were sized such that the maximum flow rate was 8% of inlet flow when recirculating around the whnle compressor, and 5% of inlet flow when recirculating around the rear of the machine.

Control Valves

The flow through each of the recirculation pipes was independently controlled using an injector unit consisting of a sleeve valve inside a duct (fig 2) with an adjustable nozzle in the compressor casing. A form of flapper valve as the nozzle would have been more aerodynamically efficient, but was not used because of the risk of damage to the engine through uncontained valve failure. The sleeve valves were generally placed just upstream of the reinjection point, but could also be positioned at the far end of the recirculation duct.

Each of the sleeve valves was designed to pass a flow comparable to one sixth of the bleed required for starting and was capable of operation at up to 300Hz. For comparison rotating stall cell frequency at design engine speed is 106Hz, and so the valves were capable of tracking the second harmonic of a developing stall cell. Some loss of performance would be expected for a rapidly changing second harmnnic signal at high engine speeds, where the amplitude and phase changes can introduce higher frequencies into the signal. Higher frequency response could have been achieved by using larger numbers of smaller valves, but the complexity of the engine geometry made this impractical.

Alternative Actuation Techniques

Twn alternative actuation techniques were investigated in addition to bleed air recirculatinn. High response bleed-off from the rear of the compressor was effected using the same control valves as for the recirculated bleed. Fuel modulation was also investigated by coupling a high response fuel dipper unit into the manifold supply line.

Inducing Stall

The VIPER is a robust engine which does nnt stall under normal test conditinns. In order to carry nut the experiments described in this paper stall had to be artificially induced using combinatinns of inbleed iato the combustor outer casing, fuel spiking, hot gas ingestion and inlet pressure spoiling.

Combustor inbleed air was taken from a large external tank pressurised to 25 atmospheres by means of a standard commercial air compressor. Air was fed from the tank into a manifold around the engine and from there into the combustion chamber through 12 adjustable nozzles. The air flow was controlled by an on/off valve coupled with a pressure control valve which compensated for falling supply pressure as the tank emptied.

For the hot gas ingestion tests a mixture of exhaust gas and bleed air was taken from a small Palouste gas turbine. A flapper valve (fig 3) was used to direct the hot gas either into a sector of the inlet or into the detuner downstream of the VIPER engine. The Palouste had two speed settings, idle and max. Hot gas ingestion was therefore off, low or high with po settings in-between. For these tests the normal air meter was replaced by a metal inlet capable of withstanding the higher temperature inlet gas.

The normal fuel control system was replaced by a manual system which allowed fuel injectinn at a rate sufficient to stall the engine. Fuel spiking was only effective at low engine speeds as the fuel flow rate could not be increased above the normal maximum.

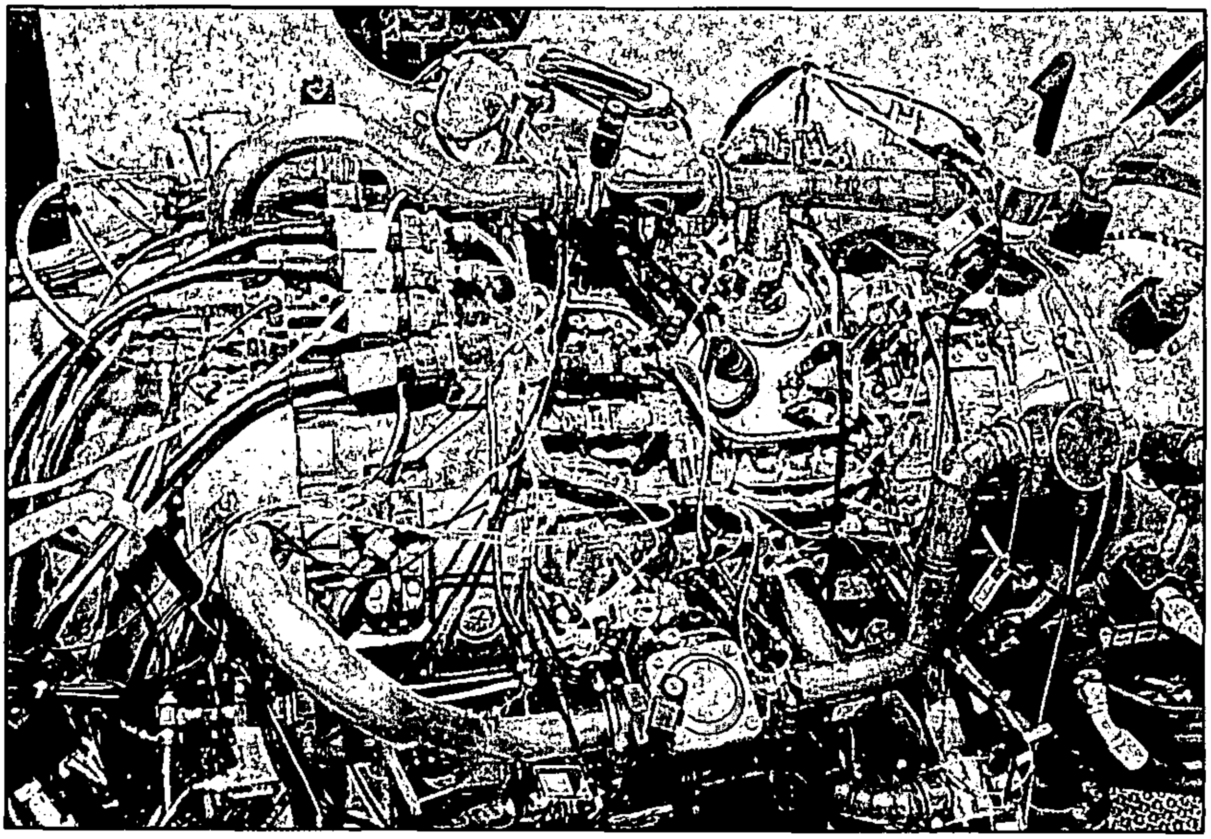

Fig. 1 Rolls-Royce VIPER Engine with Stall Control Equipment Fitted

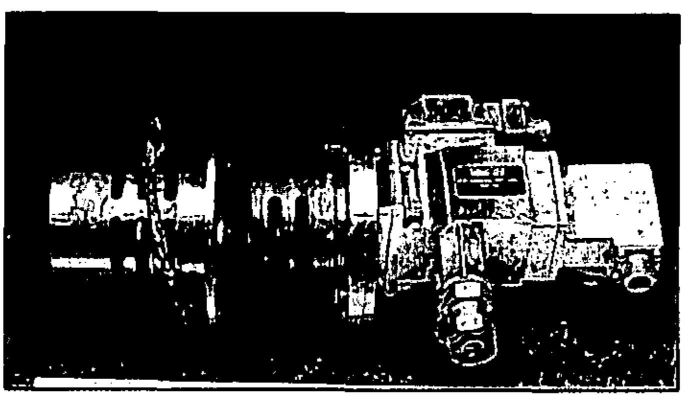

Fig. 2 Sleeve Valve Assembly

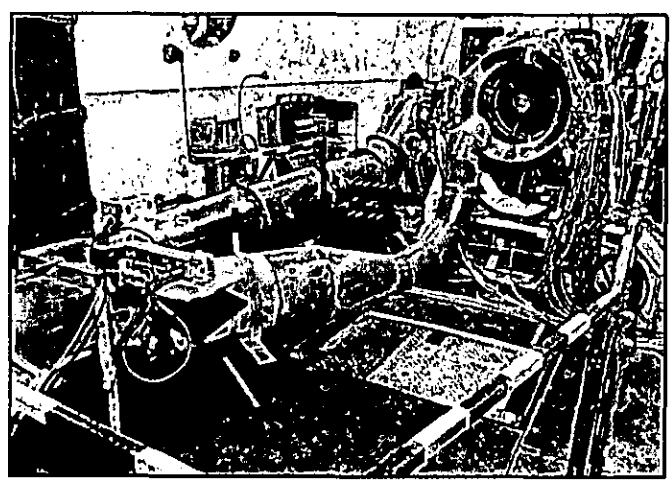

Fig. 3 Hot Gas Ingestion Unit (Flapper Valve on Far Left)

Instrumentation

High response Kulite pressure transducers were placed in rings of 5 or 6 around the compressor casing at stage 0 inlet, stage 2, stage 3, stage 4, stage 6 and stage 7 exit. A smaller number of transducers were placed at stages 1 and 5 where access is limited. The overall pressure ratio and mass flow were measured by lower response probes. Additional vibration monitors, compressor exit thermocouples and shaft speed detectors were also fitted. The pipes linking the bleed off and re-injection ports were equipped with mass flow meters.

Control Computer And Associated Hardware

A dedicated data acquisition and control system was constructed specifically for the work described in this paper. For the main series of tests a 32 input, 16 output digital signal processing unit was used based on a Motorola 96000 floating point-processor and associated mass-RAM storage. Data was sampled at 4kHz per channel and captured in the local high-speed RAM. This unit was interfaced to a 386/25 PC for subsequent data download and high-level data analysis. This enabled a wide range of real-time control algorithms to be implemented, while at the same time permitting the capture and storage of all input and output data during the course of a stall event. Immediately after an event had been captured, data was automatically downloaded to the host PC permitting on-line analysis of the results.

For some of the later tests, a second 48 channel data acquisition unit operating to similar conventions was interfaced to the first via a networked 486/66 PC. The units were externally synchronised to permit the accurate acquisition of up to 80 channels, but with the capability to perform more detailed higher-rate sampling on the second unit.

Control algorithms could be selected using appropriate menus to configure the operating set-up and parameters. The algorithm and configuration parameters were automatically stored along with the acquired data to give a comprehensive record of each test condition.

SYSTEM EVALUATION

Stall Inception Behaviour Without Control Action

The 'natural' stalling behaviour of a compressor (that is, the behaviour without any control action present) can have a large impact on the design of an effective control strategy. The VIPER engine compressor exhibits a wide variety of behaviour dependent on engine speed and the method used to induce stall.

The stall inception behaviour of the VIPER engine with fuel spiking and combustor inbleed has already been extensively analysed and modelled [Wilson and Freeman, 1994, Day and Freeman, 1994, Freeman and Wilson, 1993, Wilson, 1996], and is therefore only summarised here. Up to 75% speed (without the usual handling bleed) the compressor operates in permanent three or four cell 'tip stall' of stage 0. This stall is benign in the sense that it does not inhibit normal engine operation and disappears as the speed is increased. As the surge line is crossed one of the cells grows, leading to single cell 'locked-in' stall. Between 70% and 87% locked-in stall is initiated by a single short circumferential lengthscale 'spike' at the front of the machine. Between 90% and 100% speed stall/surge is initiated by a disturbance covering a third of the annulus downstream of stage 4, which stays in a fixed circumferential location for 3-4 rotor revolutions before starting to rotate. A 'modal' stall inception pattern has recently been detected in the VIPER engine, but only in the narrow speed range between 85% and 87% speed.

During these tests hot gas ingestion was also used to stall the engine, giving somewhat different stalling behaviour. The surge line with hot gas ingestion is compared to the clean inlet flow surge line in figure 4, and for this extreme level of distortion shows a complete loss of surge margin at high speed. At part speed some additional combustor inbleed in addition to the hot gas ingestion was required to induce stall. Pressure traces from the individual transducers at compressor inlet, stage 3 and exit are compared in figure 5 for a hot gas ingestion stall event and a combustor inbleed event, both at high speed. The pressure spikes at compressor inlet and stage 3 and corresponding troughs at compressor exit seen at around 0.07s in figure 5a represent short circumferential lengthscale stall cells that extend almost axially through the compressor. The cells quickly die out as they move around the annulus, until at around 0.17s a cell is produced that travels around the circumference and leads to surge.

At each axial position the red trace in figure 5 represents the transducer nearest top dead centre. The green trace represents the next position in the direction of rotor rotation, followed by the purple and light blue traces. The disturbances at around 0.07s in figure 5a are visible on the red trace at stage 3, but are most strongly pronounced on the green traces, indicating that the cells are strongest just after top dead centre, that is, out of phase with the circumferential position of the distortion, which was centred at 225 degrees from top dead centre in the direction of rotation. This phase difference can be compared with the distortion theory of Hynes and Greitzer [1987], which predicts that the maximum growth of stall disturbances will occur towards the end of the distorted region in the direction of rotor rotation.

The spike stall inception pattern observed with hot gas ingestion at high speed is thought to be due to the change in corrected speed. The peak inlet temperature in the distorted region is around 200 degrees centigrade, which drops the inlet corrected speed such that 98% mechanical speed becomes 75% corrected speed locally. Spikes were observed in the clean compressor at this speed. Inlet pressure distortion generated by a spoiler gauze gave similar part circumference stall cells, generated at random intervals, that eventually travel around the circumference followed by stall. It did not, however, produce spikes at high shaft speed as the corrected speed was unchanged.

Effect Of Steady State Recirculation

The surge line of the compressor was measured with steady state recirculation from compressor exit to inlet and from exit to stage 4, using combustor inbleed to induce stall. The results are compared in figure 6 with the datum surge line (no recirculation). The effect on the surge line of conventional exit bleed is also shown, plotted on a net flow (after bleed) basis. This is not a measured surge line, but is simply calculated from the datum performance neglecting movements in the steady state operating point due to efficiency changes. The quantity of bleed air taken (8%) is the same for the conventional exit bleed case as when recirculating bleed around the whole compressor.

At low speeds recirculating air from the rear of the compressor to the front removes the permanent rotating stall and there is a net gain in surge margin. The recirculation at high speed from compressor exit to stage 4 shows a sizeable gain in high speed pressure ratio, which is consistent with stage stacking studies carried out on the compressor.

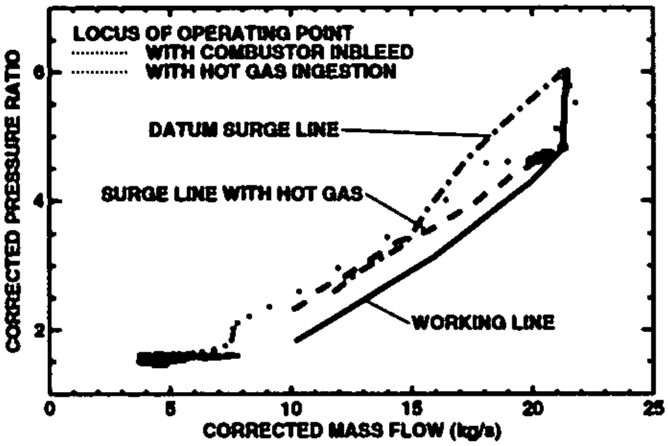

Fig. 4 Comparison of Hot Gas and Inbleed Surge Lines

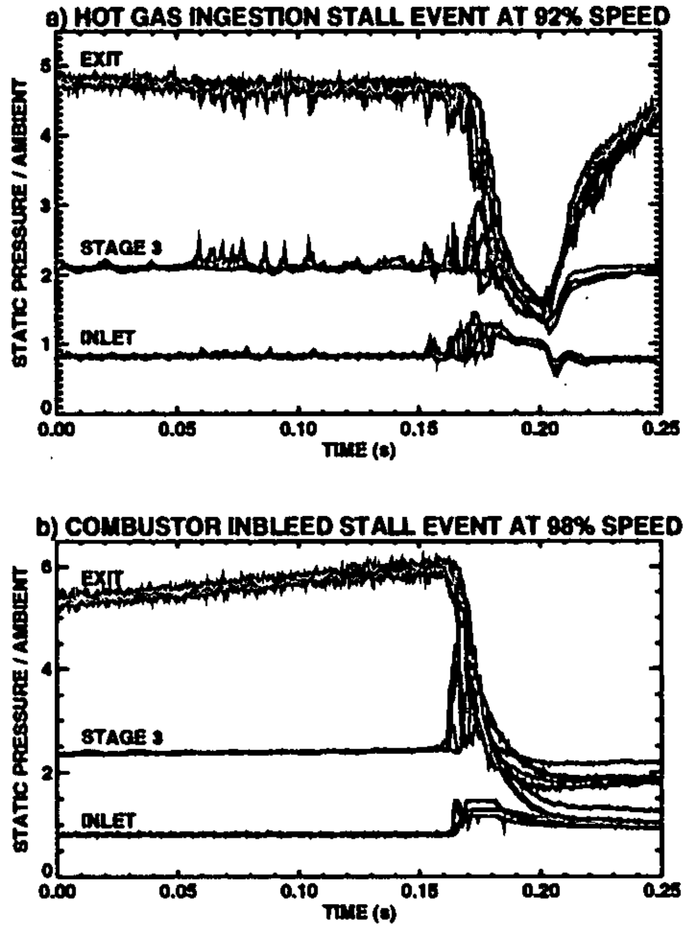

Fig. 5 Comparison of Two High Speed Stall Events

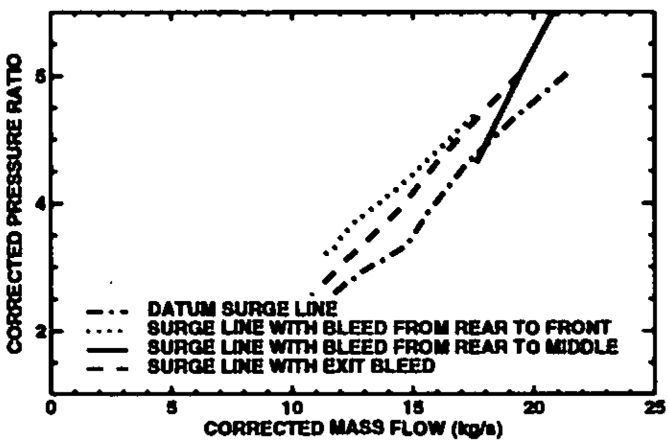

Fig. 6 Effect of Steady State Recirculated Bleed on the Surge Line Compared with the Effect of an Equivalent Amount of Exit Bleed

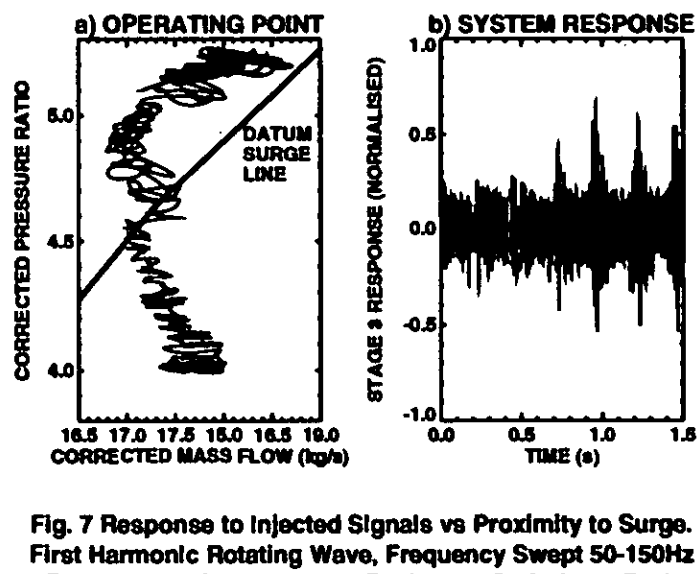

Fig. 7 Response to Injected Signals vs Proximity to Surge. First Harmonic Rotating Wave, Frequency Swept 50-150Hz Every 0.25s. Colours relate Equivalent Periods on Each Graph.

Figure 6 shows that over most of the speed range steady state gains in surge margin can be achieved by appropriate use of bleed air recirculation.

Valve Calibration

There are two elements of the performance of the valves requiring calibration; the mechanical movement in response to the electrical demand and the aerodynamic response to the mechanical movement. In order to determine the mechanical response of the valves a swept frequency signal to 300Hz was applied as the demand signal with the valve motion monitored by linear velocity displacement transducers (LVDTs). The response amplitude was flat up to 200Hz with a mean time lag of 3.1 milliseconds. Above 200Hz a reduced response was measured. In operation this was corrected by a frequency dependent gain in the control software. In practice the linearity of the actuation system was compromised above 200Hz by the aerodynamic response of the ducting.

The aerodynamic response to the movement of the valves was determined by applying a square wave demand signal to the valves and comparing the downstream nozzle drive pressure with the feed pressure and the valve opening. The duct/valve combination was observed to give 75 % pressure recovery when fully open and 37.5% when 30% open. The ducting, up to 1 metre from inlet to outlet, imposed a further lag of up to 3 milliseconds (depending on temperature) when recirculating around the whole machine and 1 millisecond when recirculating from compressor exit to stage 4. For a rotating wave input signal (that is, a sinusoidal input signal opening each valve in turn around the compressor) this time lag represents a phase shift between the effect of bleed-off at the rear of the recirculation region and mass flow injection at the front. The phase shift is 45 degrees for a typical cell speed when recirculating from the rear of the compressor to stage 4, and 150 degrees for a stall cell at the front with recirculation around the whole compressor. This phase shift proved significant during the stall control tests and is considered further below.

System Response And Actuator/Detector Interaction

Attempts were made to characterise the dynamic response of the system using frequency swept rotating input signals. Figure 7 shows the response of a stage 3 transducer to frequency sweeps from 50 to 150Hz with recirculation from compressor exit to stage 4 during a 90% speed combustor inbleed event, and shows that the response is dependent on the position of the operating point relative to the surge line; away from the surge line (marked in red on figure 7) the response is relatively small. As the pressure ratio rises (green) the response increases in amplitude. Above the datum surge line (blue - operation here is made possible by the steady state effect of the recirculated bleed air) the response remains at its maximum level. Further investigation showed that the response is also dependent on detector position (axial and circumferential), actuator position, shaft speed and the test waveform. In these circumstances a constant linear characterisation is not possible.

For the engine/control system configurations described in this paper the objective was to achieve feedforward control (simple conventional feedback control was not considered appropriate due to

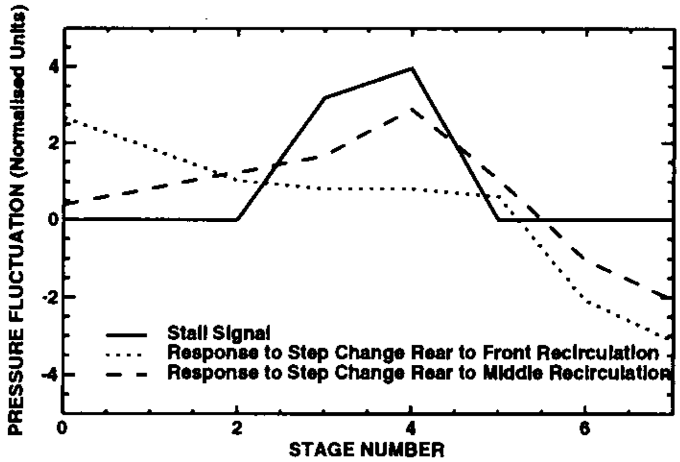

Fig. 8 Actuator/Detector Interaction. Stall Inception Signal at Stage 3 Compared with Response to Actuator Movement.

the extended, distributed nature of the system, the inherent system delays, and the non-linear operating characteristics). With control systems of the feedforward type the most tractable performance is achieved by minimising interactions between actuator and detector. A study was therefore undertaken to determine the best axial position for the detector signals, defined as the position showing the highest amplitude stall inception signals relative to the response to actuator movement. At high speed with recirculation from compressor exit to stage 4 the optimal position was found to be stage 3, as illustrated in figure 8. Note that the amplitude of the stall signal changes continuously over the inception period, and so the scaling for the line representing the stall signal is necessarily arbitrary. Below 86% speed stage 0 showed the highest amplitude stall inception signals, but also the greatest response to the actuators, and again stage 3 was found to be optimal. The control experiments presented in this paper were all performed using the stage 3 transducers for stall detection, although similar experiments were performed using the transducers at compressor inlet, stage 2 and stage 6.

Fuel Dipper And Exit Bleed Frequency Response

The response of the fuel dipper unit was tested using a square wave test signal. The fuel manifold pressure responded to the injected test signal with a delay of only 3ms. The combustor pressure, however, responded only slowly to the change in fuel pressure, with a further 40ms delay before it started to fall. This delay was due to the vaporiser dwell (air spray burners have much lower dwell times), and rendered fuel dipping ineffective as a stall control actuator mechanism.

The exit bleed-off system was also slow in dropping compressor delivery pressure. A time of 3ms was required for the valve opening and a further 7ms for an adequate pressure response. Again this was found to be too slow for stall control purposes. A relatively faster response would be expected in higher pressure ratio engines, which have in general a smaller air mass at compressor delivery pressure relative to the mass flow rate.

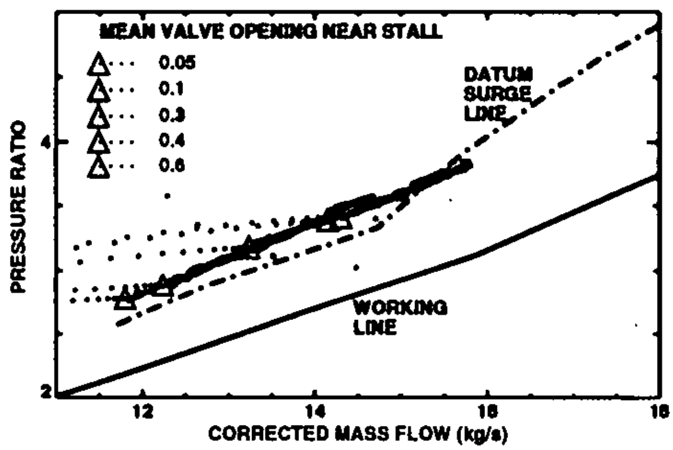

Fig. 9 Modal Control: Stall Point as a Function of Mean Valve Opening

The conclusions above relate to active control in the sense of eliminating or avoiding high amplitude rotating stall. Stall control experiments have been performed using exit bleed as an actuation device [Ludwig and Nenni, 1978, Eveker et al, 1995]. In these experiments significant improvements were recorded in the stalled behaviour of the compression system. In neither case, however, did the system prove sufficient (in general) to prevent the growth of rotating stall to significant amplitudes.

STALL CONTROL EXPERIMENTS

In the following sections three active control techniques are described which were applied to the VIPER engine; linear 'modal' control, threshold control with non-axisymmetric actuation ('threshold sequential'), and threshold control with axisymmetric actuation ('threshold simultaneous'). The threshold techniques proved most effective. In particular, the threshold simultaneous technique proved a robust method capable of extending the stable engine operating range at all speeds. A subsequent section describes the use of non-axisymmetric recirculated bleed to recover surge margin lost due to inlet distortion.

Linear Rotating Stall/Surge Modal Control

Paduano et al [1993] used a low speed compressor to demonstrate a linear 'modal' stall control system in which measured flow disturbances were decomposed into circumferential harmonics and fed to the actuators (in their case fast-moving inlet guide vanes) with a pre-set gain and phase adjustment. The compressor they used showed a 'modal' stall inception pattern, and a significant improvement in surge margin was recorded controlling only the first two harmonics of the disturbance. The VIPER engine, however, exhibits a short circumferential lengthscale ('spike') inception pattern [Day and Freeman, 1994], with no significant period of growing pre-stall modal waves [Wilson, 1996]. Even in the early stages of development where linear control might be appropriate the waveform of these short lengthscale disturbances could not be matched by the actuation system: the spikes had significant signal content up to the eighth circumferential harmonic, whereas control action was limited to the first two harmonics by the frequency response of the control valves. Scaling valves to operate with equal stress and drive pressure means the number of valves required to pass a given flow rate rises as the square of the frequency response, and ten times as many valves would be required to match the waveform of the stall cells early on in the event.

In view of the above, it was not expected that a linear modal control system would be applicable to the VIPER engine. This was verified experimentally using a system similar to that of Paduano et al, but using recirculated bleed as the control mechanism. The pressure signals from a ring of transducers at a given axial plane were first of all resolved into first and second circumferential harmonics (together with a mean level), and then filtered to pass only rotating stall signals in a given frequency band. The results were adjusted in accordance with a pre-set gain and phase setting before being sent to the control valves. At high speed the growth rate of the stall disturbance was such that the numerical filters in the control algorithm did not respond until the stall was too far developed to be stopped. At middle speeds some improvement in surge margin was recorded, but detailed investigation showed the improvement to be largely independent of phase. This indicates that the improvement was not due to true 'modal control', but rather to the mean level of valve opening.

Although largely independent of phase, the surge margin improvement at middle speeds was heavily dependent on the gain setting. Data from a series of stall events with various gain settings is shown in figure 9. In each case inbleed was introduced into the combustion chamber at 90% speed at a rate insufficient to stall the engine. The engine was then decelerated until it could no longer support the increased pressure rise due to the inbled air. The events with high gain settings, and therefore high levels of recirculation, show stable operation to lower flows as the engine decelerates.

In view of the results described above a simpler control system was developed using the modal stall detection system but with axisymmetric actuation. This new system worked well at low and middle speeds, with comparable results to those obtained using the threshold simultaneous control system described later.

Threshold Sequential Control

The 'threshold sequential' control technique is similar to that used by Day [1993]. Each valve is effectively controlled by a single pressure transducer. The ac coupled pressure signal measured by each transducer is compared to a 'threshold' level. If this level is exceeded, then appropriate valves are opened (depending on the pre-set phase relationship) until the measured pressure level falls below the threshold level. It is then held open for a further pre-defined time interval before being closed. The non-uniform spacing of the valves and transducers and the requirement of an arbitrary phase relationship between the two was catered for by assuming that the valve demand waveform was sinusoidal around the circumference and opening each valve in proportion to the positive part of the wave. The valves opened were not necessarily close to the transducer detecting the disturbance. With recirculation from compressor exit to stage 4 the response time of the control system is 4ms, whereas at high speed a

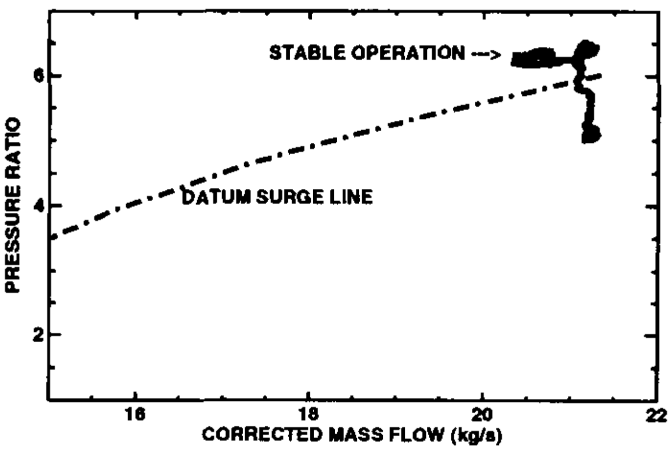

Fig. 10 Threshold Sequential Control at 98% Speed

stall cell takes 8ms to rotate around the annulus, and so the valve to be opened in this case is diametrically opposite the transducer detecting the disturbance. In practice a range of phase relationships and threshold levels was tested at each engine speed.

At high speed, stall in the VIPER engine is initiated towards the rear of the compressor [Wilson and Freeman, 1994, Day and Freeman, 1994], and recirculation from the rear of the compressor to the middle can be used as a control mechanism. Figure 10 shows a typical combustor inbleed event at 98% speed with stall control. Here the valves are controlled using the stage 3 transducers at the optimum phase angle (180 degrees), and the engine is shown to operate stably above the pressure ratio at which it had previously stalled, with a gain in surge margin of at least 11% of the pressure rise. At this speed the engine could not be stalled by inbleed with the control system in operation as the industrial compressor used to pump up the air tank was on its limit.

The threshold level used for the control experiments ensured that the valves were closed for normal engine operation below the surge line. As the surge line was crossed the threshold nature of the system meant that most of the time some low level of stall was present, continuously growing, then being removed and starting again. As the pressure level moved significantly above the surge line the level of activity increased such that the valves were kept mostly open. Close to the surge line the valves were opening and closing individually, and consequently the amount of air recirculated when operating in this form was relatively small.

Without control the stalling behaviour shows a clear circumferential bias, being concentrated around top dead centre. With control at the optimal phase setting the maximum transducer activity was seen after top dead centre and the maximum valve activity prior to top dead centre (fig 11). A degree of asymmetry is present in all aeroengines, and hence this type of behaviour, with activity levels distributed asymmetrically around the compressor, is to be expected.

The control system with the same gain and phase settings and recirculation from the rear to the middle of the compressor was also used to control stall events induced by hot gas ingestion at high speed. Without control the compressor stalled with hot gas ingestion and no

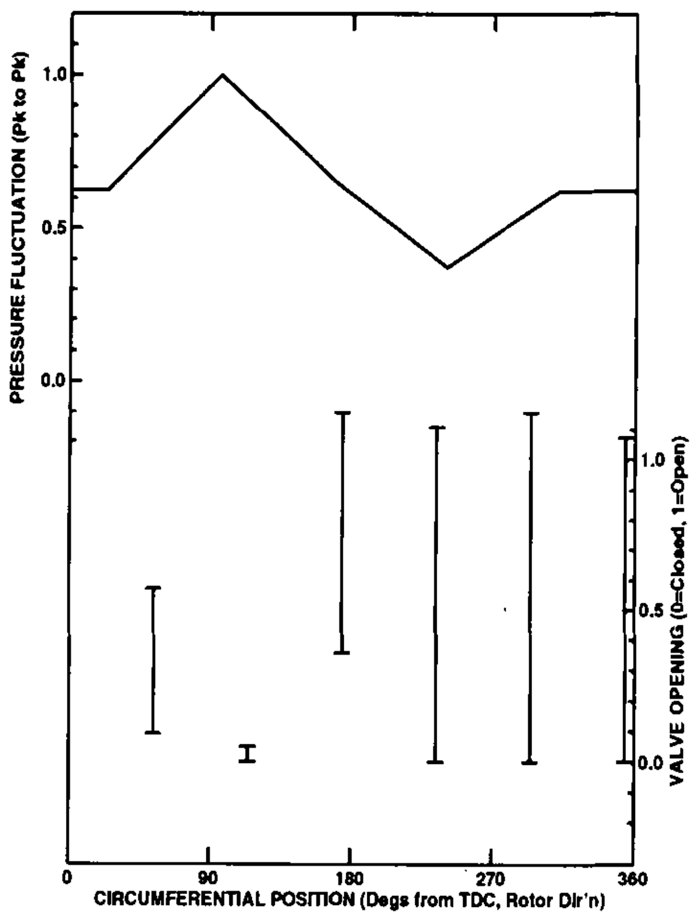

Fig. 11 Threshold Sequential Control at 98% Speed. Control Bleed Air Recirculated Rear to Middle.

inbleed; with threshold sequential control there was an improvement equal to half the loss of surge margin.

The control technique was also tested with recirculation from the rear of the compressor to the front. The results in this case were less impressive. At 92% speed there was an improvement in the surge margin of 6% of pressure rise at the optimum phase angle (180 degrees), as shown in figure 12. Furthermore, the threshold levels were required to be lower than for the simultaneous control described in the next section.

The recirculating bleed actuation system relies on the double beneficial effect of bleed off at the back of the compressor and mass flow injection at the front. One reason for the relatively poor performance with recirculation around the whole compressor is that the total gas path length for the control air is up to 2 metres, with a resulting time lag of 6 milliseconds. With this time lag the pressure signal resulting from the bleed-off at the rear of the compressor is out of phase with the signal from the mass flow injection at the front. Furthermore, it is impossible with a fixed geometry to ensure that the two effects are in phase across the entire operating speed range.

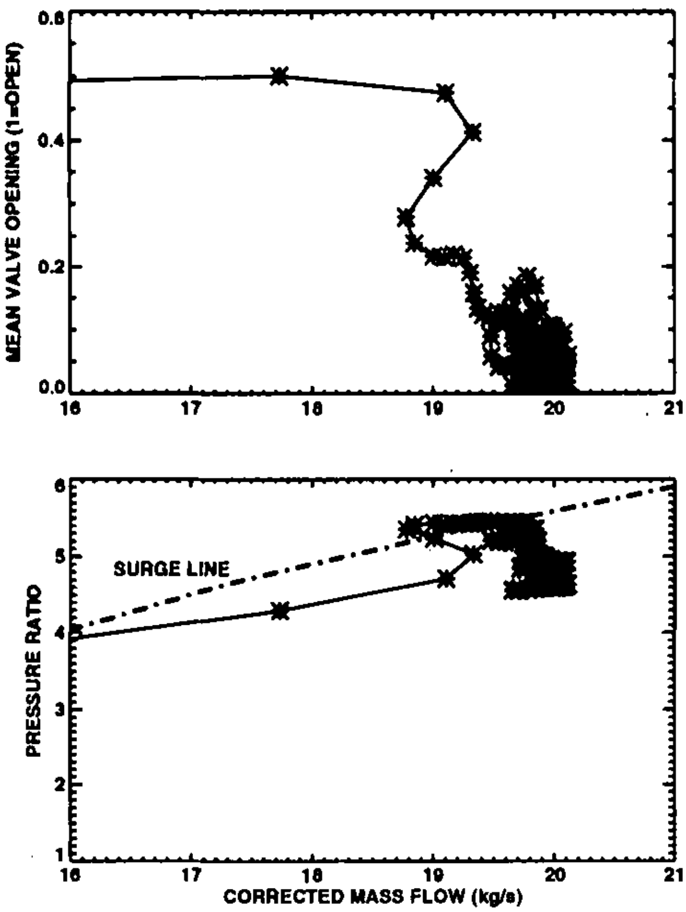

Fig. 12 Threshold Sequential Control at 92% Speed with Recirculation from Rear to Front

Threshold Control Of All Valves Simultaneously

The two stall control techniques described above which were based on non-axisymmetric actuation gave only limited benefits in terms of stall margin at low to middle speeds where recirculation was required around the whole compressor. For this reason a simpler control strategy was developed, in which all of the valves were triggered simultaneously in response to any pressure signal exceeding a threshold level. This technique was investigated for stall events induced by inbleed, hot gas and combinations of the two over the entire speed range, with recirculation from the rear of the compressor to the front and from the rear to the middle.

For successful control the threshold level must lie between upper and lower limits as illustrated in figure 13, which shows pressure traces as recorded by the transducers at stage 3 during a stall event without control at 98% speed. The first clear sign of impending stall is the slow rise in pressure on the green and red signals at 9 rotor revs. The leftmost vertical line marks the point at which a stall detection signal would be too late to reverse the growing stall cell, after accounting for the time delay introduced by the actuation signal. The threshold level must therefore be below the maximum pressure level reached prior to this point. At the same time it must be above the level (marked by the horizontal line) of the background noise to prevent 'false alarm' signals away from stall.

A picture similar to fig 13 could be drawn for each of the methods used to precipitate stall. It is possible that a very fast stalling disturbance, of the order of the stall inception time, would give a different picture, but such disturbances were not modelled in the present tests.

Detailed testing over the speed range established the upper and lower limits on threshold values which proved effective. The limits are shown in figure 14 for control using the stage 3 transducers. Within these limits the control technique proved able to prevent or delay the onset of stall at all speeds, with each of the methods used to induce stall.

During each controlled event the valves opened in response to a growing stall disturbance. With the valves open the compressor had the improved steady state surge lines shown earlier. Once the stall disturbance had been eliminated, however, the valves closed again, and the surge line returned to the datum, that is below the new operating point. The compressor would then immediately move to stall again. The more rapidly the valves closed the more rapidly a stall disturbance developed and the more difficult it was to reverse its effects. This problem was overcome by slowing the rate at which the valves closed such that subsequent stalls were no more rapid in development than the natural stall. The required closure rate was determined by experiment. Short closure times of 5 milliseconds always led to stall. Extending the time eventually resulted in stable operation with operating limits as shown in figure 15. The requirement to re-establish normal behaviour slowly is a key element of this type of control.

An example of the effectiveness of threshold simultaneous control is shown in figure 16. Four combustor inbleed events are overlaid, with recirculation from the rear to the front of the compressor at 80% speed. The mean valve opening is shown by the colour of the data points, and shows that the valves remain closed up to the normal surge line. On crossing the surge line the valves open automatically giving an improvement in the surge line of over 25% of pressure rise. The high pressure air used to raise the working line is taken from an external tank. As the pressure in this tank falls the operating point moves below the surge line again and the valves close automatically.

The effect of opening the bleed valves can be decomposed into a 'steady-state' and a 'dynamic' effect. The former is related to the adjustment of the flow to the new steady state conditions with the valves open. The latter corresponds to the transiently reduced pressure at the bleed-off port, the transiently increased pressure at the bleed-in port and the transiently increased pressure at inlet due to the inertia of the fluid in the inlet duct. This last effect is particularly strong: with the valves open for recirculation there is a reduction in the net flow requirement through the inlet duct. The deceleration of the fluid in the duct is brought about by a high static pressure at the compressor face which initially overshoots the equilibrium change in inlet pressure (due to the reduced dynamic head) by a factor of approximately two. The slow closure of the valves prevents the opposite detrimental effect happening when the valves close).

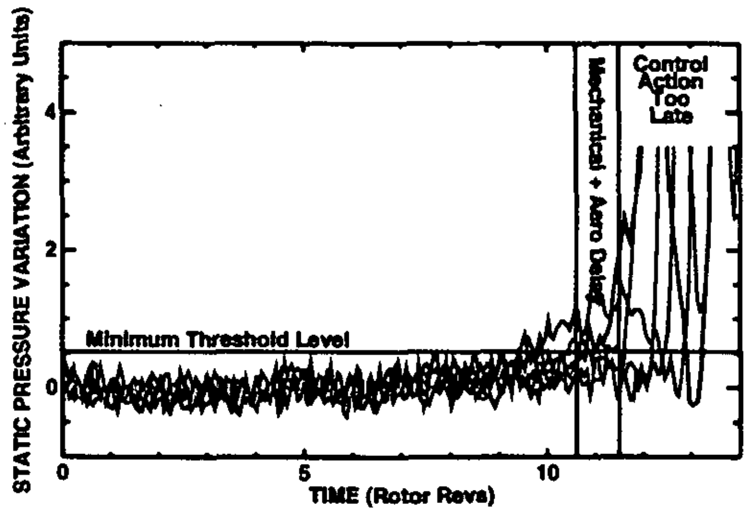

Fig. 13 Stall Event at 98% Speed Without Control, demonstrating Limits on Threshold Level

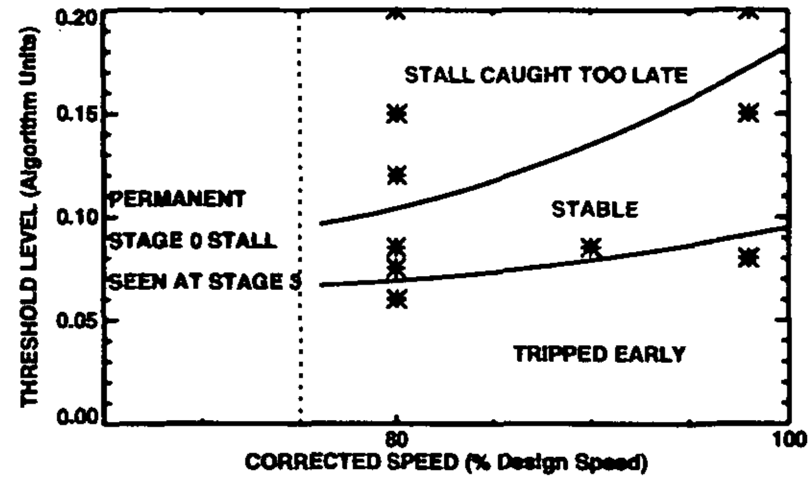

Fig. 14 Threshold Simultaneous Control: Stability with Hot Gas Ingestion. Control Bleed Air Recirculated Rear to Middle, Controlled from Stage 3 Kulites

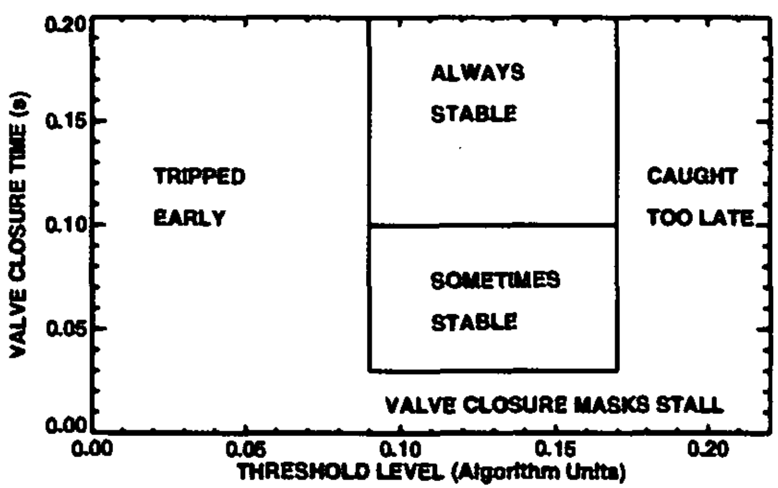

Fig. 15 Threshold Control Parameter Limits vs Valve Closure Rate at 98% Speed

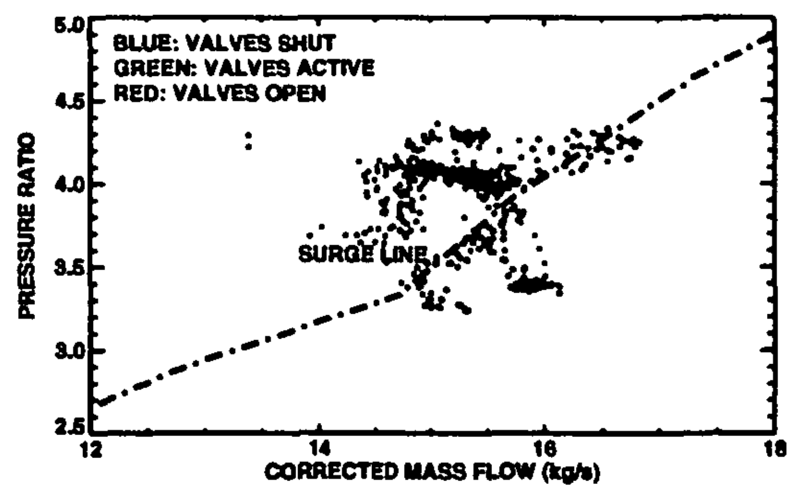

Fig. 16 Threshold Simultaneous Control at Middle Speeds. Control Bleed Air Recirculated Rear to Front, Controlled from Stage 3 Kulites.

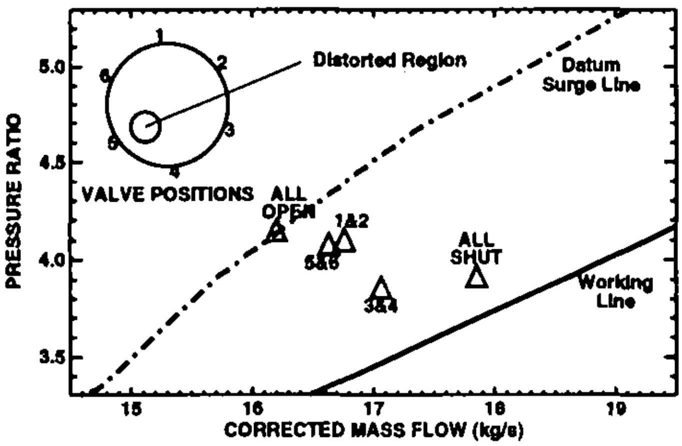

Fig. 17 Hot Gas Ingestion with Asymmetric Recirculated Bleed. Surge Points with Different Combinations of Valves Open.

The dynamic effect of opening the bleed valves cannot be ignored. At high speed the surge margin improvement with steady state recirculation around the whole compressor is comparable to that obtained with conventional exit bleed (figure 6). As an actuation device in a stall control system, however, recirculation proved capable of damping out incipient stall cells, whereas fast acting exit bleed was found to be totally ineffective.

Recovery Of Loss Of Stall Margin Due To Inlet Distortion

Non-axisymmetric inlet flow is a well known cause of stall and surge. A simple experiment was performed to investigate the use of steady non-axisymmetric recirculation to recover the loss of surge margin. The engine was set up at 90% speed with hot gas fed into a sector of the inlet as illustrated in figure 17. Various combinations of valves were opened allowing recirculation from the rear to the front of the compressor. The combustor inbleed was activated and the stall point determined (fig 17). With all of the valves closed no inbleed was required to stall the engine. 30% of the margin could be recovered with just valves 3 and 4 open, 75% of the margin with valves 1 and 2, and a similar amount with valves 5 and 6 open. With all the valves open the surge line was restored to that with undistorted inflow. The most effective valves were the ones in the region where the uncontrolled stall cell was observed to grow most rapidly.

The principle is thus demonstrated that the loss of stall margin due to asymmetric flow can be recovered with asymmetric recirculation. As a further refinement, the level of recirculation was set automatically by driving the valves from the measurements at stage 3 using a threshold technique similar to that described above, applying a phase shift to move from the position of maximum signal (just after top dead centre) to the position where the distortion was introduced. This method proved equally effective in cancelling the surge margin deterioration.

Summary of Results

The experiments discussed above represent only a subset of the tests performed, which included detailed parametric studies of a number of possible control strategies. The threshold simultaneous control strategy outlined above, recirculating air axisymmetrically from the rear to the front of the compressor controlled by the stage 3 pressure measurements, was found to be effective across the whole operating speed range, regardless of the method used to induce stall, and in spite of the wide variety of stalling behaviour observed. Control using the pressure measurements at inlet was possible at middle speeds, but was sometimes rendered ineffective by actuator/detector interaction effects. At high speeds, where stall starts towards the back of the machine, more effective control could be obtained by recirculating air over only the rear of the compressor.

The threshold sequential control method was effective at high speed when recirculating air around the rear of the compressor, and was more efficient than the threshold simultaneous method in terms of the amount of bleed air required. At middle speeds, recirculating air around the whole compressor, control was less effective than the threshold simultaneous method due to the phase shift between the bleed-off and bleed re-injection effects.

The low circumferential harmonic 'modal' stall control method demonstrated at low speed by Paduano et al [1993] was ineffective due to the fact that the long lengthscale disturbances for which this system was designed did not exist in the VIPER engine outside of the 85-87% speed range.

Experiments were performed concerning the use of conventional bleed-off and fuel modulation at high response rates as alternative actuation mechanisms; these proved too slow for stall control purposes.

Further experiments were carried out with inlet distortion. A system to restore the surge margin based on the controlled recirculation of bleed air is outlined in the previous section.

DISCUSSION

The threshold simultaneous control system described earlier was found to be a reliable method of eliminating incipient stall cells. The system relies on both a dynamic effect as the control valves are opened and the beneficial steady-state effect on surge margin of recirculating bleed air. In this respect it is different from linear 'modal' control, which relies on changing the dynamic response of the system with no change in the steady-state performance of the compressor. The steady-state effect alone, however, would be insufficient for successful stall control; conventional exit bleed can give a similar steady-state improvement, but was found to be too slow for use as an actuation mechanism.

This type of control, with axisymmetric response to non-axisymmetric disturbances, uses the disturbances present during stall inception to initiate a change to a more stall tolerant but less efficient machine, in a similar manner to that demonstrated by Ludwig and Nenni [1978]. In the present case, however, the control system reacts to the initial stages of stall development, and does not wait for rotating stall to develop first. Furthermore, the control system has been demonstrated to be effective across the entire operating range of the engine, whereas the system described by Ludwig and Nenni was demonstrated only at low engine speeds.

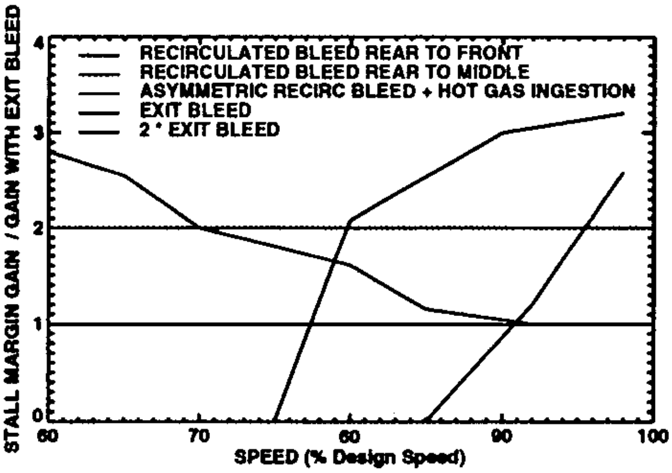

Fig. 18 Effect on Surge Margin of Steady State Recirculated Bleed. Normalised by Effect of Equivalent Amount of Exit Bleed.

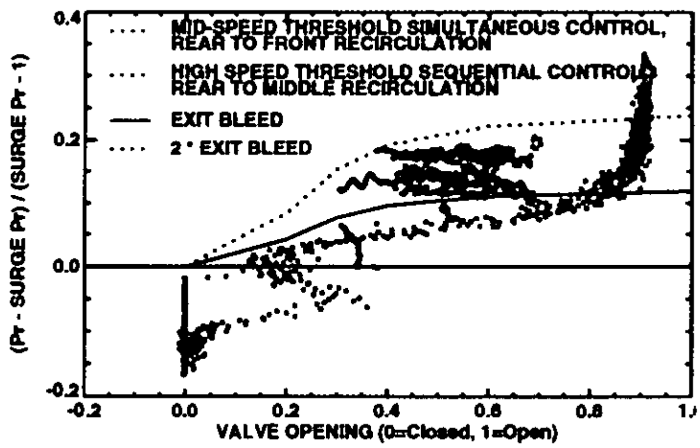

Fig. 19 Mean Valve Opening vs Surge Margin with Threshold Control

The gradual loss of stall margin due to irreversible damage during the life of an engine creates the requirement that a control system would need a reliability and life at least as good as the basic engine. Whilst it has been demonstrated that surge can be held at bay substantially more efficiently than with conventional bleed valves the type of actuators used in these investigations are not compatible with the life and cost requirements of an aeroengine. Further developments in the design of actuators are needed before active control can be applied to a flightworthy aeroengine. Ideally actuation would be provided by the mechanical equivalent of transistors, cheap, usable in large numbers, allowing air flow or not according to electronic control.

Control System Effectiveness

The thermodynamic efficiency of the compressor with stall control in operation was not measured directly. Nonetheless, significant conclusions can be drawn as to the effectiveness of the control systems. In this section the threshold control systems presented earlier are compared with conventional exit bleed and with an idealised linear control system. The threshold control systems are shown to be similarly effective to the idealised system. A more thorough comparison of the effectiveness of different control systems requires a full engine cycle analysis, yielding results that are heavily dependent on the particular engine application. Such a study is beyond the scope of this paper.

The threshold control systems described earlier provide a more efficient method of increasing surge margin than conventional exit bleed. There are three reasons for this. The major efficiency benefit derives from the fact that no operation is required below the normal surge line, whereas conventional bleed has to be scheduled to come into operation on the stable side of the surge line. This benefit is independent of the type of control system used. The second benefit concerns the steady state effect of recirculated bleed compared to pure exit bleed. Figure 18 shows the effect of steady state recirculated bleed on surge margin when compared with an equivalent amount of exit bleed, and shows considerable improvement over most of the operating speed range. Although the thermodynamic efficiency of the compressor with recirculating bleed was not measured directly, the fact that less air is required suggests that the efficiency penalty is likely to be lower for a given surge margin requirement.

The third efficiency benefit of the threshold control systems when compared to conventional exit bleed relates to the control system itself; how effective the control system is at using the available bleed capability. The threshold systems are designed to operate only when a stall disturbance is present. Even above the normal surge line stall disturbances are not continuously present, and so the valves close for part of the time, giving an efficiency advantage over continuous bleed. In practice this improvement is tempered by an inability to match precisely the amount of bleed required using the threshold system. Figure 19 shows the operating point relative to the normal surge line against valve opening (and therefore bleed rate) for a high speed event with threshold sequential control. This figure shows too the average valve opening for 4 nominally similar middle speed events with threshold simultaneous control. Also marked is the surge line which would be obtained with an equivalent amount of exit bleed for a given valve opening. The sequential control case shows a lower bleed rate for a given improvement in surge margin than with simultaneous control and an effectiveness of up to two times that of exit bleed. Operations at higher back pressures were not possible due to the limits on the combustor inbleed pressure, and so the ultimate performance was not known.

When the valves are predominantly open (the right hand side of figure 19) the simultaneous control case shows stable behaviour at substantially higher pressure ratios than with conventional exit bleed. At lower pressure ratios, however, just above the surge point, the nature of the control system is such that on average the valves are half open. In this case more air is being bled than required, and an equivalent improvement in operating range could have been obtained with a smaller amount of conventional bleed-off. The valve opening seen below the surge line in figure 19 is not due to premature opening on the stable side of the normal surge line, but is a result of the slow closure rate of the valves (0.25s) as the operating point fell below the surge line at the end of each event.

It is commonly assumed that the ideal stall control system would be a form of linear control which would allow stable operation at ever lower compressor flows with negligible energy input. In well-matched core compressors, however, compressor efficiency falls as the flow is reduced even before the natural surge line is reached, and it is undesirable to operate the compressor near the surge line for any length of time. In the VIPER compressor the efficiency drops by approximately 1% for 2% of flow as stall is approached; this figure thus represents the maximum efficiency of a linear stall control system. In practice, with a limited number of stages of bleed-off and reinjection, the axial movement of the position of stall inception from the front to the rear with increasing engine speed cannot be tracked exactly. Hence the stall cell will have grown prior to actuator movement, and some level of energy input would be required to restore axisymmetric operation. Thus the efficiency of a practical linear control system would be some way below this maximum value.

If a control system could be devised that scheduled exactly the amount of exit bleed required to keep the compressor stable, there would be a 2% efficiency penalty for achieving a 2% lower net flow. The earlier discussion suggested that the threshold control systems described in this paper are more efficient than pure exit bleed, and hence the efficiency is likely to be comparable to that of more complex systems designed to allow stable compressor operation at very low flows.

CONCLUSIONS

1. Results have been presented from a number of active stall control experiments on a VIPER aeroengine using high response valves to control bleed air recirculation around all or part of the compressor.

2. Best results were obtained with detection of non-axisymmetric disturbances coupled with axisymmetric control action. Such a control system ('threshold simultaneous') has been developed that is capable of extending the stable engine operating range at all speeds.

3. The operating envelope extension was effective for stalls induced by raising the working line as well as lowering the surge line with inlet distortion.

4. The change in net flow stall margin with controlled recirculation was up to 3.5 times that obtained by steady state exit bleed.

5. The efficiency penalty associated with the threshold simultaneous control system is comparable to that which proprietary data suggests would be obtained by running the compressor at very low flows using a more complex control strategy.

6. Non-axisymmetric actuation with threshold control gave some improvement in efficiency over part of the speed range in terms of the amount of bleed air required, but at the expense of a considerably more complex control system.

7. Non-axisymmetric linear control of the initial stall disturbances was not possible because the long lengthscale disturbances for which this type of control was designed do not appear in the VIPER compressor, except over a very narrow speed range.

8. Fuel dipping and exit bleed-off were found to be too slow to prevent stall when triggered by the first appearance of a stall cell.

9. Non-axisymmetric steady-state recirculated bleed can be used to restore stall margin lost due to inlet distortion. Using threshold detection the system can be automated such that it only operates when required.

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