THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

92-GT-83

The Effect of Compressor Rotor Tip Crops on Turboshaft Engine Performance

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ABSTRACT

The results from an experimental study into the effect of compressor rotor tip clearance changes on the steady-state performance and stability margins of a free-power turbine turboshaft engine are presented and discussed. This work was directed at the development of methods to diagnose engine condition from gas path measurements. It was found that the normal production suite of engine instrumentation was able to measure the deterioration in engine performance due to the implanted compressor degradation and the resultant deviations in the measured parameters from their respective nominal baselines do provide useful indicators of engine condition.

INTRODUCTION

Modern aircraft gas turbine engines are modular in construction and maintained on an 'on-condition' basis. Recent developments in modular construction have greatly facilitated the quick and easy replacement of suspect modules and accessories. What has lagged behind is the implementation of engine health monitoring methods to initiate the original engine/module removal and to correctly isolate the fault to a specific module. To overcome this deficiency techniques are being developed at the Aeronautical Research Laboratory to diagnose engine gas path condition. The approaches taken have involved both the development of predictive aero-thermodynamic models and the experimental implantation of common faults to help develop a set of fault signatures, Merrington (1989).

The work reported here addresses the experimental portion of a study into the diagnosis of long-term deterioration in engine performance due to compressor degradation. Compressor degradation was represented by a series of rotor blade tip crops to the axial stages of a combined five stage axial and one stage centrifugal compressor. The tests involved crops to two single axial stages, the first and fifth, followed by simultaneous crops to all five axial stages.

The objectives of the experiments were: firstly, to determine the sensitivity of engine steady-state performance and stability margins to rotor tip clearance changes in the axial compressor stages; secondly, to determine the adequacy of the normal production set of engine instrumentation to provide a reliable indication of the resultant degradation; and thirdly, to provide a data base against which the predictive models being developed to isolate compressor degradation can be validated.

COMPRESSOR DEGRADATION

Over the operating life of the engine, the compressor performance will degrade:

a. due to the ingestion of air borne particles causing fouling, corrosion, erosion and/or foreign object damage, and

b. due to engine transients and variations in flight loads causing blade tip and seal rubs.

The rate at which the compressor component and hence engine performance degrades will be dependent on the aircraft's mission profile, the severity of the operating environment, the presence or lack of inlet particle filters/separators, and the use of performance recovery procedures such as water washes etc..

Erosion and tip rubs introduce changes to the flow path geometry of the compressor, in particular, to the blade profiles and the rotor tip clearances. A study of performance deterioration of commercial high-bypass ratio turbofan engines showed that approximately one half of the long-term deterioration of compressor performance was attributable to increased blade tip clearances, Mehalic and Ziemianski (1980). In helicopter engines the erosion/burring of the first stage blades and blade tip clearance changes were identified as major performance loss mechanisms, Przedpelski (1982). The sand ingestion studies of Tabakoff (1987)

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cologne, Germany June 1-4, 1992
This paper has been accepted for publication in the Transactions of the ASME
Discussion of it will be accepted at ASME Headquarters until September 30, 1992

for a five stage axial compressor of a helicopter engine and those of Batcho et al. (1987) for both the high and low pressure axial compressors of two twin-spool engines showed that the severity of the resultant erosion increased towards the latter stages of the compressor. Furthermore, the compressor blade erosion was greatest at the leading edge tip corners. From the above, it was decided to represent compressor degradation by cropping the tips of the rotor blades in the axial compressor stages.

The topic of tip clearance effects in axial turbomachinery has received much attention in the literature, Sieverding (1985). As a result, the basic mechanisms of tip clearance flows and the general effect of tip clearance changes on stage and overall compressor performance are well understood. In this study, the tip clearance changes were introduced within an engine test rig, as distinct from a compressor rig, where the interpretation is further complicated by the matching constraints imposed by the other engine components.

As stated in the *INTRODUCTION*, one objective of the present work was to investigate the adequacy of the normal production set of engine instrumentation in assessing engine degradation due to tip crops. However, inter-stage compressor probes were also included to help validate the models being developed to predict the effect of compressor degradation on engine performance. These models go down to the individual stage level because the mechanisms of erosion etc. produce uneven and progressive geometry changes throughout the compressor. The approach being followed revolves around the generation of a degraded compressor component map. It uses semi-empirical correlations to model the effect of degradation on the individual axial stage characteristics and combines these into the total compressor map via an axial stage-stacking method and an off-design centrifugal compressor model. The degraded compressor map is then introduced into a component based, aero-thermodynamic engine model to generate the steady-state operating line characteristics.

ENGINE TEST RIG

The tests were carried out on a Lycoming T53-L11 turboshaft engine which was installed in the Small Engines Test House at the Aeronautical Research Laboratory. The main aero-thermodynamic components of the engine are: a combined five stage axial and one stage centrifugal compressor, a reverse flow annular combustion chamber, a single stage gas generator turbine and a free-power turbine. At take-off, the engine produces a rated power of 820 kW (1100 SHP) at an output shaft speed of 6600 RPM.

The T53-L11 compressor configuration - a combined axial-centrifugal- is similar to most modern helicopter engines. The main differences are the high aspect ratio blade design and the absence of variable inlet guide vanes or stator vanes. The compressor was designed to provide an overall pressure ratio of 6.2 with a mass flow of 4.9 kg/s at a spool speed of 24600 RPM. At the design point, half the pressure rise is obtained from the five axial stages and the other half from the centrifugal stage. Essentially, this ratio holds across the entire engine operating range. Compressor inter-stage bleed is provided aft of the fifth stage double row exit guide vanes. Some six percent of the compressor air is removed continuously from ground idle (50%) to just above flight idle(68%) with the bleed band fully closed at approximately 73% of the engine reference speed of 25100 RPM.

The relevant first and fifth stage rotor blade dimensions are given in Table 1. Each stage used NACA 65 series constant chord blades. The nominal tip clearances in each of the five stages stages were on average 0.9mm, i.e. 1.8% of the first stage blade height, and fell within the limits specified by the overhaul manual - 0.5mm to 1.0 mm.

Table 1. First and Fifth Stage Rotor Dimensions

	First Stage	Fifth Stage
Blade Height	48.7mm	26.2mm
Chord	22.7mm	17.2mm
Mean Flow Radius	101mm	105mm
Number of Blades	26	38
Solidity	1.1	1.0

The only gas path parameters normally monitored on the T53 engine are engine (gas generator) speed, output shaft speed, exhaust gas temperature and output shaft torque. Additional parameters measured in the test-cell were engine fuel and air flow, as well as total temperature, total pressure and static pressure at the compressor outlet, the axial compressor outlet and each axial stage outlet. Also, vibration accelerometers were located at the compressor inlet housing and compressor outlet casing to monitor any vibration level changes induced by the tip crops.

All the parameters were automatically recorded on the cell's data aquisition system - a DEC LSI-11 based system. The system was set up to simultaneously measure 32 analogue signals and 8 pulse-rate signals at a sampling rate of 32 Hz. The signals from the pressure transducers and temperature thermocouples were recorded in volts and the signals from the fuel flow meters and spool speed optical tachometers were recorded as frequency counts. The results were converted to engineering units via calibration factors.

TEST PROCEDURES

Tests to establish the effect of tip crops on steady-state performance and stability margins were carried out for each crop. Initially, a comprehensive set of baseline data was obtained for the engine with its production level clearances. These tests were then repeated with the first stage blades successively cropped by 1.5mm, 3.5mm, 5.5mm and 7.5mm beyond the nominal tip clearance, i.e. respectively, 3%, 7%, 11% and 15% of the first stage blade height. The first stage blades were then replaced with new blades at the nominal tip clearance. The engine performance baseline was re-established and the tests repeated for the same magnitude crops to the fifth stage blades, i.e. 3%, 7% and 11% of the first stage blade height. On completion, the engine was re-bladed with new fifth stage blades at nominal clearances and the baseline performance again checked. The final test for this report was a crop of 3% of the first stage blade height to all five axial stages. Unless otherwise indicated all further references to the magnitude of the crops will be expressed as a percentage of the first stage blade height.

The steady-state operating line was measured from ground idle to take-off power. Data were obtained at 2% speed increments up to 88% engine speed and at 1% speed increments thereafter. The engine was stabilised at each test point for 3 minutes prior to taking a 16 second record. For the initial baseline the water-brake load was also varied from full load to minimum load at each engine speed, subject to maximum torque and shaft speed limits. The resultant matrix of loading curves showed that the gas generator parameters at a given corrected engine speed were independent of the water-brake load applied and of the corresponding variations in output shaft speed. Consequently, for the remaining tests, full loading curves were only generated at engine speeds greater than 90% i.e. in the region where engine output power was of primary interest. The loading curves also determined the sensitivity of the free-power turbine parameters which are affected by the load (i.e. shaft power and exhaust gas temperature) to the value of the shaft speed. This allowed discrimination between changes in shaft power and exhaust gas temperature due to shaft speed fluctuations and those due to tip crops.

The effect of the tip crops on the stability margins of the engine was assessed by carrying out a series of wave-off tests. These tests move the compressor towards surge by over-fuelling the engine during the acceleration transients. The tests involved a series of rapid decelerations and accelerations which were carried out by chopping the throttle from maximum to a specified part power position and then slamming the throttle back to maximum within a one second period. The accelerations were performed from 85%, 80%, 75%, 68% (flight idle),65%,60% and 50% (ground idle) engine speed. The technique used to bring about the over-fuelling was to pressurise the intake air pressure tube on the fuel control unit. The T53-L11 engine was deemed to be acceptable at overhaul if it was surge free at a pressurisation of 20 inches of water above atmospheric. Here, the intake tube was pressurised at increments of 10 inches of water up to a maximum of 100 inches of water to help discern any trend towards surge as the tip clearances were increased.

DATA ANALYSIS

Most analyses of stage and compressor performance are based on data obtained at constant corrected spool speed. On compressor component rigs for all speeds and direct coupled turboshaft engines for a single operating speed, the compressor can be moved up a constant speed line towards surge by increasing the load and hence the power turbine inlet temperature. However, for a free-power turbine engine the operation of the gas generator section is independent of the output shaft load. Hence, the compressor is constrained to run at a single compressor- turbine match point for each engine speed. Consequently, the constant speed operating lines of the compressor characteristic could not be generated and it was appropriate to use the corrected spool speed as the independent parameter on the baseline curves.

The individual parameters were corrected to standard day conditions and plotted against corrected engine speed. Deterioration was indicated by the resultant deviation of the parameter versus speed curves from their respective baseline values at nominal tip clearance. For compressor degradation the complete operating line from ground idle to take-off power is useful whereas for assessing engine performance only the higher power levels, greater than 75% normal, are relevant. Consequently, in the performance assessment only the data obtained in 88% to 98% engine speed range was used.

A normal power rating point of 670 kW (900 SHP), i.e. the maximum continuous operating point, was chosen as the reference condition. The minimum specification engine achieved this at 94% engine speed and 6600 RPM output shaft speed. Data for each parameter versus engine speed plot were fitted by a linear regression fit across the 88 to 98% speed range. The parameter value for 94% speed was then calculated from the regression equation and expressed as a percentage difference from the nominal parameter value.

EXPERIMENTAL RESULTS

Effect of Re-blade to Nominal Tip Clearances

The results obtained from the two tests where the compressor was re-bladed to nominal tip clearances after completing the first and then the fifth stage crops were compared with the original set of parameter baselines. There were no discernible shifts from these original baselines and, consequently, the effects presented below can be attributed to the tip clearance changes and not to some other engine re-build effect.

Effect on Engine Performance

The test results showed that the majority of the tip crops produced a significant drop in the output power of the engine. Typical deviations from the nominal engine output power versus corrected speed baseline are shown in Figure 1. It compares the data obtained from the 7% crops to the first and fifth stages and the 3% crop to all five axial stages with the nominal tip clearance baseline. Both the single-stage crops resulted in a similar 5.5% drop in output power at the reference condition of 94% engine speed whereas the all-stage crop produced an 8.0% drop. The reduction in output power for the individual stage crops is summarised in Figure 2. In both stages the first crop had little effect on the output power, less than one per cent, but the latter crops showed a significant loss. The main difference in the results was that the loss in shaft horsepower flattened off for the last two crops of the first stage but not for the fifth stage.

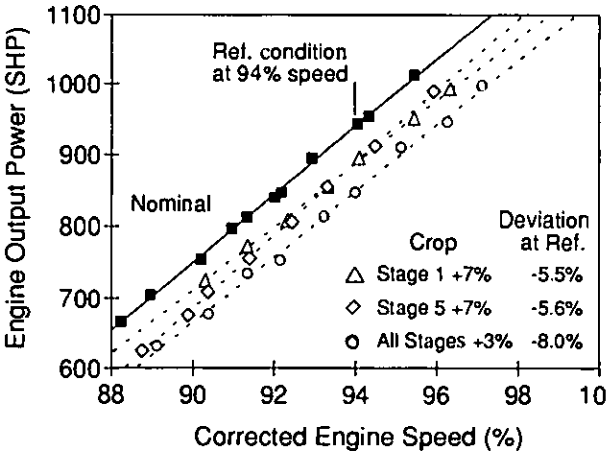

Figure 1 : Typical Loss of Power due to Tip Crops.

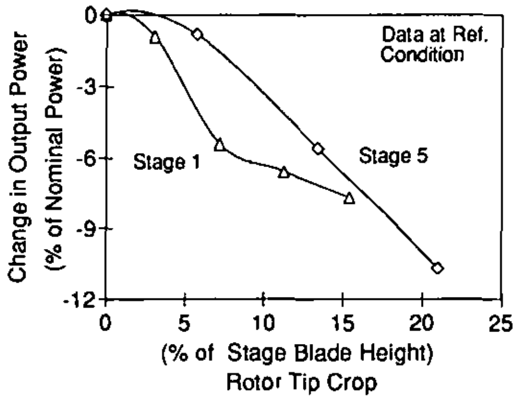

Figure 2 : Loss of Power for Stage 1 and Stage 5 Tip Crops.

Of the other overall engine parameters, the tip crops reduced the fuel flow and air flow in a similar manner to the output power but had no effect on the exhaust gas temperature. Even with the maximum 11% loss in power which was obtained for the last fifth stage crop the corresponding change in exhaust gas temperature was an insignificant 0.6% (5 °C). The deviations of the various parameters from their respective nominal reference condition are given in Table 2 for the two 7% single-stage crops and the 3% all-stage crop.

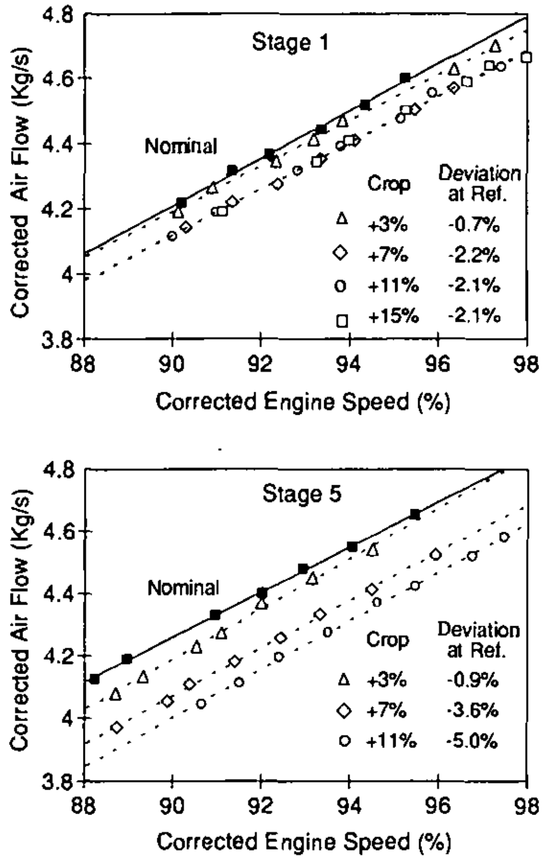

Figure 3 : Comparison of Mass Flow Reduction for Stage 1 and Stage 5 tip crops.

Table 2 Typical Engine Parameter Deviations.

TEST	Stage 1	Stage 5	All Axial
Crop	7%	7%	3%
PARAMETER	Deviation from Nominal Value(%)		
Output Power	-5.5	-5.6	-8.0
Exhaust Gas Temperature	-0.65	+0.6	+0.63
Fuel Flow	-3.3	-2.8	-4.6
Air Flow	-2.2	-3.6	-4.6

The reductions in air mass flow for each of the stage 1 and stage 5 crops are shown in the corrected air flow versus corrected engine speed plots of Figure 3. Clearly, for the same size crop, there is a greater reduction in airflow for the fifth stage crops. Again the main difference between the results for the first and fifth stage is that the data for the second, third and fourth crops to the first stage fall on the same operating line. The flattening of the output power loss curve of Figure 2 can be attributed to these last two crops producing no further reduction in the engine air flow.

Effect on compressor performance

The test results showed that the compressor pressure ratio generated at a given corrected speed was progressively reduced as the tip crops were increased. This is illustrated in Figure 4 for the fifth-stage crops where the last crop (11%) produced the maximum reduction in pressure ratio of 4.4% at 94% engine speed. In contrast, as shown in Figure 5, there were no significant shifts from the nominal baseline for the corresponding compressor temperatures. Indeed, over the complete test program, the maximum deviation in the compressor temperature was -0.6% (3°C). A typical set of compressor parameter deviations is summarised in Table 3.

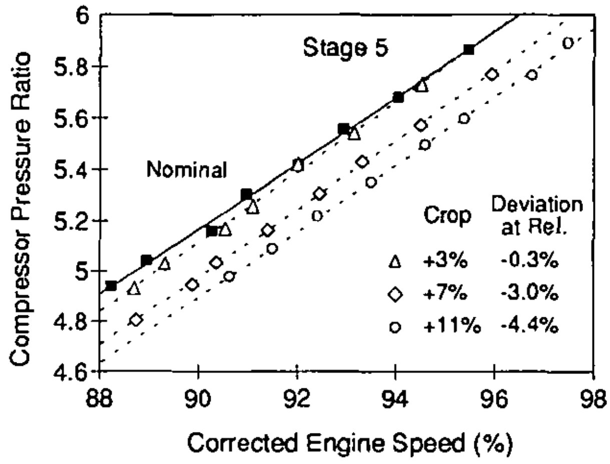

Figure 4 : Reduction in Compressor Pressure Ratio.

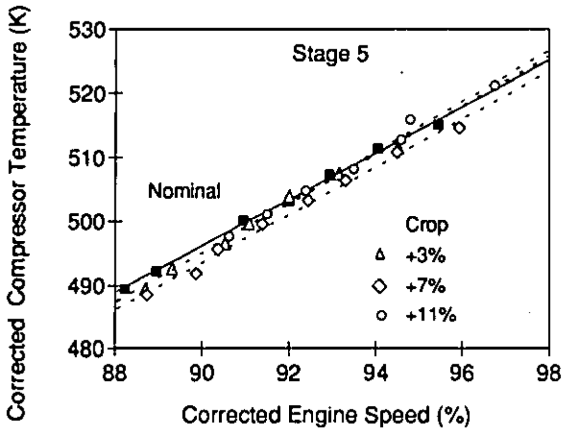

Figure 5 : No Shift in Compressor Outlet Temperature

Table 3 Typical Compressor Parameter Deviations.

TEST	Stage 1	Stage 5	All Axial
Crop	7%	7%	3%
PARAMETER	Deviation from Nominal Value(%)		
OVERALL			
Pressure Ratio			
total	-2.2	-3.0	-3.8
static	-1.2	-3.0	-3.6
Temperature	-0.6	-0.4	-0.3
AXIAL			
Pressure Ratio			
total	-1.7	-2.5	-2.4
static	-2.0	-5.9	-5.7
Temperature	-0.3	+0.4	+0.3
CHARACTERISTIC MAP			
Pressure Ratio	+0.9	+2.3	+2.6

The test data from the last two fifth-stage crops and the all-stage crop when plotted on the compressor characteristic did show a significant shift of the engine operating line towards the surge line. This is illustrated in Figure 6 where the complete operating line for the last fifth-stage crop is compared with the nominal tip clearance operating line. Also, the operating line shifts for the three typical crops are given in Table 3. The results for the first-stage crops were different in that all the stage 1 crops produced an insignificant, i.e. less than one per cent, shift in the operating line.

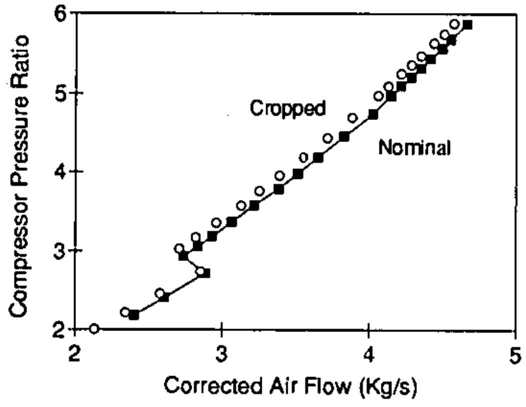

Figure 6 : Positive shift of Engine Operating Line on Compressor Characteristic

Effect on axial compressor stages

Of the inter-stage axial compressor probes the static wall tappings provided the most sensitive and consistent response to the tip crops, and some typical results from these are shown below. Generally, the total pressure probes resulted in similar but less sensitive shifts from the nominal baselines. Again, the total temperature measurements showed no significant deviations from the nominal tip clearance baselines.

The effect of the first-stage tip crops on the ratio of the static pressure at the first stage stator to the total pressure at the engine inlet, from ground idle to take-off speed, is shown in Figure 7. In the operating power range, 88% to 98% engine speed, the curves are linear and there is a monotonic departure from the nominal curve as the tip clearance is progressively increased. The shift at 94% engine speed for each crop is given in Table 4. In contrast, as shown in Figure 7, a much more complex set of data curves were obtained below 88% speed. The sharp kinks in these curves were confirmed by repeat tests.

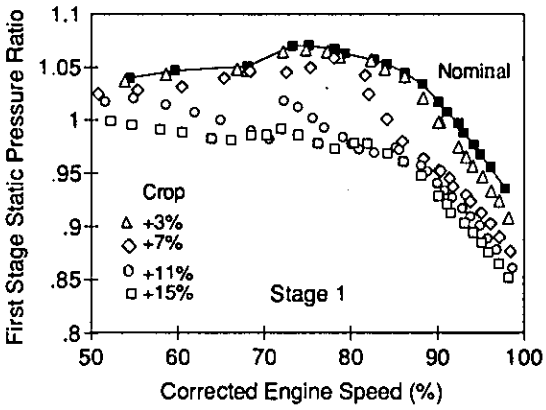

Figure 7 : Shift in First Stage Static Pressure Ratios due to Stage 1 Crops.

Table 4 First Stage Static Pressure Ratio Deviations

	Deviation from Nominal Value(%)		
Crop	Stage 1	Stage 5	All Stage
3%	-2.1	+1.7	+3.2
7%	-5.94	+3.6	
11%	-7.09	+4.4	
15%	-8.46		

The effect of the fifth stage crops on the static pressure rise across the fifth stage for the entire operating range is shown in Figure 8. The graph clearly demonstrates significant and readily measurable reductions in the stage pressure rise. The shift at 94% speed for each crop is given in Table 5.

Table 5 Fifth Stage Static Pressure Ratio Deviations

	Deviation from Nominal Value(%)	
Crop	Stage 5	All Stage
3%	-4.2	-4.2
7%	-7.1	
11%	-9.6	

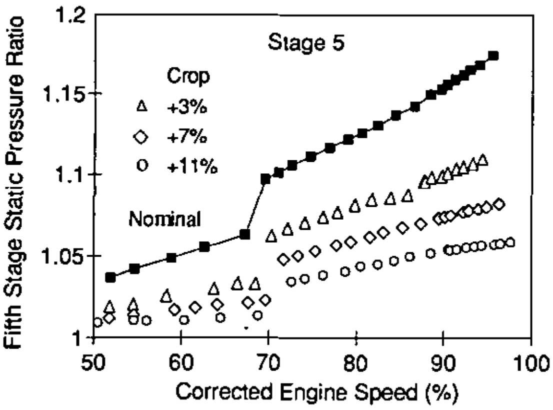

Figure 8 : Shift in Fifth Stage Static Pressure Ratios due to Stage 5 Crops.

As well, in a multi-stage compressor, the individual stage crops do affect the operating characteristics of the other stages. This is illustrated by a comparison of Figures 7 and 9 where the nominal first stage static pressure ratios were reduced by the first-stage crops and increased by the fifth-stage crops. The corresponding shifts at 94% speed are given in Table 4. In the case of the 3% crop to all five axial stages, the stage static pressure ratios were shifted from their respective nominal values by a positive 3.2% at the first stage through to a negative 4.2% at the fifth stage. Clearly, the interaction between the various stage crops produces a different stage ratio shift than does the same single stage crop. The above interaction can be related to moves on the individual stage characteristics as a result of the reduction in mass flow through the compressor.

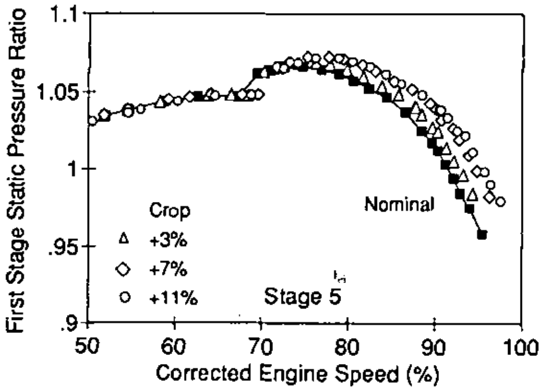

Figure 9 : Shift in First Stage Static Pressure Ratios due to Stage 5 Crops.

Effect on engine stability

The wave-off tests showed that the stability of the engine was affected by the first-stage tip crops. For the nominal clearance and the initial crop (3%) the complete set of wave-off accelerations failed to surge the engine up to the maximum pressurisation of 100 inches of water on the fuel control intake probe. For the second crop (7%), the accelerations from ground idle and flight idle surged the engine at pressurisations of 80 and 90 inches of water, respectively. The remaining accelerations from the higher engine speeds were surge free up to the maximum pressurisation. For the third crop (11%), the accelerations from ground idle surged the engine at a pressurisation of only 20 inches of water, those from flight idle similarly at 20 inches of water, and those from 75% engine speed at 40 inches of water. Again, the accelerations from the higher speeds were free of surges. For the last crop (15%), none of the wave-off accelerations up to the maximum probe pressurisation surged the engine. This last result went against the trend established in the previous tests, that is the engine surging during accelerations from progressively higher engine speeds and lower probe pressurisations as the tip clearance was increased.

The surges induced by the accelerations were not severe enough to prevent the engine from completing its acceleration to full power. A typical set of compressor pressure-time traces obtained for surge on acceleration from 75% speed and flight idle are shown in Figure 10.

In contrast to the results for the first stage crops, the complete set of wave-off tests for each of the three fifth stage crops and the single all stage crop failed to surge the engine.

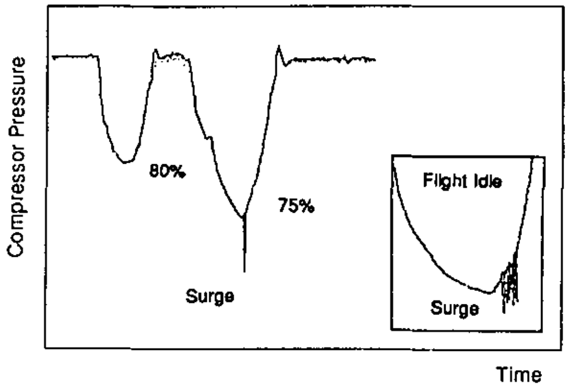

Figure 10 : Typical Surges on Wave-Off Compressor Pressure - Time Traces.

DISCUSSION

The results showed that a small tip clearance change to all five axial stages produced a greater performance loss than a very large crop to any one single stage. The effects of the initial 3% of first stage blade height crop to either the first or fifth stage were only significant at the inter-stage level whereas the same crop to all five stages produced near maximum deviations from the various nominal parameter versus speed baselines. The magnitude of the deviations were second only to the largest fifth stage crop (11%).

Although measured primarily to validate the stage-stacking models the inter-stage static wall pressure tappings did provide the most sensitive indication of rotor tip clearance changes. Even the smallest single stage crops produced significant reductions in the stage static pressure ratios. However, as demonstrated by the all-stage crops, the use of the resultant deviations as condition monitors will not be straightforward, since the behaviour of the individual stage static pressure ratios for a given stage crop was different from that obtained when combined with other stage crops. Consequently, a proper interpretation of the inter-stage operating line shifts will require knowledge of the individual stage characteristics and how they stack together to give the overall compressor performance. This is being pursued in the development of the predictive models, in particular, through the use of a stage-stacking technique.

On the basis of the wave-off tests, only the first stage crops adversely affected the stability of the engine. The mildness of the resultant surges may be attributed to the fact that the automatic opening of the bleed band during the acceleration was sufficient to stabilize the engine and allow acceleration to full power. Surge on engine acceleration from low-speed regions has been attributed to discontinuities in the performance characteristics of the front stages of multi-stage axial compressors. The series of distinct kinks found in the low-speed region of the first stage operating curves of Figure 7 may indicate that the first stage tip crops are producing such discontinuities in the stage characteristic and therefore more prone to surge.

From the point of view of engine health monitoring the most interesting result was the lack of sensitivity of the temperature measurements to the implanted compressor degradation. Haq and Saravanamuttoo (1991) found a similar result from measurements of compressor fouling. This has implications for the Health Indicator Test (HIT) check which is used by many helicopter operators. The HIT check essentially establishes an exhaust gas temperature versus corrected engine speed baseline and trends the day to day deviations from it. Typically, on the T53, a shift greater than 20 °C would prompt a maintenance notification and a shift greater than 30 °C would result in the aircraft being grounded until troubleshooting could determine the cause. In these tests, the tip crops to the compressor rotor blades produced performance losses as great as 12% with a corresponding deviation in exhaust gas temperature of only 5 °C. Clearly, for the compressor degradation investigated here the HIT check would not be an appropriate indicator of overall engine health.

Most aircraft turboshaft engines have a measure of output shaft horsepower, via output shaft speed and torquemeter gauges, and this parameter proved to be the best indicator of overall performance loss in this investigation. In addition, air flow, fuel flow and compressor pressure ratio, both static and total, provided a useful set of parameters to indicate performance degradation. Of these, air flow reduction was the next best measure of performance degradation. Whilst airflow is unlikely to be measured on an operational engine, efforts should be made to include it on engine test stands which are used for intermediate or depot level maintenance testing.

The tests have produced a set of parameter deviations from the nominal baseline values which represent fault signatures for the effect of one type of compressor degradation on engine performance. However, these signatures are not necessarily unique. For example, turbine degradation can also result in reductions of compressor pressure ratio and air flow due to the rematching of the gas generator compressor and the degraded turbine components. So, whilst the measurements do provide an indication of degradation, there is still the problem of isolating the degradation to a specific module. Possibly, as indicated by the above results, the simplest signature for isolating cold end degradation from hot end degradation would be a significant drop in output power without a similar change in either the compressor temperature or exhaust gas temperature. In contrast, an indicator of hot end degradation would be a significant shift from the baseline variation of exhaust gas temperature versus corrected engine speed.

CONCLUSIONS

The experimental program has demonstrated the effect of rotor tip clearance changes to the axial stages of a combined axial centrifugal compressor on the steady-state performance and stability of a free-power turbine turboshaft engine.

The majority of the engine parameters were sensitive to the rotor tip crops and the resultant deviations from their respective baseline values at nominal tip clearance do provide a useful indicator of engine condition. The effects of single stage crops were not evident until a crop greater than 3.0% of the first stage blade height was made whereas the same level of crop to all five stages produced more than an 8.0% drop in power.

The present results show that the Health Indicator Test, commonly used in helicopter engines, is not a good indicator of overall engine condition when operating with a degraded compressor.

ACKNOWLEDGEMENTS

The author would like to thank Mr A. Vivian, Mr A. Godbold, Mr D. Dyett and Mr G. Wells of the Aeronautical Research Laboratory for their help in developing and operating the engine test rig.

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