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TURBO-MACHINERY MONITORING MEASURES FOR PROPULSION SAFETY AND AFFORDABLE READINESS

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ABSTRACT

The US Department of Defense initiative for propulsion safety and affordable readiness (P-SAR) has been engaged by all three services as a means to mitigate the operational and environmental hazards to aircraft propulsion system integrity, dependability and life cycle cost in military service. This paper focuses on the turbo-machinery of military propulsion systems and addresses the options available to manage turbo-machinery health and life cycle cost.[1]

Three primary turbo-machinery integrity and performance degraders are identified: foreign object damage, erosion and corrosion, and high cycle fatigue due to aero-elastic response of turbo-machine blades & vanes. A variety of sensors have been proposed as measures to monitor and mitigate the hazards created by such degradation. Many of these were developed as tools for use in component models & design verification, such as non-intrusive stress measurement systems [NSMS] - an indirect means to supplement direct on-blade strain measurements. Others tools have been defined specifically for in service monitoring, such as the use of miniature radar to detect blade motion.

This paper follows a systems engineering analysis identifying alternative functional hazard mitigations and a qualitative reliability centered maintenance (RCM) view to assess alternative approaches to mitigation of each hazard. Finally, synergies across the three priority degraders are considered to recommended topics for research.

NOMENCLATURE

P-SAR	propulsion safety and affordable readiness
NSMS	non-intrusive stress measurement systems
RCM	reliability centered maintenance
HCF	high cycle fatigue
FOD	foreign object damage
FMECA	failure mode, effects and criticality analysis

INTRODUCTION: SCOPE & BACKGROUND

Military aircraft operate in challenging and often hazardous environments that affect the safety of operation, availability and life cycle cost of aircraft propulsion systems. In 2004 United States Air Force, Navy and Army joined forces to launch a Propulsion Safety and Affordable Readiness [P-SAR] [1] initiative to mitigate the effects of this severe usage. Military aircraft operate in demanding roles from often minimally prepared sites, or seaborne platforms, that expose their propulsion systems to usage and degraders that challenge the best efforts of their designers, developers, builders, operators and maintainers. In particular, the turbo-machinery in military aircraft propulsion systems is highly stressed and more exposed to damage and degradation than that in commercial aircraft, while the difficulties of maintenance and logistical support are exceptional.

The P-SAR inspired study reported here was funded by the Office of Naval Research to address three major factors affecting gas turbine propulsion system reliability and durability: foreign object damage, erosion and corrosion, and high cycle fatigue due to aero-elastic response of blades & vanes, excluding shafts and bearings. The emphasis is thus on the propulsion system fan and compression sections, the gas turbine modules most exposed to these hazards.

The motivation for this study was the availability of relatively mature technologies developed to perform blade tip timing, i.e., detection and precise timing of the passage of the tips of turbo-machine blade past sensors in the turbo-machine shroud or

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[1] The work resulting in this paper was performed under funding by the Office of Naval, under the direction of Dr. Joseph Doychak.

casing. These technologies were developed as part of a systematic approach to a major challenge in the design of highly loaded turbo-machinery; high cycle fatigue [HCF] due to aero-elastic excitation of blade vibration resulting in blade mechanical failure causing costly damage and hazardous engine failures.

Blade tip timing provides a cost effective alternative to the prior state of the art method for validating that compressor designs were free of dangerous high cycle fatigue, i.e., extensive strain gauging of the compressor blades during compressor rig testing. It is less intrusive, requires only instrumentation of static components and is usually more dependable. The method was developed using optical probes that are reasonably durable in the compressor test bed environment. (See Dhadwal, et al [2] for example.) Such blade tip timing instrumentation is used for "non-intrusive stress measurement systems" [NSMS], as they enable the inference of dynamic strain and stress levels in compressor blades with well characterized mechanical properties and vibration modes.

As blade tip timing technology proved itself in design and development test and evaluation it attracted attention in another sphere, the health and maintenance management of propulsion systems in military service. Despite the advances in preempting HCF in compressor design and development, some legacy propulsion systems remain vulnerable, current engine designs may exhibit HCF when installed due to unanticipated inlet airflow distortion, and compressors sometimes develop unanticipated HCF modes as they degrade in service. The demanding and unpredictable operation usage of military propulsion systems can aggravate these concerns.

As noted by Lawson & Ivey [3], Cardwell, Chana and Russhard [4], the optical probe approach is sensitive to contamination in service which renders it impractical and these and other investigators developed capacitive and eddy-current blade passage sensors. Joung, et al [5] have even applied this technique to turbine blade NSMS.

Furthermore, other service related challenges appeared amenable to mitigation using blade tip timing techniques. The operational environments of military aircraft make their propulsion systems vulnerable to foreign object damage [FOD] and compressor blade erosion by ingested sand and dust. Shipboard naval aviation exposes propulsion systems to corrosion that can also contribute to compressor blade degradation and failures. It seems an easy extension to apply blade tip timing to detect compressor blade damage and degradation from these causes. As a result, work was started to develop FOD detection systems using eddy-current tip timing (Chana & Cardwell [6]) and continues (Cardwell, Chana and Gilboy [7]) in combination with acoustic emissions sensors. The propulsion system of the F-35 Lightning II utilizes an eddy current sensor to monitor the structural health of fan blades.

However, there are alternative technical approaches to be considered. Fan and compressor shaft torsional vibration measurements might detect foreign object ingestion. Others have developed "engine health diagnostics using radar" which has demonstrated capability to measure blade row vibration [8] and foreign object ingestion [9].

These health management options are of interest in military aviation as the primary maintenance mitigation for these the risks of concern - fan and compressor HCF, foreign object damage and erosion and corrosion – is intensive and intrusive periodic inspection. This reduces aircraft availability and adds to maintenance workload. Increased maintenance workload requires the costly sustainment of more maintenance personnel, often in harm's way. Periodic inspection seldom eliminates all risk, as damage may remain undetected or develop too quickly for inspection to prevent hazardous failures.

However, developing and deploying equipment that is satisfactory for field service from instrumentation and systems suited to rig and test bed use is not trivial, nor cost free. Nor is it free of unwelcome impacts to aircraft performance, maintenance effort and affordability. Sensors, interconnections, signal acquisition and data processing to make the results useful to the maintainer add to aircraft weight and cost, and take up precious volume. Retrofit to existing aircraft is likely to require extensive modification and possibly replacement of existing propulsion system and aircraft components. Such complex kit itself adds to the maintainers' workload and degrades aircraft availability if, as it may, it is considered dispatch critical. Spares and replacement parts add to already difficult sustainment challenges.

Furthermore, periodic inspection has certain virtues. It is predictable in terms of effort and timing, and can detect and adapt procedurally to the unexpected, not a strength of automated equipment. Since the unexpected is the norm in military operations, and configuration change is the baseline approach to degraded operational reliability and availability, any health management equipment must adapt rapidly to changing needs to be useful. It must also be intelligent, in the sense of not adding additional tasks (such as data collection, transmission, analysis and interpretation) that are more demanding that the periodic inspection it is intended to displace.

Thus we have a difficult tradeoff to resolve in exploiting the promise of blade tip timing, or other technologies that might be more suitable to the needs of propulsion system turbo-machinery maintenance and health management. This is reflected in the facts that although the technical capability has been demonstrated for many years, blade tip timing and the alternatives have yet to enter service.

The purpose of the work reported here was not to make definitive determination of these tradeoffs, but to identify the range of maintenance process options created by the availability of such tools and qualitatively assess their relative suitability to the operational needs. The objective addressed is to identify relevant technical and procedural options while accepting that the specifics of each aircraft & propulsion system's operational context, reliability and susceptibility, known or probable failure modes, and their effects would decide the appropriate measure(s) to be taken to mitigate these risks. The expectation was that this might provide insight into the requirements and metrics for the technologies described above in mitigating the identified hazards to propulsion turbo-machinery, but primarily to define capability gaps limiting the exploitation of the technologies to identify appropriate research and development priorities.

The established and prescribed method at the Navy to resolve such tradeoffs is reliability centered maintenance [RCM] introduced at the Navy in 1986 by MIL-STD-2173 [10] and more recently promulgated by NAVAIR 00-25-403 [11]. Thus the perspective of RCM is adopted below to address the purpose and expectations of this work.

RELIABILITY CENTERED MAINTENANCE

The RCM process illustrated in fig. 1 follows systems engineering principles in adapting the systems engineering process to the needs of the maintenance process.

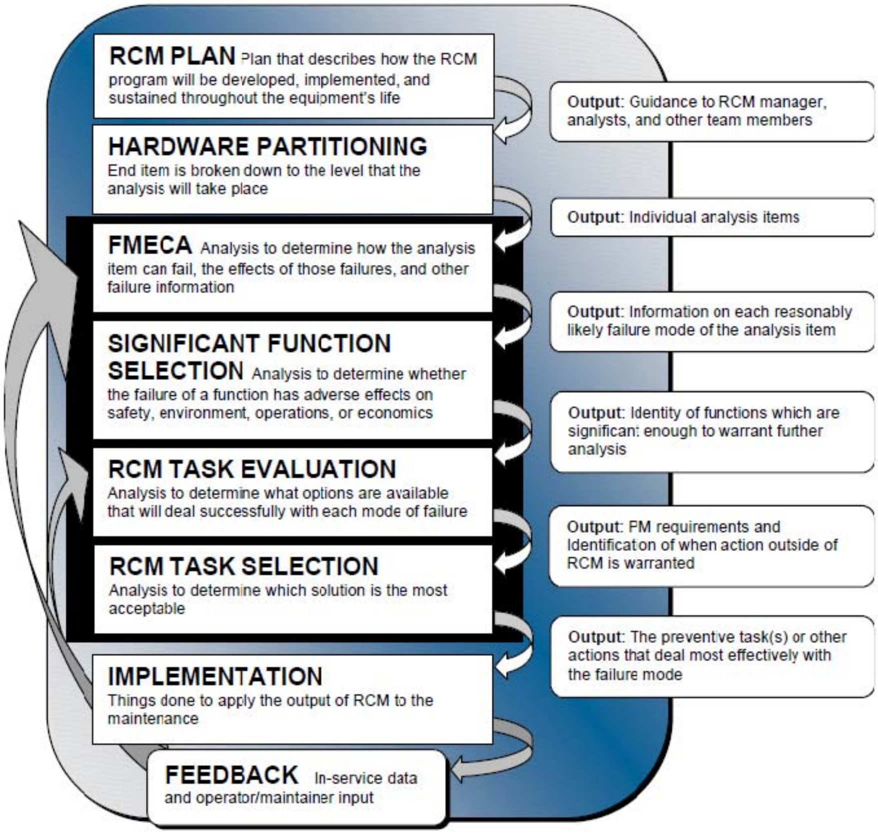

Figure 1: US Navy Reliability Centered Process (Extracted from NAVAIR 00-25-403 [11])

Failure mode, effects and criticality analysis [FMECA] (Refer to MIL-STD-1629A (1980) [12] and numerous more recent documents.) defines the need, implicitly "mitigate the identified failure modes impact on safety, reliability and affordability". Analysis then prioritizes these needs vs. the "adverse effects on safety, environment, operations, or economics" to define the RCM requirements.

For each priority requirement alternative approaches are generated and assessed to select the RCM tasks to be implemented. The fruits of that implementation in service are fed back to guide corrective action and FMECA updates to trigger timely RCM response to emergent failure modes.

Consider the following generic hierarchy of preventative and condition based maintenance approaches that might progressively exploit blade tip timing or alternative technologies:

a) Periodic visual & physical inspection; direct or remote (bore scope / manipulator)
    i. cycle or flight hour based
    ii. exposure (usage) based
b) Periodic evaluation using embedded or test only sensors and ground test equipment;
    i. static, or
    ii. during ground running
c) Periodic flight check using embedded or test sensors with:
    i. test only, or
    ii. embedded signal acquisition/recording/ analysis provisions
d) Continuous in flight monitoring with:
    i. post flight assessment and maintenance action, or
    ii. pilot annunciation/action.

Progress through this hierarchy implies increasing criticality and severity of the effects of the failure mode of interest, higher frequency of occurrence and shorter delay between the detection threshold and failure. Similarly, there is likely to be progressive increase in operational, performance and affordability implications with greater reliance on monitoring equipment dependability.

If the technical approach being considered can address more than one failure mode, the improved payback might shift the optimum solution to the more intrusive end of the spectrum.

A major consideration must also be the overriding alternative of turbo-machinery configuration change to mitigate the failure mode, which also becomes progressively more likely as the RCM mitigation becomes more onerous. Once this alternative enters the picture the optimum RCM solution will tend to shift to the labor intensive, low investment end of the scale as a transient mitigation pending incorporation of more durable and resistant components.

CONSIDERATION OF SPECIFIC FAILURE MODES

Focusing on the three failure modes of concern (foreign object damage, erosion and corrosion, and high cycle fatigue) one can apply a qualitative RCM perspective while considering their specific characteristics.

Foreign Object Damage [FOD]

FOD is highly variable with the character of the object ingested, from immediate engine surge or shutdown with ingestion of a large bird to insidious damage accumulation from small hard objects such as pebbles, nuts, and lock wire. The severe events are less common and usually apparent to the pilot; the mission may be aborted or the event reported on landing. Intermediate damage levels may result in degraded performance that may or may not be apparent to the pilot. Our concern here is the mid to lower end of the scale where relatively minor damage, imperceptible to the pilot, can precipitate later blade failure with secondary damage that results in engine failure and avoidable repair costs for secondary damage to the engine.

Ideally the imperceptible damage levels are partially mitigated by post or preflight visual inspection of the fan/compressor face; although many military engine installations make this difficult. However the primary purpose of periodic inspections is to detect incipient blade failure; the goal is to move to “condition based” inspection triggered by evidence of foreign object ingestion, or the resultant FOD.

Blade tip timing may accomplish this goal by detecting ingestion by either sensing blade motion or sensing blade deformation or breakage. In the first case the blade tip timing would have to be operational at the time of the event, perhaps only during high risk takeoff, landing and ground operation. In the latter case option b. ii above (checks during ground running) might suffice. Acoustic noise detection, radar and shaft torsion transients have been suggested as alternatives, see above.

More direct alternatives for detecting foreign object ingestion have been proposed, e.g., electrostatic sensing [13] and microwave radar [9]. All options carry the burden of significant signal acquisition and computational overhead.

Erosion and Corrosion

The primary hazard to be mitigated here is secondary mechanical failure, with options similar to FOD. Blade erosion can also trigger HCF, so this possibility is considered below. Erosion also degrades compressor performance and thus available power, a particular concern for vertical takeoff & landing platforms.

Blade tip timing should have the capability to detect some erosion patterns and some impending failures due to either erosion or corrosion, either through leading edge removal or blade displacement. It is not established that this would be effective enough to displace visual inspection, and seems more of a secondary benefit where justified by another failure mode.

An alternative could be usage based scheduling of visual inspections, e.g., a count of operations from unimproved landing zones. Automated power check (available power meter) is a more direct and broadly useful tool to assure adequate engine power output.

High Cycle Fatigue [HCF]

Great strides have been made in design and development methods (including NSMS) that assure that propulsion system compressors are less subject to failure due to high cycle fatigue. Nevertheless, blade tip timing has evident potential for the mitigation of HCF induced failure where it does appear; ab initio, e.g., from installation effects, or due to deterioration in service, such as rework, erosion or fouling. It should be capable of tracking aero-elastic excitation and the resultant vibration modes and amplitudes to provide precise information on blade HCF life usage, similar to its use in NSMS, as long as the blade characteristics are similar to the as new, to print, configuration.

However, the number of sensors required per blade row, the number of blade rows to be monitored, the multiple signal acquisition channels needed and the computational overhead to implement this approach are a high hurdle to overcome. The operator can be expected to prefer a robust compressor design that reliably survives expected usage between major service intervals.

More pragmatically, simply by detecting and logging abnormal blade motion, which could need fewer sensors and simpler signal processing, blade tip timing (or microwave radar) might be used to flag the need for inspection on condition, preempting aggressive periodic inspection requirements in circumstances where HCF is less predictable. Such minimalist blade tip timing also promises the capability to detect incipient blade failure due to HCF induced cracking by detecting blade deformation, similar to its use to detect FOD. If these risks can be localized to one or two blade rows, this may be an effective alternative. If the end can be achieved by means of periodic ground runs or flight checks - options b) ii and c) i above – this might be yet more cost effective and acceptable.

However, the alternative to redesign and upgrade the compressor to mitigate such risks may be preferred, particularly if it can be accomplished within the comparable timeframe to deploy a blade health management system.

CONCLUSIONS & RECOMMENDATIONS

Blade tip timing is no panacea promising the wholesale elimination of periodic compressor inspections but does have promise in targeted applications, particularly where blade rows are inaccessible or subject to the risk of both FOD and HCF induced failure, e.g., highly loaded fan stages. A side benefit might be the partial mitigation of erosion damage. Other alternatives need to be assessed using rigorous RCM analysis, fully considering the likely need for change to the FMECA and RCM update as the equipment degrades in service. (See Millar [14] for an expanded discussion.)

Other, simpler, technical approaches, including ones that are inadequate for NSMS use, may offer a better match to maintenance needs and should be considered as alternatives. However, to avoid or significantly reduce the need for periodic inspection, the method selected will preferably address the risks of all three root causes of fan and compressor failures.

Qualitative functional objectives and considerations for a compressor turbo-machinery monitoring system optimized to satisfy requirements for in-flight or ground run assessment of compressor blade health for FOD, erosion/corrosion, and HCF to guide on-condition maintenance might include:

1. Detect and quantify individual blade deformation and loss of material (tip breakage, tears & erosion).
2. Detect and quantify abnormal motion of blade rows as an ensemble or individually, preferably with some discrimination of known modes.
3. Minimize sensor numbers per blade row monitored, and the associated case penetrations and sensor and harness size & weight, i.e., intrusiveness.
4. Minimize signal acquisition and computational infrastructure. (E.g., provide the capability to sequentially monitor blade rows, innovative and parsimonious signal processing, etc.)
5. Minimize need for maintainer data collection and analysis.
6. Provide unambiguous and reliable operationally appropriate direction.
7. Minimize transmission of time critical and high bandwidth data.
8. Provide capability for analysis of fleet wide effectiveness and rapid system update.
9. Implemented and upgraded relatively quickly and economically to address emergent hazards affecting equipment in service, including maintenance process criteria and change.

Considering the increasing initial and recurring cost, complexity, inflexibility and intrusiveness of moving down the RCM maintenance alternatives hierarchy, and the above requirements, it seems safe to recommend RCM analysis take due consideration of the intermediate options of:

- inspections driven by exposure or usage logging vs. flight cycles or flight hours,
- ground runs using embedded sensors and ground support equipment [GSE] based data acquisition and analysis,
- periodic (e.g., during ground operations and takeoff) vs. continuous in-flight monitoring.

In terms of a responsive science and technology program exploring and improving the utility and suitability of the technical options, the writer recommends the following research topics:

A. Investigate the feasibility of optical fiber based capacitive or eddy current sensors, particularly those amenable to wavelength, code or time division multiplexing of multiple sensors in-line. This could improve BTT suitability for monitoring multiple blade rows.
B. Investigate the applicability and feasibility of computationally less intensive signal analysis for HCF exposure logging, e.g., frequency / intensity bins analogous to vibration monitoring.
C. Investigate the potential of shaft torsion transients and vibration for FOD and blade flutter detection, possibly combined with shaft &and bearing monitoring.

Note: Some types of blade tip timing equipment have also proven to be capable of monitoring tip clearance, suggesting synergies, but the best payoffs for this application are likely to be in the high pressure (and temperature) sections of the turbo-machine, possibly requiring additional and different technical and physical implementation. Thus, this has not been considered in the work reported here.

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