TITLE

A REVIEW OF AEROENGINE FATIGUE FAILURES IN THE CANADIAN FORCES

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Executive Summary

This study was undertaken to identify the Canadian Forces' experience with high cycle fatigue failures in aeroengines. The three specific objectives were to determine any trends based on an analysis of historical data, provide some direction to research and development efforts that would lead to a better understanding of HCF failures, and lastly, to offer comment on areas of collaboration amongst The Technical Cooperation Program partners. The two sources of information consulted were the flight safety data held in the aircraft accident and incident information system (ACAIRS) and the pool of failure analysis reports held at the Quality Engineering and Testing Establishment in Hull, Quebec. In this study, it was found that whenever an HCF problem has occurred, the CF had it addressed and resolved largely through the engine manufacturer. The HCF problems were most prevalent in thrust engines and have a very high hidden cost as they usually affect the majority, if not all, of the engine fleet. A technology program to control the costs and risks associated with HCF failures is possible, and would be focussed on F404 engine materials. The program elements proposed would build on the current dynamic structural response project under the 3.g.a DND/NRC-IAR collaborative program in aeropropulsion.

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Introduction

1. Military services within the United States, United Kingdom, Canada, Australia, and New Zealand have and/or have had significant high cycle fatigue (HCF) driven problems on their military aircraft engines. These HCF driven problems are predicted to increase with the advent of new and advanced high performance engine designs; particularly in the compressor section. Since the above nations have or will have to deal with HCF problems, The Technical Cooperation Panel Aerospace Systems Technical Panel 3, Propulsive and Mechanical Systems Condition Monitoring and Diagnostics, (AER-TP3) has undertaken a study assignment to define the current needs, technology state-of-the-art, and the status of HCF monitoring and diagnostic programs underway for engine compressor sections.

2. Currently, there is a mixed degree of emphasis, visibility, and funding in the diagnostic and damage assessment areas. United States Air Force experience indicates that HCF is currently the number one cause of engine-related fighter mishaps, accounting for over 60% of these mishaps between 1982 and 1992. Reports from New Zealand indicate some HCF problems, but all appear to result from foreign object damage. UK representatives have stated that they have not experienced the same level of HCF failures as experienced by the USAF. The Canadian Forces have had HCF problems within their engines, but most problems have been resolved through hardware changes in consultation with the equipment manufacturers.

3. To determine where various possible HCF monitoring and/or any other known engine health monitoring techniques would have had a significant impact as a diagnostic tool, AER-TP3 members are examining the history of HCF compressor failures and their root causes. Only when a root cause is identified will research staff be able to identify, define, and/or develop the sensor and signal processing requirements to diagnose the onset of an HCF

failure.

4. Unfortunately, high cycle fatigue failures cannot always be recognized and differentiated categorically from other forms of damage accumulation and failure that occur in engine parts. A difference between low cycle and high cycle fatigue can be defined, perhaps somewhat arbitrarily, but to differentiate between these two types of failures in engineering practice can be difficult. Furthermore, there is the attitude that HCF is not a problem inherent to jet engines. This is largely due to the fact that HCF avoidance is so well inculcated into the design, manufacturing, and testing processes for turbine engines. When there is a failure that can be attributed to HCF, it is automatically thought of as being due to a parameter being "off-design."

Objective

5. There are three objectives to this study. The first objective is to determine any trends based on an analysis of historical data. Secondly, this survey should provide some direction to research and development efforts that would lead to a better understanding of HCF failures. Lastly, to offer comment on areas of collaboration amongst the TTCP partners.

Study Data Sources

6. Two sources of information were consulted to determine the Canadian experience of HCF. The first source was the Canadian Forces flight safety data held in the aircraft accident and incident information system (ACAIRS). The other source of information was the pool of failure analysis reports held at the Quality Engineering and Testing Establishment in Hull, Quebec. Fortunately, QETE had performed a survey of all engine component failures that they had investigated in the period 1974-1990.[1]

7. During this study, it became apparent that both the ACAIRS and QETE had simply used the generic term "fatigue", and rarely was there a specific mention of high cycle or low cycle fatigue. Based on the information provided in the ACAIRS reports, only those incidents where there was a sudden failure, pronounced cracking or excessive vibrations were first considered. The information within the reports was also examined to ensure that HCF was a realistic and probable factor. Admittedly, this calls for some judgement on part of the author; however, this served as a starting point in organizing and tabulating the data.

Canadian Forces Flight Safety Data

8. The ACAIRS survey considered only those incidents involving the engine compressor and/or stator where there was an assigned material cause factor of "progressive and undetected breakdown." Another search was performed for all the engine compressor stalls with the same assigned material cause factor. This was thought to identify the incidents within the engine compressor section that have been the result of high cycle fatigue, but may also include failures from other causes such as stress corrosion cracking or foreign object damage. All the aircraft fleets which use a gas turbine propulsion system were considered back to 1968; this even includes such aircraft as the venerable CF-100 Canuck. The narrative text for each incident was reviewed to gain an understanding of the impact of these failures during operations. Among other information included in the data records are the aircraft type, date, location, phase of flight, and incident category. The categories of aircraft occurrences reflect the degree of damage as follows[2]:

A Category - the aircraft is destroyed or damaged beyond economical repair.
B Category - the aircraft must be shipped to a contractor or depot-level facility for repair.
C Category - the aircraft must be flown to a contractor or depot-level facilities for repairs; repairs are carried out by a mobile repair party; or a major component has to be replaced.
D Category - damage to any component that can be replaced within field level resources.
E Category - no aircraft damage but accident potential exists.

9. A total of 377 incidents were recalled from the flight safety database. Rarely was there a direct mention of a report or analysis where HCF was determined to be the failure mode. For the data given below, the nature and context of the failure led to a reasonable assumption that the failure cause was fatigue related, and likely to be high cycle vice low cycle fatigue. In fact, both may be involved, HCF leading to LCF. For this report, however, HCF is considered to be in the critical chain of events leading to the failure.

10. Table 1 below compares the stage of flight and the category of incident. Almost all of the incidents were D category incidents. For the purpose of this analysis, several E category incidents were considered to be D category, based on the damage described in the narrative. Surprisingly, there were no C category incidents found or apparently reported, as surely some engines were damaged beyond second line repair.

Table 1: Occurrences by stage of flight.

Stage of Flight	E	D	B	A	Remarks
Pwr Plant Running to T/O Roll		5			
T/O Roll	1	7			
Initial Climb/Climb Out		13		2	A cat - two separate CF101 ac
Sub Total	1	25		2	28 occurrences (28%)
Normal/Enroute		20			
Armament/Photopass	1	5			
Aerobatics		9			
Low Level Flight		13			
Initial/Final Approach		5	1		B Cat - CH 124
Sub Total	1	[illegible]			54 occurrences (54%)
Ground - Serv - Maint	22	21 1			17 occurrences (17%)
TOTALS	6	90	1	2	100%

11. Over half of the total number of incidents occurred during the "in-flight" phase, but some 28% occurred between the engine start and levelling out at cruise. When the ground occurrences are left out, roughly one-third of all engine failures considered occur in the first phases of flight, where the engine is at full power on take-off. On review of the "in-flight" incidents, there does not appear to be a relationship between engine power setting and the occurrence; however, over half of these incidents were reported during manoeuvres which do involve throttle changes.

12. There were, in general, three different types of occurrences involving the compressor section where high cycle fatigue is the suspected failure mode. (Again for this analysis, the circumstances and description of the failure are used to infer that HCF was in the critical chain of events leading to the failure.) The first type of failure given below in Table 2 are those failures that occurred in the compressor core itself. The second type consists of those incidents where it was not clear if fatigue was a factor in the failure. The last type consists of those components located outside of the core of the compressor which failed by HCF. These component failures either caused an engine shut-down or resulted in objects, such as a sheared

rivet, passing through the compressor section causing extensive foreign object damage, FOD. These occurrences are separate from those where FOD was given as the material cause factor: those FOD occurrences are not considered as part of this survey.

Table 2: Results of Flight Safety Data Survey Ranked by Number of Occurrences.

Aircraft Type	Compressor Core	Not Clear	HCF / FOD
CF-116 (F-5)	24		
CT-114 Tutor	15	1	2
CF-101 Voodoo	11		1
CF-188 Hornet	10	3	2
CH-136 Kiowa	8	3	
CC-137 (B707)	6		
CT-133 T-Bird	4		
CH-124 Sea King	3	1	3
CF-104 Starfighter	2		
CH-147 Chinook	2		
CC-130 Hercules	1		
CC-150 (A310)	1		
CC-115 Buffalo		3	
CP-140 Aurora		3	
CH-118 Iroquois			2
CH-113 Labrador		1	
CH-135 Twin Huey		1	

13. Of the top six aircraft types that experienced fatigue related failures, five have thrust engines and of these five, three are fighters. The CF-104 Starfighter appears to have suffered very few HCF failures, which immediately raises a question of what is significantly different about this aircraft and engine.

14. By far the most incidents involved the J85 engine as it is installed on both the CF-116 (F-5) Freedom Fighter and the CT-114 Tutor aircraft. Some eighteen failures, possibly a few

more, of the J85-CAN-15 engine on the CF-116 could be attributed to an aerodynamic design flaw at the fourth stage of the compressor.[3] The airflow passing through the fifth and later stages induced stresses in the components which resulted in HCF failures. The problem was fixed by the manufacturer, General Electric, through a modification of the compressor. The number of failures reported to the flight safety network steadily decreased from nine in 1975 to one in 1980.

15. The J85-CAN-40 as installed in the CT-114 aircraft has experienced a significant problem in the fatigue cracking and failure of the first stage compressor blade at the blade root. QETE has reviewed the first stage failures as the exact mode of failure was under dispute.[4] The root cause of the first stage cracking is the slow response of the inlet guide vane control system to changes in temperature. The control system can take as long as 10-15 seconds to respond to a step change in temperature, resulting in a period of aerodynamic instability at the first stage blades. The cracking has been alleviated through improved maintenance and component change-out at overhaul. The slow response of the control system has been investigated, but no solution is readily apparent.[5]

16. Historically, the CF-101 Voodoo was infamous for fatigue problems with the J-57 engine, particularly in the early 70's.[6] Unfortunately, there are no engineering details readily available. Included in this survey are two aircraft which were lost from failures of the fifth stage compressor blades and also from a compressor disc failure. There is no immediate record in the flight safety messages of the root causes of these failures. However as will be seen below, some failures investigated by QETE have determined manufacturing flaws as a major cause factor in fifth stage blade failures.

17. The T63 engine as installed on the CH-136 had some problems early in its service life. Introduced into service in 1971, the compressor rotors were re-lifed to 2600 hours in 1973. It is likely that this re-lifing addressed an LCF problem, but the exact reason has not been uncovered in this study. This situation accounts for one half of the recorded flight safety incidents with this engine. The other incidents occurred in 1984 as a result of the compressor lining delaminating from the compressor case. This destabilized the airflow and induced HCF failures of the compressor blades. The problem was so severe that the compressors on all engines were changed.[7]

18. Unexpectedly, there were several compressor failures in the JT3 engine on the CC-137 (B707). Of the two investigations undertaken by QETE, one failure was attributed to braze

failure and the other to abnormal vibration as a result of maintenance. Other factors that could be considered include FOD ingestion on thrust reverse and inlet distortion during thrust reverse or air-to-air refueling exercises.

19. As is readily apparent, most of the reported incidents arose due to one root cause. When discounting the 18 plus incidents reported with the J85-CAN-15 engine, at most 6 (or less than 25% of the incidents reported), had some other root cause. Considering the number of hours flown on this fleet, the occurrence rate would be very low. Similar points are noted for the CAN-40 derivative, the J57, and the T63. Notably, the JT3 engine appears to have had no two failures from the same root cause. As the CF-188 is the only aircraft of the top six that is currently in the CF inventory, its failure history will be examined in greater detail below.

CF Failure Analysis Experience

20. In September 1990, QETE was tasked to conduct a survey of the CF gas turbine engines. The objectives were to:

a. determine and record failure modes and causes;
b. identify susceptible engine components which cause high rates of failure and engine removal; and
c. identify the materials of such components wherever possible.

21. The QETE findings within more than 118 engine related failure analysis reports authored by QETE personnel were used as a source of information for the tasking. The reports reviewed covered a span of some 16 years, 1974 to 1990. This represents only a partial sampling of all the engine component failures experienced in the Canadian Forces, as a large number of failures were investigated at the engine overhaul contractors because of the large number of tools and special fixtures required to disassemble an engine. The engines included in the QETE survey were the J57-P-13, J79-GE-11A, NENE 10, R1820, T53-13B, T55-11C, T56 Series II and III, T58-GE, T63, and T64. (The R1820 is a radial piston engine and those incidents were removed from consideration in the analysis within the present report.) The QETE survey reviewed their own failure analysis experience to determine the failure mechanism/mode and causes, and the materials of the failed components whenever possible. The data included the engine type, aircraft, component/system, materials (if known), failure cause (or mode) and corrective action. The failure causes were classified into several categories which were comprised of abnormal use/abuse, improper maintenance, design

deficiencies relating to material selection and/or geometry of the component, and manufacturing/assembly related defects. Note that fatigue is not listed as a cause, but as a mode of failure.

22. The resulting QETE survey[8] gives a broad interpretation of their failure investigation experience. Of particular note is that in all their investigations, some 70% attributed the mode of failure to be fatigue. Unfortunately, no complete breakdown of the failures was given, but summary data tabulated by failed component, aircraft, engine, failure mode and cause, were given. It is this data, given in Table 11 of their survey, that has been further examined below.

23. To start, it may be instructive to tabulate the failure investigations undertaken by QETE and compare them to the flight safety history given above. Where possible, the engine make and model is matched with an airframe and the QETE investigations are compiled at Table 3.

Table 3: Results of QETE Survey:
Failure Investigations by Aircraft Type Ranked by Number of Investigations.

Aircraft Type	Compressor Section	Total Investigations
CF-188 Hornet	7	7
CF-101 Voodoo	6	20
CF-104 Starfighter	5	11
CT-114 Tutor	3	3
CC-137 (B707)	2	3
CT-133 T-Bird	2	3
CH-136 Kiowa	1	5
CC-115 Buffalo	1	4
CH-147 Chinook	1	3
CP-140 Aurora	1	3
CF-116 (F-5)	1	2
CC-144 (CL-601)	1	1
CC-130 Hercules	0	3

24. In comparing the compressor failure investigations, this table is not significantly different from the results from the flight safety survey above. The top four engines are thrust engines, the top three from fighter aircraft. Here, however, the J85 powered aircraft, the CT-114 and the CF-116, are relatively under-represented. It is reasonable to assume that as the J85 suffered from a known design problem, the compressor failures were not sent to QETE for failure analysis. Conversely, CF-104 Starfighter has higher representation here. It would be reasonable to make a similar assumption in that the nature of the compressor failures (cracked IGV's, stator shrouds) may not have resulted in a flight safety incident, but were of sufficient concern to the engineering authority to warrant a QETE investigation. In all, both Tables 2 and 3 clearly show that HCF is a problem for thrust engines.

25. On first examination of the fatigue failures listed within the QETE survey, they can be broken down by engine section: compressor, hot end, and other. The "other" category includes engine components such as bearings, pumps, gearboxes, and generators. The results are presented at Table 4. Of the 75 failure investigations, there were 34 carried out on compressor components. It should be noted that in seven investigations, two failure causes were given.

Table 4: Failure Causes by Engine Section.

Section	Design	Maintenance	Manufacturing	Environment	Undetermined
Compressor	16	11	8	0	1
Hot End	9	6	4	1	2
Other	11	11	2	0	0

26. The data here suggest that the compressor and turbine components have a majority of the fatigue failures. The turbine failures were almost all due to high temperature phenomena such as creep and thermal fatigue. Of note is that the failures attributed to the manufacturing and maintenance categories combined are slightly higher than those attributed to design. This may indicate that a fatigue failure will likely be the result of an action taken to make or maintain the engine, as opposed to a fundamental design problem. Another interpretation is that the failures may be related to a design weakness that is aggravated by poor manufacture and maintenance practices. Further examination of the compressor failures by components leads to the breakdown given at Table 5.

Table 5: Failure Causes by Compressor Sections

Component	Design	Maintenance	Manufacturing	Undetermined
core	14	9	7	
lever arms	2			
ducts		2	1	1

27. The core category includes the failure of blades, inlet guide vanes, stators, and discs. As such, it is not surprising that the compressor core is responsible for the largest fraction of fatigue failures. As this breakdown by component does not offer any novel insight, a different breakdown is attempted at Table 6 where the failures are listed by the cause factor assigned to that failure. Unfortunately, a cause factor of cracking was assigned in six investigations and no initiation mechanism could be determined given within the QETE survey. There were three investigations listed within the survey which could not be fit into this breakdown as the failure mechanism was not clearly stated.

Table 6: Compressor Failures by Failure Modes

Cause Assigned	Design	Maintenance	Manufacturing	Undetermined
vibration	2	5		
resonance	4			
cracking	4	1	1	
stress concentration	3		1	
poor braze			4	
fretting		2		
wear				1
excessive clearance		1		
inherent defect	1			

28. Of these failure modes, vibration and resonance are typically associated with HCF failures. The cracked components include inlet guide vanes, blades at the dovetail, and at bolt holes in discs. The vane and blade cracks could be caused through vibration induced HCF,

and by the bolt holes acting as stress concentrators. The actual failure analysis report could be consulted for clarification but, if there was an initiation mechanism given in the original analysis, then it is reasonable to assume that it would have been listed in the survey. Stress concentration is a typical contributor to LCF failures but again, it can be difficult to distinguish between HCF and LCF. For the failures due to a poor braze, three of the four braze failures attributed to manufacturing were associated with the J57 fifth stage blades and one failure is clearly denoted as having occurred through HCF. Of all 34 fatigue failures considered in the QETE survey, HCF has been clearly stated for only four failure investigations.

29. There are a few trends that can be discerned from a closer examination of each investigation and cause factor in Table 6. The design cause factor appears common to all failures, where most failures attributed to maintenance or manufacturing factors result from a task being completed that was outside of specification or tolerance; for example, poorly machined radius or poor quality braze joint. On review of the resonance failures, these occurred on the T56 IGV's and on both the J57 and F404 compressor blades. The maintenance induced vibrations were due to improper installation, including improperly applied torque. This may have resulted in a form of resonance. It appears that the resonance modes can be associated with design failures; and vibration to maintenance, but this could also be, in part, due to the definition of resonance and vibration used in the failure analyses.

CF-188 Experience

30. The trend for HCF failures has been that it is a problem for fighter engines. As Canada's most advanced, and only, fighter aircraft, it would be prudent to examine some of the HCF failures that have occurred with the F404 engine. In the past, there have been several HCF failures, all of which have had fixes developed by the manufacturer, General Electric. Some failures have been well investigated and documented by QETE[9]. Various discussions with the F404 engineering office has produced the following three points:

a. HPC stage first and third blade failures have occurred because of variable stator oscillation (lever arm connections broken or disconnected). These failures caused fires in the titanium cases. Engines have been refitted with steel cases and the lever arms have been redesigned.

b. HPC first and third stage blades have cracked and failed due to improper blade twist. The blades were replaced in 1990-1991.

c. LPT blade failures as a result of combustor inner and outer liner failures. These combustor failures disturbed the airflow which in turn caused a once per revolution excitation in the LPT section.

31. The engineering staff have stated that as no additional problems are anticipated by the operators, they have no great priority for HCF detection. Most recently, however, there was an incident where a fan blade was lost in flight. The failure investigation by GE was not conclusive, but did suggest that the root cause was aggressive grit blasting during overhaul. This would change the properties of the surface of the fan blade and increase the susceptibility to HCF. On further investigation, there are some 9,000 blades in service that have had this aggressive treatment and the cost associated with changing these blades is on the order of nine million dollars in parts alone.

Discussion

32. Overall, HCF failures have occurred in a number of engine models and in a variety of locations in the engines, including both rotating and stationary components. High frequency stresses and energies are characteristic of both gas turbines and HCF failures. It is clear from this study that despite the fact that HCF is taken into account in the design, manufacture, and maintenance of the equipment, HCF failures still occur in the failure chain of events. For the engines with the highest number of occurrences; the J85, F404, and J57; many D Category incidents were due to the same root cause, usually related to a design or lifing issue. Other occurrences arose due to a systematic maintenance fault that affected the whole fleet at a tremendous cost. In this regard, the CH-136 compressor coating delamination problem is an interesting parallel with the current in-service problem with the F404 fan blade. From the flight safety data, the CF experience has been that the circumstances surrounding the failure will apply to the entire fleet with an associated high cost. For the engines with a lower number of occurrences, the failures of separate components do not appear to be related, such as for the CC-137 aircraft. Although this aircraft/engine placed sixth, there is no apparent trend in the failed components nor root causes of failure.

33. A complete assessment of the costs associated with these occurrences is outside the scope of this survey. However, the repair costs could be calculated to a rough order of magnitude. Given that there were 87 D Category incidents reported through the flight safety

system and assuming that each incident resulted in a repair cost of about $200,000 (not counting the A and B category accidents), the total repair cost would be on the order of $17 million. This does not include maintenance actions taken such as the complete change out of the CH-136 compressors, or the current $9 million cost to lower the risk associated with the F404 fan blades. Thus without properly addressing the costs, it is already apparent that the impact of an HCF problem on the operations and maintenance is considerable. The challenge is to reduce the impact of future HCF problems within the present resources.

34. The thrust engines currently in Canadian service are the F404 (CF-188), the J85 (CT-114), and the CF6-80 (CC-150 (Airbus A310)). The CC-150 aircraft are maintained by Canadian Airlines to a civil standard; however, that does not mean that its CF6-80 engine would be immune to HCF failures. An aircraft has already experienced an incident where fatigue in the compressor may have played a role. (The failure was reported in the CF Flight Safety system, but the follow-up was conducted through the CAL system.) The CF-6 engine is common throughout the commercial industry and improvements may be better pursued through that community. Although the J85 engine is fairly mature, the first stage blade remains susceptible to high cycle fatigue. As mentioned above, this susceptibility has been controlled through increased vigilance in maintenance. The F404 engine is relatively mature; however, the engine is much more sophisticated and requires significantly more resources to maintain. Furthermore, there is not a great deal of experience in Canada with titanium metallurgy, particularly with respect to fracture behaviour and lifing issues. A research program that would identify some important parameters would be a valuable resource to the CF in controlling the costs and managing the risks associated with HCF problems.

35. The flight safety survey gives the nature of the HCF problems, but it is the QETE failure analysis that gives some indication of how these problems manifest themselves in the engine. As has been mentioned, differentiating between a high cycle and a low cycle fatigue failure may not be straight forward. Establishing the mechanical response and failure behaviour of titanium metals, particularly those in use in the F404, would clarify this issue. The research outcome may then be used to develop advanced vibration techniques which would address the fact that resonance and vibration were characteristic of over one half of the failures examined. To address the maintenance and manufacturing flaws that may appear from time to time, a better understanding of the resonance modes of the engine for off-design components or maintenance actions would be required. Perhaps only a modest upgrade in vibration monitoring would result in a capability of detecting known trends and/or step changes in the signals which would indicate a progressive or sudden deterioration in

condition.

36. USAF HCF initiative[10] has developed several promising technologies that may be adapted by the Canadian Forces. Laser shock peening, which induces very high compressive stresses in titanium, is currently being tested and validated by the USAF at Wright-Patterson Air Force Base. Other advanced technologies, such as a fan blade eddy current sensor which detects blade displacements and hence vibration and fretting modes, have been transitioned to the joint strike fighter.[11] Both may be useful technologies in application to the F404, and in the case of the eddy current sensor, applicable to monitoring the first stage blades in the J85 engine. As the National Research Council of Canada's Institute for Aerospace Research (NRC-IAR) has extensive experience with both of these engines and has also worked closely with the overhaul contractor for these engines, it would be the ideal organization to examine and evaluate such technologies on behalf of the Canadian Forces.

37. The current DND/NRC-IAR collaborative research program includes an initiative to study the dynamic response of gas turbine components, bringing together the present expertise on material properties, lifing technologies, and vibration analysis. This modest technology investment addresses the need for a better understanding of low cycle fatigue mechanisms and is directed at increasing the Canadian Forces' ability to manage risk, component life, and control the cost associated with this failure mode within gas turbine engines. As part of this collaborative research program, NRC-IAR also actively participates within the AER-TP3 panel. A collaborative program, CP3C.2: High Cycle Fatigue (HCF) Diagnostic Development, is exploring the idea of defining and monitoring HCF forcing function regimes and developing the necessary algorithms in an attempt to monitor HCF usage. Thus, the current efforts undertaken by the DND/NRC-IAR program may be expanded at some cost to include an examination of HCF issues, complementing the direction and application of international programs.

Summary

38. The Canadian Forces have had HCF problems with their engines; whenever an HCF problem has occurred, the CF had it addressed and resolved largely through the engine manufacturer. However, the detection of HCF remains a worthy goal for two reasons. Firstly, the failure is likely to be sudden and catastrophic. Secondly, the costs incurred to prevent a repeat failure is very high. Specific points that can be drawn from this study are:

a. The HCF problem is most prevalent in thrust engines, particularly those used on fighter aircraft,

b. For the HCF failures that have occurred in flight, one third occurred between engine start and end of climb,

c. The resonance and vibration failure mode categories accounted for most of the failures,

d. Improperly conducted maintenance and problems in manufacturing may result in failures through resonance or vibration, and

e. HCF problems have a very high hidden cost as they usually affect the majority, if not all, of the engine fleet.

39. The dynamic structural response project under the DND/NRC-IAR collaborative program could be seen as a first step in addressing the materials, lifing, and vibration issues related to gas turbine component failures. This project could be expanded, at the expense of the other projects within the collaborative program, so that NRC-IAR could pursue programs under partnership with QETE, TTCP AER-TP3, or other collaborative arrangements. These programs would address issues raised in this study and could include such areas as:

a. the fracture behaviour of titanium alloys in both low cycle and high cycle fatigue,

b. vibration sensors to detect an active resonance mode of a component; and

c. diagnostic routines to determine what is resonating or vibrating, or to determine changes in the vibration signature of the engine (component).

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This study was undertaken to identify the Canadian Forces' experience with high cycle fatigue failures in aeroengines. The three specific objectives were to determine any trends based on an analysis of historical data, provide some direction to research and development efforts that would lead to a better understanding of HCF failures, and lastly, to offer comment on areas of collaboration amongst The Technical Cooperation Program partners. The two sources of information consulted were the flight safety data held in the aircraft accident and incident information system (ACAIRS) and the pool of failure analysis reports held at the Quality Engineering and Testing Establishment in Hull, Quebec. In this study, it was found that whenever an HCF problem has occurred, the CF had it addressed and resolved largely through the engine manufacturer. The HCF problems were most prevalent in thrust engines and have a very high hidden cost as they usually affect the majority, if not all, of the engine fleet. A technology program to control the costs and risks associated with HCF failures is possible, and would be focussed on F404 engine materials. The program elements proposed would build on the current dynamic structural response project under the 3.g.a DND/NRC-IAR collaborative program in aeropropulsion.

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