Design Concepts to Meet EASA SC-VTOL-01 Single Failure Criteria

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ABSTRACT

The objective of the current work is to discuss European Union Aviation Safety Agency (EASA) SC-VTOL-01 single failure criteria, VTOL.2250(c). VTOL.2250(c) increases safety metrics compared to existing Vertical Takeoff and Landing (VTOL) regulations, creating new engineering challenges that must be addressed. Additionally, research and development targeting compliance against VTOL.2250(c) will more broadly benefit the VTOL industry, providing guidance for safer system designs. Prior studies have developed concept distributed propulsion and flight control (DPFC) system architectures and found they comply with EASA SC-VTOL-01 probabilistic failure criteria, VTOL.2510(a). Prior work developed two all-electric DPFC systems utilized in a quadrotor concept aircraft developed by the National Aeronautics and Space Administration (NASA); one uses interconnecting shafts and gearboxes to interconnect redundant motors with each rotor system and the other uses gearboxes to connect redundant motors locally, near each rotor. Common between the two electric DPFC systems were rotor shafts, epicyclic systems, and motors. The current work explores Category I failures in drive systems, relevant research to support fail-safe design practices for gear systems, research and adjacent industry trends in motor fail-safety and reliability, and proposed design concepts to comply with VTOL.2250(c). Continued research in fail-safe design concepts and design guidance will benefit eVTOL and conventional rotorcraft, alike. Continued research in these areas will benefit eVTOL certification against SC-VTOL-01, and could optimistically translate to more widespread adoption of similar fail-safe design concepts into new rotorcraft designs certified against CS-29.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) has developed a series of concept aircraft. These aircraft were developed by NASA's Revolutionary Vertical Lift Technology (RVLT) team for Urban Air Mobility (UAM) missions in order to guide industry research and as tools for the industry to prepare for certification of UAM aircraft. Prior studies have developed conceptual distributed propulsion and flight control (DPFC) system architectures to evaluate the safety of various NASA RVLT Concept Vehicles (Ref. 1, 2, 3). Concept DPFC systems and safety analysis have been previously presented to the Vertical Flight Society (VFS) community (Ref. 4, 5). Results of prior work found that a system safety approach should be taken during the conceptual design phase of any new aircraft configuration giving consideration to type certification requirements to reduce or eliminate costly redesign efforts. Prior work also found that adding rotors to balance static equilibrium requirements (as is the stated benefit of many multirotor designs) does not necessarily relate to improvements in occupant safety, reinforcing the need for early system safety analysis.

Unique attributes of the NASA RVLT concept vehicles and propulsion system mean that obtaining a type certificate under typical certification specifications (CS) would be difficult, at best. The European Union Aviation Safety Agency (EASA) has recognized this and has published SC-VTOL-01 (Ref. 6) which establishes certification criteria for vertical takeoff and landing (VTOL) vehicles with unique propulsion and control architectures, including distributing the flight controls and electric propulsion elements as is typical for UAM multirotors, such as the Joby S4 tilting hexarotor (Ref. 7).

SC-VTOL-01 increases the desired safety metrics beyond what is required for CS-27 (Ref. 8), and even CS-29 (Ref. 9). For example, CS-29.1309 requires for Category "A" rotorcraft "the occurrence of any failure condition which would prevent the continued safe flight and landing of the rotorcraft is extremely improbable." In contrast, SC-VTOL-01 requires, "each catastrophic failure condition is extremely improbable and does not result from a single failure." Note that SC-VTOL-01 defines "catastrophic failure" for Category "Enhanced" as the loss of continued safe flight and landing. The notable difference between how CS-29 and SC-VTOL-01 prevent loss of continued safe flight and landing is that SC-VTOL-01 requires that no single failure results in loss of continued safe flight and landing, which is similar to CS-25 (Ref. 10) large, commercial airplanes.

SC-VTOL-01 SUMMARY

EASA issued SC-VTOL-01 in July of 2019, focused on emerging multirotor aircraft for the UAM mission. This criteria is the first regulatory document released in efforts to govern multirotor aircraft. SC-VTOL-01 was not meant to govern aircraft with conventional propulsion and flight control architectures with fewer than three rotors to create lift in hover or low speed flight. It focuses primarily on reliability assessments based on vehicle size, onboard members, use case, and location. SC-VTOL-01 establishes that catastrophic failures of equipment, systems, and installations are “extremely improbable and does not result from a single failure,” and establishes a threshold for Category Enhanced vehicles of 10^{-9} catastrophic failures per flight hour for equipment, systems, and installations.

SC-VTOL-01 requires of Category Enhanced vehicles, the most stringent category for commercial aircraft, that “a single failure must not have a catastrophic effect upon the aircraft”. The means of compliance (MOC) for SC-VTOL-01, MOC SC-VTOL, (Ref. 11) released May of 2021, outlines a method to comply with Category Enhanced structural design criteria. The method includes a safety assessment which should be performed and how it should be performed. A complete list of structural parts and their interfaces should be provided, along with what functions they may perform. The safety assessment should then be performed to identify all structural elements and parts which would lead to catastrophic consequences. All failure modes that are reasonably anticipated and likely possible should be considered along with all stages of flight and operating conditions. The conclusion of the safety assessment should show that non-catastrophic classifications of all single failures show direct compliance with SC-VTOL-01 single failure criteria, VTOL.2250(c).

In the case that single failure leading to a catastrophic failure is identified, structural redesign or reconfiguration must be explored by the original equipment manufacturer (OEM) (Ref. 12). If redesign or reconfiguration is impractical, it should be thoroughly demonstrated that the catastrophic consequence is extremely improbable with compensating provisions, like fatigue tolerance evaluation, operational limits, etc.

The MOC also indicates that multiple failures should be accounted for when the first failure would not be detected during normal operations, like pre-flight checks. Within the single failure criteria, two failure combinations, where one failure can be described as latent and can lead to a catastrophic failure should be avoided in system design.

MOC VTOL.2510.6, similar to AMC 25.1309.6.b (Ref. 10), goes on to describe a fail-safe design concept comprised of two primary elements: (a) a basic objective that a single failure should not prevent continued safe flight and landing and (b) design principles or techniques.

The design principles or techniques are intended to be used in conjunction with each another and “the use of only one of these principles or techniques is seldom adequate.” MOC VTOL.2510.6 fail-safe design philosophies or techniques are:

- MOC VTOL.2510.6.(1): Designed Integrity and Quality, including Life Limits, to ensure intended function and prevent failures.
- MOC VTOL.2510.6.(2): Redundancy or Backup Systems to enable continued function after any single (or other defined number of) failure(s); e.g. two or more engines, hydraulic systems, flight control systems, etc.
- MOC VTOL.2510.6.(3): Isolation and/or Segregation of Systems, Components, and Elements so that the failure of one does not cause the failure of another.
- MOC VTOL.2510.6.(4): Proven Reliability so that multiple, independent failures are unlikely to occur during the same flight.
- MOC VTOL.2510.6.(5): Failure Warning or Indication to provide detection.
- MOC VTOL.2510.6.(6): Flight Crew Procedures specifying corrective action for use after failure detection.
- MOC VTOL.2510.6.(7): Checkability: the capability to check a component's condition.
- MOC VTOL.2510.6.(8): Designed Failure Effect Limits, including the capability to sustain damage, to limit the safety impact or effects of a failure.
- MOC VTOL.2510.6.(9): Designed Failure Path to control and direct the effects of a failure in a way that limits its safety impact.
- MOC VTOL.2510.6.(10): Margins or Factors of Safety to allow for any undefined or unforeseeable adverse conditions.
- MOC VTOL.2510.6.(11): Error-Tolerance that considers adverse effects of foreseeable errors during the VTOL aircraft’s design, test, manufacture, operation, and maintenance.

OBSERVATIONS

Helicopter drive systems have historically been used to transmit power from gas-powered engines to the main rotors and tail rotors. Drive systems are typically flight critical, single load paths, but they are designed to fail in progressive failure modes that will alert the pilot and crew of an impending failure. Gear tooth pitting or bearing spalling are progressive failure modes that create metallic particles that are detected by onboard debris monitors and annunciated to the pilot and crew. Gear tooth bending fatigue cracks and fatigue cracks in shafting are more difficult to detect. Specifically, gear tooth bending fatigue cracks, if left undetected, may lead to gearbox jams in which the two gear teeth try to occupy the same space and prevent the gearbox from rotating freely. Gearbox jams have scarcely occurred, but there are some instances in which a gearbox jam has led to a catastrophic event.

Historical Probability of Drive System Jams

Greaves, et al, reported on European accidents and failure modes for rotating parts. Review of the incident or accident reports for transmission system failures revealed two accidents that were likely related to gearbox jams, tail numbers G-REDL and 9M-SSC. The accident report for G-REDL (Ref. 13) reported that a section of a failed planet gear became entrained between the remaining second stage planet gears and the ring gear, leading to a catastrophic event. The accident report for G-REDL (Ref. 13) also noted that 9M-SSC was subject to a similar main gearbox failure to that of G-REDL, also leading to a catastrophic event. G-REDL crashed in 2009 and 9M-SSC in 1980.

A more recent event, occurring after reporting done by Greaves, occurred on tail number LN-OJF. The accident report for LN-OJF reported that a seizure of the second stage epicyclic gears lead to a catastrophic event (Ref. 14). Based on the accident report, the root cause of the LN-OJF crash may be categorized as a gearbox jam. LN-OJF crashed in 2016.

9M-SSC was an Aerospatiale SA330J Puma (Ref. 13), G-REDL was an Aerospatiale (Eurocopter) AS332 L2 Super Puma (Ref. 13), and LN-OJF was an Airbus Helicopters EC 225 LP Super Puma (Ref. 14). The main gearbox on 9M-SSC is “fundamentally similar in layout” to that on G-REDL (Ref. 13). The main gearboxes on G-REDL and LJ-ONF have “identical epicyclic modules and second stage planet gears,” (Ref. 14). The root of these values was reported to be a crack that initiated at the bearing outer raceway (planet gear inside diameter) and grew through the gear rim, creating a condition in which two gear teeth attempted to occupy the same space (Ref. 14).

A cursory investigation found the Part 135 Rotorcraft have flown a total of 37,534,000 hours between 2009 and 2020 (Ref. 15, 16). Although these flight hours were logged for United States (US) operations, the number of flight hours can be conglomerated with the European accident rates to characterize the historical probability of gearbox jams. Taking the two accidents found between 2009 and 2020, G-REDL and LJ-ONF, and dividing by the number of Part 135 helicopter flight hours yields 5.33×10^{-8} gearbox jams per flight hour, which is close to meeting the SC-VTOL probability of catastrophic failure requirement.

Worldwide rotorcraft commercial flight activity should be investigated further to better characterize worldwide incidents, accidents, and flight time across a consistent dataset. Also, lessons learned from the three noted accidents should be used to inform new aircraft designs, both “conventional” rotorcraft as well as electric Vertical Takeoff and Landing (eVTOL) aircraft. More recent research into gear system design guidelines and their effect on crack propagation should also be employed when developing new aircraft and drive systems.

Observations from 9M-SSC, G-REDL, and LJ-ONF

9M-SSC, G-REDL, and LJ-ONF accidents all resulted from similar, uncommon failure modes in which planet bearing raceway damage propagated into a crack that progressed through the gear rim. Bearing spalling is a common failure mode that is typically detected by onboard chip detectors or electrified debris screens. Moreover, planet bearing spalling is usually isolated and does not cascade into other catastrophic failure modes.

Following the accident of LJ-ONF, the Accident Investigation Board Norway (AIBN) recommended that EASA certification specifications introduce a design requirement that no failure of internal main gearbox components should lead to a catastrophic failure. They also recommended that EASA introduce requirements for transmission chip detection performance. The AIBN goes on to emphasize that a diagnostic system is not a means to maintain structural integrity of a system.

The G-REDL accident report (Ref. 13) also cites crack growth prediction analysis performed by the OEM. The LJ-ONF accident report (Ref. 14) recovered a plant gear segment that could be compared against the crack growth prediction analysis. The crack growth prediction analysis and the recovered part have similar crack propagation paths, showing that simulation can predict such failures.

The similarity of the crack propagation paths suggests that analysis and testing may be used for new designs to prevent these types of failures. The fail-safe design concept and the more general safety assessment process outlined in MOC SC-VTOL would likely eliminate these types of failures, if executed properly. Specifically, MOC VTOL.2510.6.(3), (5), (6), (9), and (11) design philosophies or techniques are recommended for new designs and robust verification (extensive, proven analysis or analysis and test) should be undertaken for planetary systems:

Properly utilizing the fail-safe design concept will help protect against such failures. New designs should consider all failures of neighboring functional elements and ensure that failures don’t propagate between components or functional elements. In planetary systems, this would include the interaction between the planet gear and bearing. In drive systems, this would include features like damping ring grooves and gear heads. In electric motors, this would include bearing failures and rotor/stator contact.

Improvements in Gear-System Safety

Recent research into gear-system configurations and failure modes may help develop a robust safety case when properly utilized in conjunction with MOC VTOL.2510.6 fail-safe design criteria. Recent research has touched on MOC VTOL.2510.6.(2), (3), (5), (8), (9), and (11) fail-safe design philosophies or techniques.

In 1997, Drago, Brown, and Sane introduced a design philosophy concept for ultra-safe rotorcraft transmissions (Ref. 17). The strategy was to elevate the existing reliability, safety, and weight characteristics of rotorcraft transmissions (designed to meet the applicable allowable stress levels so that the possibility of a failure occurring is reduced to a finite but acceptable level) to ultra-safe levels through an alternate design approach. The ultra-safe design philosophy added to the typical process that designs components to "prevent a failure from occurring.” The ultra-safe design philosophy adds consideration of "what happens when a failure occurs".

A split-tooth gear design concept was proposed to manage crack propagation in desired direction such that at least half of the gear tooth would remain intact if a gear tooth bending failure were to occur. The split-tooth gear concept maintains similar weight, performance, and reliability characteristics as the conventional single-tooth designs. Research in the ultra-safe design philosophy aligns with MOC VTOL.2510.6.(2), (8), (9), and (11).

In the same time period, Lewicki was investigating gear tooth crack propagation and the gear design implications for benign or catastrophic failure modes. Lewicki performed finite element analyses and conducted experimental studies to investigate the effect of rim thickness on gear tooth crack propagation (Ref. 18, 19). The objective was to determine whether cracks grew through gear teeth (benign failure mode) or through gear rims (catastrophic failure mode) for various rim thicknesses, Figure 1. For the analysis, crack-tip stress intensity factors were estimated and used to determine crack propagation direction and fatigue crack growth rate. Additionally, to validate the analytical crack path predictions, gear bending fatigue experiments were performed in a spur gear fatigue rig using gears fabricated with various backup ratios (rim thickness divided by tooth height). Lewicki's work in gear tooth crack propagation aligns with MOC VTOL.2510.6.(3), (8), (9), and (11).

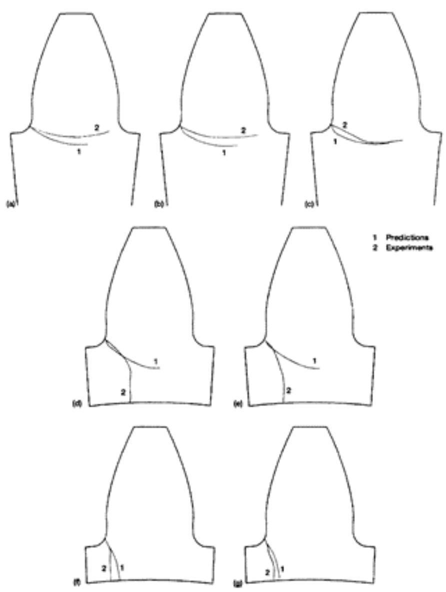

Figure 1: Comparison of analytical and experimental crack propagation paths.

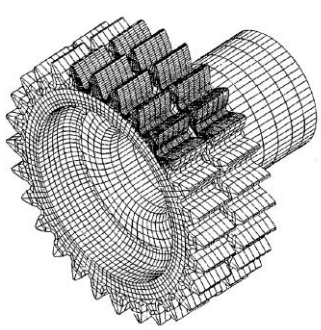
Figure 2: Finite element model of split-tooth gear configuration.

The split-tooth gear design concept was analyzed using three-dimensional crack growth simulations, Figure 2 (Ref. 20). The analyses found that for an initial crack in the tooth fillet region, tooth fracture was predicted, and this was the desired mode of failure consistent with the ultra-safe design philosophy.

In 2000, Drago, Isaacson, and Sonti reported on experiments performed on gears that were manufactured with seeded faults that were intended to simulate unexpected defects in the highly loaded regions of gear teeth and gear rim sections (Ref. 21). The experiments monitored the effective gear mesh stiffness and the applied load to provide a warning of impending failure. Consistent with the ultra-safe design philosophy to consider "what happens when a failure occurs." The experiments monitored the period of operating time after initiation of a failure to assess the potential to enable a safe landing, aligning with MOC VTOL.2510.6.(3), (5), (8), (9), and (11).

In 2001, for gear tooth bending fatigue, a guideline for ultra-safe design was published (Ref. 22). The design guideline provides design information to prevent catastrophic rim fracture failure modes, Figure 3. The design guideline

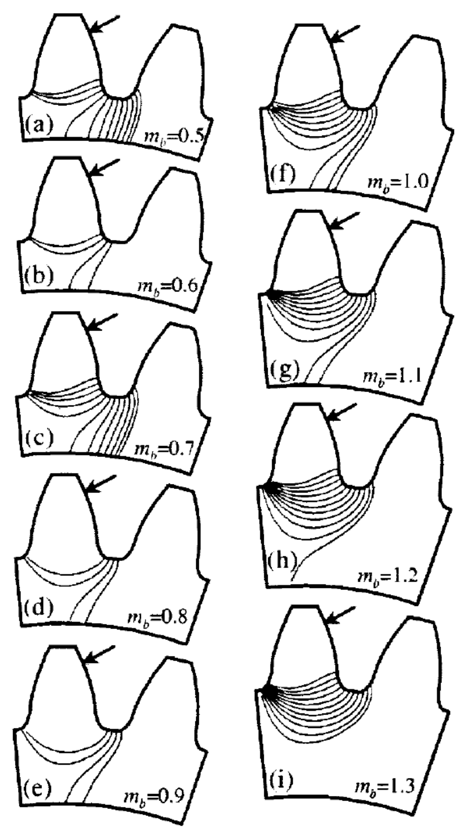

Figure 3: Effect of backup ratio and initial crack location on propagation path.

included gear tooth geometry factors of diametral pitch, number of teeth, pitch radius, and tooth pressure angle. Lewicki's design guidance aligns with MOC VTOL.2510.6.(3), (8), (9), and (11).

Ultra-Safe, High-Ratio Compound Planetary Transmission

The National Rotorcraft Technology Center - Rotorcraft Industry Technology Association (NRTC/RITA) sponsored the design of an ultra-safe, high-ratio compound planetary transmission, for application as a helicopter main rotor drive. The features of the ultra-safe planetary transmission were reported by Brown, et. al. (Ref. 23). The planetary transmission offered improvements relative to the state-of-the-art including, reduced weight, reduced transmitted noise, and improved fail-safety. The planetary transmission design utilized a compound planetary configuration with a 17.5:1 reduction ratio and is intended to serve in place of the typical two-stage simple planetary as the final stage of a helicopter transmission. The design employed ultra-safe principles such as split-torque paths and high combined contact ratio gearing. The double helical gears in the planet/ring meshes balanced axial tooth forces so that axial bearing reactions are not required, and the spur gear sun/planet meshes are staggered to achieve a compact spatial arrangement. The ultra-safe high-ratio compound planetary configuration was subsequently patented by Drago, et. al., Figure 4 (Ref. 24).

Flaw Tolerance within Safe-Life Design

Helicopter dynamic systems utilize flaw tolerance in design and maintenance procedures in order to achieve a robust system design. Manufacturing anomalies and field damage can create flaws that may reduce a component's structural integrity. Helicopter dynamic systems include design philosophies to preclude the propagation of probable flaws, such as crack-like defects within certain size limits. Maintenance manuals will also prescribe maintenance actions based on the type and size of a flaw. Incorporating flaw tolerance into new SC-VTOL-01 targeted designs aligns with MOC VTOL.2510.6.(1), (4), (10), and (11).

Recent Testing in Real-Time Diagnostics

Health usage monitoring systems (HUMS) began development in the early 1980's, with the first operational HUMS in 1991 (Ref. 25). Since its early adoption, HUMS has been continually improving. Available sensors are expanding beyond accelerometer-based sensor-suites with recent research in acoustic emissions and surface acoustic wave (SAW) sensors, among others. Processing techniques are continuing to improve, as well, continuing to reduce accident rates. Onboard diagnostic systems align with MOC VTOL.2510.6.(5), (6), and (7).

A comprehensive bench test program ran through the 1990's to characterize the ability to detect gear tooth bending fatigue failures using accelerometers and associated processing equipment. Specifically, seeded fault testing on the CH-47D forward transmission spiral bevel pinion showed continued safe operation for over two hours in a "get-home" cruise power setting after the crack was detected (Ref. 26). Additional testing included rotor transmission planetary gear seeded faults with similar results.

Three notable EASA sponsored studies have also included seeded fault testing in order to determine the likelihood of detecting various failure modes within helicopter drive systems.

(1) Published in 2015, acoustic emissions sensors were investigated to detect failures in the rotating frame. A study on an EC225 main rotor gearbox showed that acoustic emission sensors showed improved detection of planetary bearing failures over accelerometer-based systems (Ref. 27).

(2) Published in 2017, Zhou, et al reported on an EASA sponsored study to investigate the diagnosis of bearing

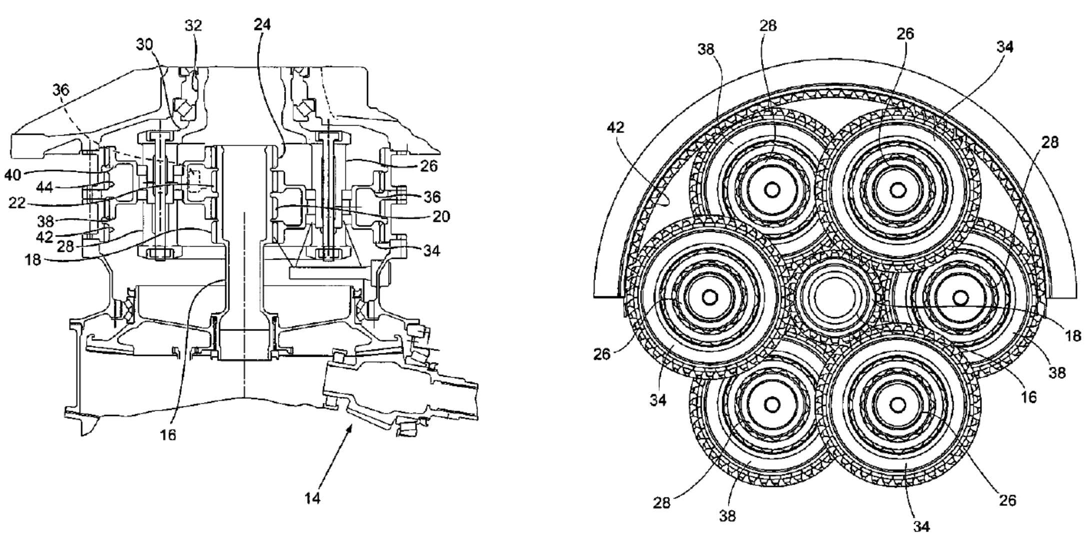

Figure 4: Ultra-safe high-ratio compound planetary configuration.

failures in SA330 main gearboxes (Ref. 28). The study used accelerometers and various processing techniques to determine if bearing failures could be detected. Results of the study found that accelerometers can be used to diagnosis planet bearing failures, but that the processing technique also plays a large role in successful diagnosis.

(3) Published in 2019, Gryllias, et al furthered Zhou's work, developing a processing technique, referred to as "IESFOgram" (improved envelope spectrum via feature optimization-gram) (Ref. 29). It was found that the IESFOgram processing technique successfully detected planet bearing failures.

QUADROTOR BASELINE DRIVE AND POWER SYSTEM

NASA developed a family of multirotor VTOL aircraft for the RVLT Program to provide a framework for research topics related to eVTOL technology areas. One such vehicle was a six occupant Quadrotor (Ref. 30) which Boeing has studied as part of safety and certification related research programs (Ref. 1, 2). The six occupant quadrotor, herein referred to as the quadrotor, is shown in Figure 5.

The quadrotor is the basis of this paper because in order to meet SC-VTOL-01 probabilistic failure criteria it required mechanical interconnections such as gear or shaft systems in order to combine power from multiple electric motor sources for one (or more) motor inoperative (OMI) conditions.

Two quadrotor drive and power systems were conceptualized, under NASA's direction. One system was designed with mechanical shafts interconnecting each of the four rotors, herein referred to as the cross-shafted quadrotor. The other system was designed without mechanical interconnection between rotors, herein referred to as the non-shafted quadrotor. Both concepts utilized a single-axis, through-shaft actuator and link for collective control at each rotor. Single-axis collective control at each rotor is used for pitch, roll, and yaw flight control in all axes.

The cross-shafted quadrotor consists of four motors and associated inverters, four rotor gearboxes, two mix boxes, four pylon shaft assemblies with associated adapters, and one intermediate shaft assembly with associated adapters as shown in Figure 6.

The non-shafted quadrotor did not include shafts to interconnect each rotor; however, safety analysis of the non-

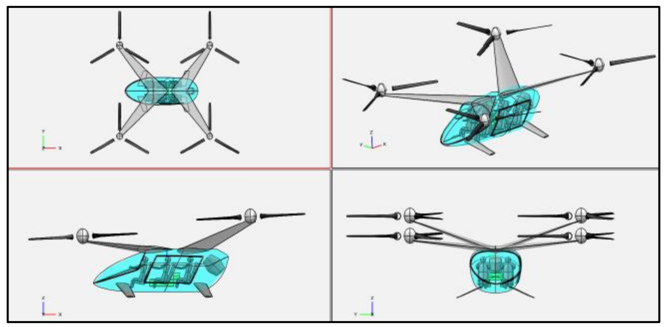

Figure 5: NASA RVLT Six-Occupant Quadrotor

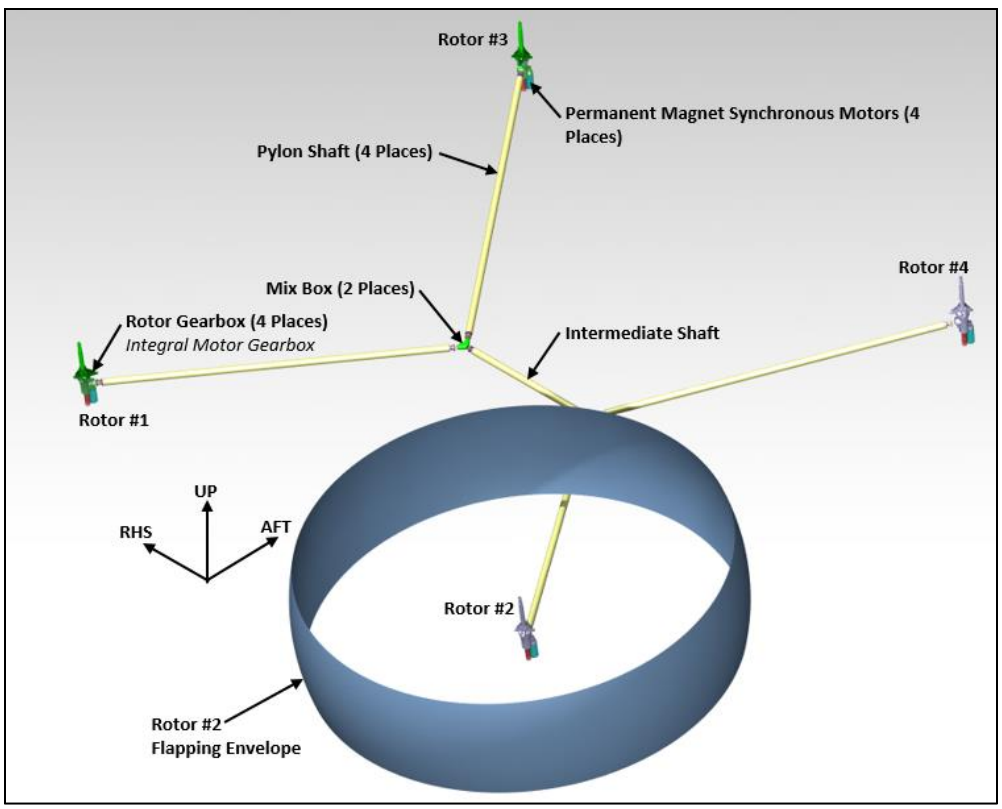

Figure 6: Quadrotor Drive and Power System

shafted quadrotor showed that local mechanical interconnection of multiple electric motors was still required (Ref. 2). In other words each rotor was independent from the other, but power from two motors was combined into a single rotor shaft via a gearbox located near each rotor. The non-shafted quadrotor consists of eight motors and associated inverters and four rotor gearboxes. Figure 7 illustrates the concept with only one motor shown. Future work should incorporate the second motor into the propulsion package, but, conceptually, the second motor will send power through a second input pinion and idler gear and the idler gear will mesh with the existing collector gear.

Common between both the cross-shafted and non-shafted quadrotors is an epicyclic gear system and rotor shaft as shown in Figure 8. The baseline epicyclic gear system is a two stage, sun-input, ring-fixed, simple planetary system with an overall reduction ratio of 19.196:1 and consisting of an array of spur gears, supporting bearings, and planet carriers. The epicyclic system is the final gear reduction stage before sending power to the respective rotor shaft and rotor. The rotor shaft sends power from the epicyclic system to the rotor system and also transmits aerodynamic loads from the rotor system into two supporting tapered roller bearings. The tapered roller bearings are mounted into the transmission upper cover. The rotor shaft has an integral planet carrier that serves as the epicyclic system's 2^{nd} stage planet carrier.

In the case of the NASA RVLT quadrotor, loss of function of a single rotor is assumed catastrophic. The reliability of both the epicyclic system and rotor shaft will meet VTOL.2510(a) requirements for probabilistic failure criteria (Ref. 2); however, both the baseline epicyclic system and rotor shaft include single load paths with failure modes that could lead to catastrophic events. In order for direct compliance with VTOL.2250(c), multiple load path designs must be studied for the epicyclic system and rotor shaft to comply with the single failure criteria, VTOL.2250(c). Alternate design philosophies are also explored so that the reasonable and conceivable failure modes of a single and multi-load path elements can be reliably detected and appropriate pilot action can be completed prior to a catastrophic event.

REASONABLE AND CONCEIVABLE FAILURE MODES

Reasonable and conceivable failure modes were postulated for the quadrotor in order to assess its safety against SC-VTOL-01. Reasonable and conceivable failure modes postulated are shown in Table 1. Of the reasonable and conceivable failure modes postulated, failures that had a low probability of being detected during regular inspections or by state-of-the-art detection systems, such as debris monitoring or HUMS, are considered to be Category I, Catastrophic. Failure modes which could be reliably detected were

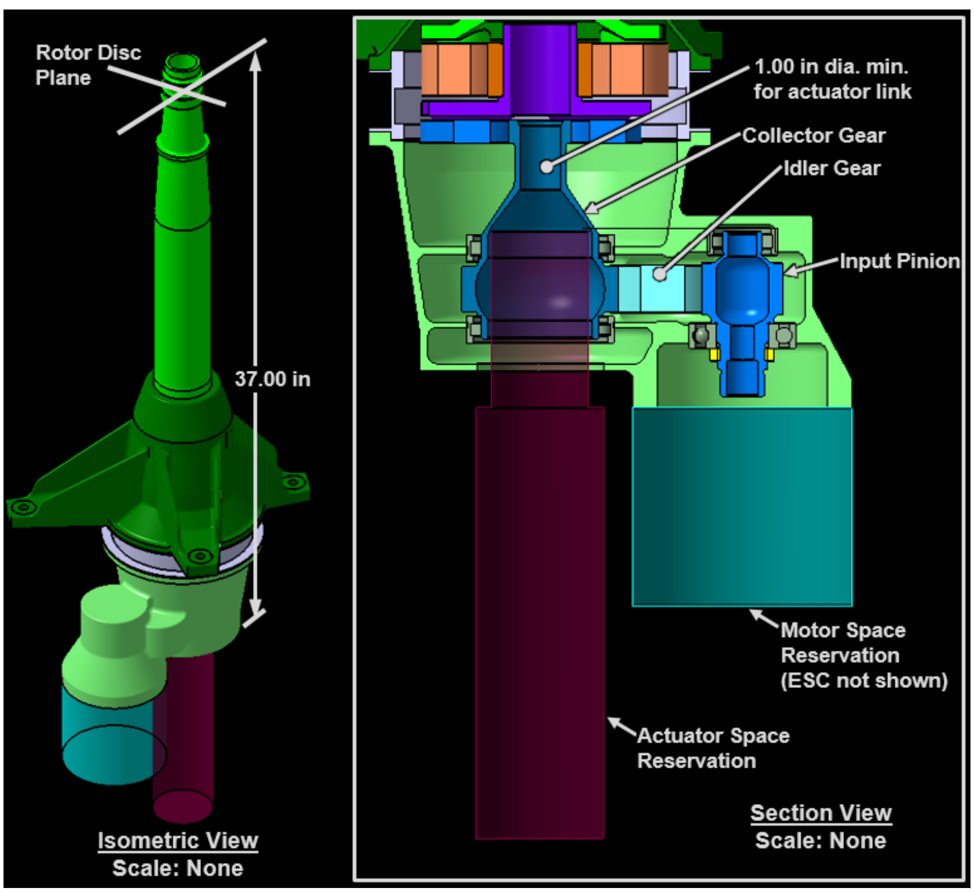

Figure 7: Rotor Gearbox and Motor for Non-Shaft Quadrotor.

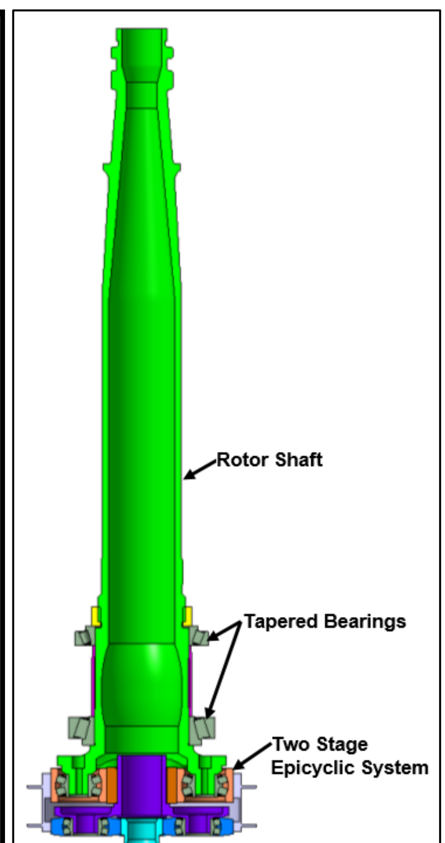

Figure 8: Common Rotor Shaft and Epicyclic System.

considered Category II, Hazardous. Category III and IV failure modes were not the focus of this study.

Table 1: Reasonable and Conceivable Failure Modes Postulated for the Drive and Power System.

Component	Reasonable & Conceivable Failure Modes
Gears	Pitting, Tooth Bending Fatigue
Bearings	Spalling, Brinelling, Cracked Rings, Arc Burns
Splines	Wear
Shafts	Fatigue, Fretting
Armatures	Shorted Winding, Overheating

The epicyclic system is comprised of gears, bearings, splines, and shafts. Gear tooth bending fatigue is considered a Category I failure mode affecting the epicyclic system. The rotor shaft system is comprised of bearings, splines, and a shaft. All rotor shaft system failures are considered Category II because they could be detected via daily visual inspections or HUMS; however, design practices and testing must validate continued safe flight during crack growth. The motor system is considered to be comprised of bearings, splines, a shaft, and an armature. Shorted windings are considered a Category I failure mode affecting the motor system.

ALTERNATE ROTOR SHAFT CONCEPT

Alternate rotor shaft designs were conceptualized to replace the baseline rotor shaft and meet VTOL.2250(c) single load path criteria. The baseline rotor shaft system includes a single load path structure, but FMECA resulted in all rotor shaft system failure modes leading to Category II events. However, design practices, full-scale testing, on-board diagnostics, and regular inspections are needed to verify that shaft fatigue or fretting cracks are detectable with at least 30 minutes of flight time prior to losing the ability to transmit load. Alternate rotor shafts were conceptualized to potentially replace the baseline design for two reasons, (1) the baseline rotor shaft failure modes may not be detectable and (2) the structural integrity of the rotor shaft may not meet the 30 minute get home criteria. If either failure mode is not detectable or the get home criteria cannot be met, then some of the rotor shaft failure modes would be raised to Category I and the rotor shaft will not comply with VTOL.2250(c).

A common design approach already utilized for production rotorcraft is a static mast and drive shaft to replace a single rotor shaft. Helicopters such as the MD 500E utilize this arrangement. The static mast is non-rotating and transmits aerodynamic loads from the rotor system to supporting static structure. The static mast requires a bearing set located between the rotor system and the static mast to permit rotation of the rotor system; the bearing set must transmit all aerodynamic loads from the rotor system into the static mast. The drive shaft transmits torque from the transmission system to the main rotor, without transmitting shear or bending aerodynamic loads between the two.

However, the static mast and drive shaft arrangement has its own limitations and challenges. While direct compliance with VTOL.2250(c) allows for HUMS equipment to be used on simply loaded, single load path, static structure, like the static mast, the drive shaft is a single load path dynamic component that, if failed, will lead to a catastrophic desynchronization of the quadrotor. VTOL.2250(c) does not directly allow for health monitoring on dynamic components, and, therefore, will not directly comply with VTOL.2250(c).

In order to develop a multi-load path design a hybrid between the live rotor shaft in the baseline design and the static mast and drive shaft arrangement was considered, see Figure 9. The alternate design uses three bearings, a live rotor shaft, and a drive shaft to create two fully redundant load paths. One load path is a combination of the live rotor shaft and two tapered bearings and the other load path is a combination of the third bearing and the drive shaft. The live rotor shaft will be designed to transmit torque from the transmission planet carrier to the rotor system and transmits aerodynamic loads from the rotor system to two tapered bearings. A rotor head bearing, likely a large ball bearing, transmits aerodynamic loads directly from the rotor system into the airframe. The drive shaft transmits torque from a lower spline interface, through the live rotor shaft, and into an

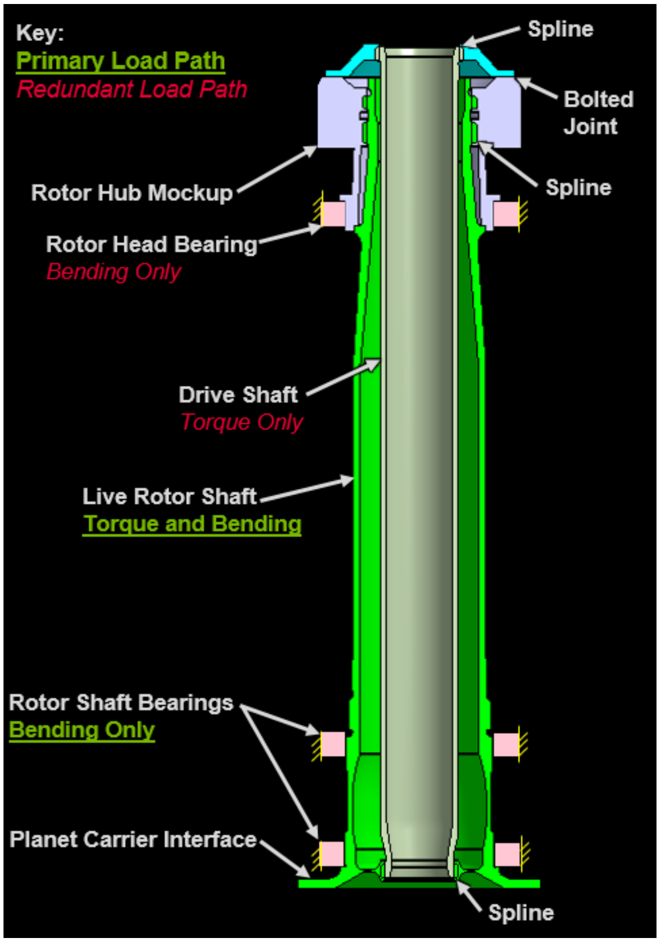

Figure 9: Alternate Live Rotor Shaft and Drive Shaft Concept.

upper spline interface. A torque plate transmits the torque from the upper spline into the rotor hub via a bolted joint. It is envisioned that the large ball bearing would be mounted in a thrust housing and connected to the airframe through struts, similar to the SA330, Figure 10 (Ref. 28).

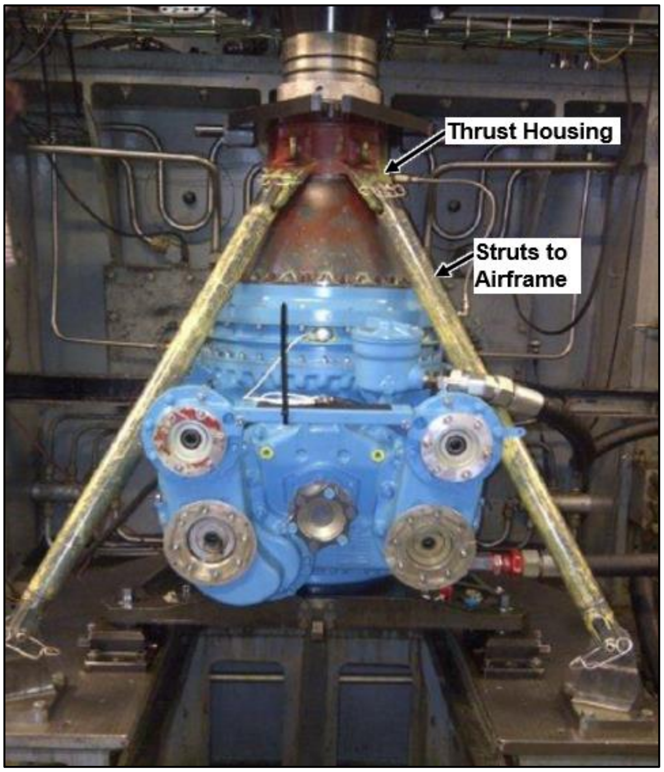

Figure 10: SA330 Main Rotor Gearbox in Lab Test.

Component stiffness and design attributes should be tailored in order to provide a primary and secondary load path. Under normal operating conditions, the primary load path will take most, if not all, of the shear, bending, and torque loads with the secondary load path taking minimal loads. In emergency conditions, however, the secondary load path will need to take most of the shear and bending or torque loads. The secondary load path is envisioned to take minimal loading to improve the reliability of the secondary load path and improve the probability that it will be available for use in emergency conditions. It is envisioned that the live rotor shaft and tapered bearing pair would be the primary load path because it is assumed that the large diameter rotor shaft with preloaded tapered bearings would be the stiffer of the two load paths. Future analysis should verify this assumption.

The live rotor shaft bending and torsional stiffness should be optimized to ensure that when the live rotor shaft is manufactured and operating within spec limits that minimal load is being transmitted into the secondary load path. Similarly, the radial and axial clearance of the large ball bearing in the secondary load path should be designed to take minimal loads during normal operation at the rotor head. The clearance in the drive shaft spline should also be designed so that it is taking minimal load during normal operation.

Limitations with the alternate dual-load path rotor shaft include size, weight, cost, assemblability, and inspectability. Size (volume), weight, and cost increase with the alternate design due to increased rotor shaft size to accommodate the drive shaft, the large bearing near the rotor system, and part count increases, among others. An assembly scheme will need to be developed that will align the three concentric bearings to within a very close tolerance, typical for bearing/shaft interfaces. Future analysis should investigate the required positional tolerance of each bearing and shaft and determine a means to achieve that tolerance in a production environment (through shimming, precision component tolerances, or other). Inspectability must also be considered in the future. Design features for easy daily inspections of the primary load path and tolerable periodic inspections of the secondary load path must be considered in future work. Critical crack sizes and crack growth rates for the live rotor shaft and drive shaft should be determined in order to ensure structural integrity of both the primary and secondary load paths. Critical crack size and crack growth values may be different for the easier-to-see live rotor shaft than for the difficult-to-inspect embedded drive shaft. It is foreseeable to automate inspections if health monitoring equipment can be shown to detect the applicable failure modes.

PROPOSED EPICYCLIC SYSTEM CONCEPT

An ultra-safe, high reduction-ratio compound planetary system concept, Figure 11, is proposed based on the patented concept by Drago, et al (Ref. 23, 24). The proposed compound planetary system replaces the two-stage simple planetary described as the baseline configuration.

The compound planetary system transmits power from the input sun gear, into six planet gears; the planet gears react against the stationary ring gear and transit power through the output carrier to the rotor shaft system. The dual load path system for application in the NASA RVLT concept vehicles utilizes staggered long and short planet gears to create two rows of spur gear teeth at the sun/planet mesh. The long/short

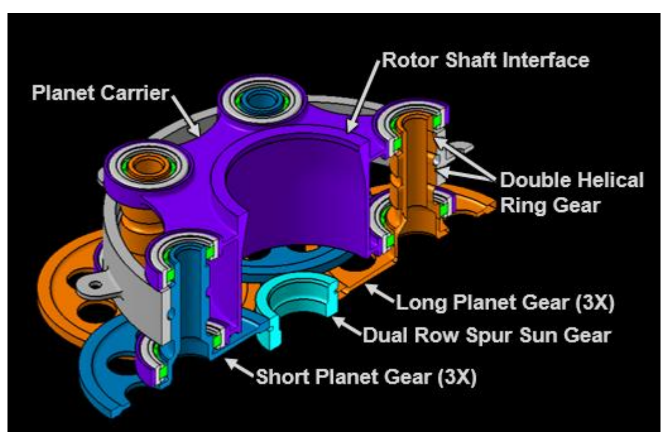

Figure 11: Proposed Ultra-Safe, Staggered Planet, Double Helical Compound Planetary System.

planet gears then transmit load into a high contact ratio double helical planet/ring mesh.

Tooth counts have not been finalized for this configuration, but it is expected that a reduction-ratio acceptable for the NASA RVLT Quadrotor can be found. It is expected that the reduction-ratio will be between the patented 17.5:1 ratio reported by Brown, et al, (Ref. 23) and the 19.196:1 baseline two-stage planetary system ratio.

Unlike the rotor shaft system, the final stage epicyclic system is assumed to transmit torque only. Aerodynamic loads are considered negligible for this early study, although, in practice, a small kick-load associated with rotor shaft displacement should be expected. Under normal operating conditions it is assumed that load distribution between the six planets gears will be near unity. If a crack begins to propagate in a planet gear, the load will begin to redistribute into "healthy" areas of the system due to stiffness variations between cracked and "healthy" areas. The "healthy" areas will begin to transmit more load. This load redistribution will inherently slow crack propagation but also creates derived design requirements in which remaining "healthy" areas must transmit more load for a limited duration.

Design, analysis, and testing over decades of seeded fault and overload testing have shown that in similar final reduction stages a propagating crack in the root of a well-designed gear tooth will locally fracture or sever one gear tooth and not propagate to neighboring teeth. Crack growth simulation can be used to model behavior of tooth fractures to control crack propagation direction through manipulation of tooth to rim thickness and stiffness variations from tooth to tooth. Additional design, analysis, and verification testing are required to substantiate the fail-safe features of this gear train in this application.

MOTOR SAFETY AND RELIABILITY

In previous sections, two quadrotor propulsion systems were described. One propulsion system features four motors and mechanical cross-shafting with a common interconnection of the four rotors. The cross-shafting provides redundancy of functionality, providing torque to all rotors after loss of torque production by any one motor. Furthermore, the nonfunctioning motor would become disengaged from rotation via the function of the overrunning clutch. The alternate propulsion system was conceptualized without cross-shafting. However, redundancy is provided locally via two motors connected mechanically to the rotor. Using failure modes, effects, and criticality analysis (FMECA) and fault tree analysis (FTA) to quantify catastrophic failure, previous work showed feasibility that either of these propulsion system arrangements could meet the target of VTOL.2510(a), 10^{-9} catastrophic failures per flight hour (Ref. 2). These two example arrangements however may incur undue unit or operating costs burdening the end user, and differing methods of achieving the required safety may result in differences of vehicle gross weight.

One can envision other design choices with potential to meet aviation high reliability requirements. One approach studied and proposed is the use of multi-phase motors. In such approach, fault-tolerance specifications impose that the loss of one phase owing to failure does not affect the capability of delivering the nominal power of the actuator, whereas with a further second loss it is possible to supply reduced power, decreasing torque or speed depending on the application requirement (Ref. 31). Multi-phase designs to achieve fault tolerance have been proposed and studied for naval propulsion (Ref. 32), high-speed elevators (Ref. 33), and aviation (Ref. 34, 35). These articles are just a few of many studies in the literature of multi-phase electric machines. Understanding and demonstrating the behavior of the system for a given faulted state is important to ensure needed safety requirement. Bolvashenkov, et al. (Ref. 36) studied potential internal faults of a three-phase permanent magnet motor leading to development of a failure modes and effects (FMEA) diagram of potential causes, fault modes, and effects. Machine design choices influence all of the resulting post-fault behavior, capability to detect the fault, and mitigation actions to avoid complete failure.

Another approach for a fault-tolerant motor that was motivated by NASA RVLT eVTOL concept vehicles is a modular motor concept (Ref. 37). This motor concept features modular stator segments, each excited by a dedicated inverter. The selected design is a 4-module approach using double-layer windings. The motor with integrated electronics was specified to be able to deliver full torque after the loss of one module (e.g., winding or power electronics failure), and partial torque after the loss of a second module. Both 36s/24p (SPP = 1/2) and 24s/28p (SPP = 2/7) slot-pole combinations were evaluated as suitable candidates for four-module fault-tolerant motor drives. Overall, the 36s/24p machine has superior power density capability compared to the 24s/28p machine due to its compact end windings. A single-layer variant of the 24s/28p machine was also evaluated but it exhibited degraded performance compared to the double-layer options. Experiments confirmed the predicted effects of electromagnetic module coupling during a fault event.

Fault tree analysis and Markov analysis are two primary methods used for calculating system probability of failure (Ref. 38). Markov models have been applied to VTOL electrical propulsion concepts. Results using Markov analyses of multi-phase machines (Ref. 35, 39) highlight that the appropriate number of phases is highly dependent on the performance demand after occurrence of a phase failure. Results of a study applying Markov models to modular electric machines (Ref. 40) demonstrated that modularity combined with rapid fault detection and repair significantly improves the potential of the modular drive to achieve significant reliability improvements. The high safety potential of the modularity concept can only be fully realized if the single-source failure rates are suppressed to the greatest possible extent. These studies just mentioned made use of traditional Markov chain modeling where the failure rates are assumed as a constant rate. Certain probabilistic failure modes of electric machines are more accurately described using Weibull or other distributions with increasing rather than constant failure rates. Markov state models can be adapted for failure modes with increasing failure rates (wear-out modes) and common cause failures (Ref. 41, 42, 43).

Regardless if safety requirements are met by redundancy, fault tolerance, or some combinations of both approaches, motors having qualified, high inherent reliability will be needed for reasons of maintenance logistics and operating cost. The most prevalent failure mode for motors is failure of the stator insulation. The use of high-frequency wide band gap devices creates new and difficult challenges for the insulation technologist and motor designer (Ref. 44). Recent surveys of insulation research provide guidance on research trends, and the increasing research attention toward improving insulation technologies is evident (Ref. 45, 46). UAM eVTOL vehicle requirements motivate works toward improvements of insulation reliability from both the design and qualification perspectives (Ref. 47). Although originally written for industrial applications, standard IEC 60034-18-41 has proven to provide useful guidance for the transportation sector including aviation, and some considerations for the second edition of the standard have recently been published (Ref. 48).

IN-SERVICE MONITORING

The drive and power system needs an in-service monitoring plan in accordance with VTOL.2510(c) and to comply with VTOL.2250(c). The baseline and alternate rotor shaft designs, the proposed epicyclic design, and the motor system require on-board diagnostic systems in order to meet probabilistic failure criteria of VTOL.2510(a). Bearings in each of the noted systems have a high probability of failure, and, therefore, require on-board diagnostic equipment to warn the pilot and crew of an impending failure. The baseline rotor shaft and epicyclic systems require diagnostic systems in order to comply with VTOL.2250(c). The alternate rotor shaft, proposed epicyclic, and motor systems may also require diagnostic systems to comply with VTOL.2250(c).

Additional design and development is required to mature the design of a diagnostic system that will bring the quadrotor drive and power system into compliance with SC-VTOL-01. However, some design practices and observations are discussed in order to highlight design or technology gaps. Inspection criteria are also discussed as part of the quadrotor’s in-service monitoring plan, in accordance with VTOL.2510(c).

The baseline rotor shaft system has a large exposed section between the two tapered roller bearings and the rotor system that could be inspected during daily visual inspections. Field experience has shown that rotor shaft cracks can propagate in a controlled manner, be detected by daily visual inspections, and have generated vibrations that were detected by the pilot or crew during flight. Additionally, health monitoring sensors could be placed in the load zones of the tapered roller bearings to detect crack propagation in the integral carrier or in the shaft section. In order to meet VTOL.2510(a) probabilistic failure criteria of less than 10^{-7} for Category II hazards, dual redundant sensors or two different types of single string sensors are likely required. One accelerometer array and one acoustic emission sensor array is envisioned to comply with VTOL.2510(a) and reduce the likelihood of common-cause failures. The two tapered roller bearings would be monitored by the sensor suite and by the rotor transmission chip detector and electrified debris screen. Cracks in the rotor shaft would be monitored by the sensor suite and via daily visual inspections. Cracks in the integral carrier would be monitored by the sensor suite.

The alternate rotor shaft concept also has a large exposed section of the live rotor shaft that could be inspected during daily inspections. Health monitoring sensors may not be required to meet VTOL.2250(c), but may be desirable to reduce inspection time of the more complex rotor shaft system. On-board diagnostic systems would not require real-time feedback to the pilot or crew, but could be downloaded on the ground at regular intervals to verify integrity. Neither the large ball bearing between the rotor system and airframe nor the drive shaft are designed to transmit large loads during normal operations, so the sensor suite will need to detect a flaw when some of the components are lightly loaded.

Each rotor transmission includes chip detectors and electrified debris screens to monitor metallic debris that is free in the lubrication system. The rotor transmission chip detectors and electrified screens will monitor bearing spalling and gear pitting failures, including the proposed epicyclic system. Additionally, redundant sensor suites would be utilized to monitor gear bending fatigue failures. Similar to the baseline rotor shaft system, two types of sensors are utilized to reduce the probability of common-cause failures. An accelerometer array and an acoustic emissions sensor array are envisioned. The epicyclic system will utilize single-axis accelerometers mounted in two primary locations, (1) on the stationary ring gear to monitor both the vertical (along the rotor shaft axis) and the radial directions and (2) on the sun gear support to monitor the radial direction. Acoustic emission sensor placement needs to be evaluated for a compound planetary system, but it is anticipated that acoustic emissions sensors will be placed above and below the ring gear in order to monitor the planet gears.

The baseline motor concepts utilized an array of sensors for continued airworthiness. Improvements to motor fail-safety or changes to motor configuration will change the required sensor package. The baseline motor requires cockpit displays of torque, shaft speed, oil temperature, and oil pressure, as well as warning/caution/advisory indications for torque, shaft speed, oil temperature, oil pressure, torque ripple, bearing failure, insulation quality, and short detection with motor shutoff.

CONCLUDING REMARKS

1. SC-VTOL-01 attempts to increase safety regulations for eVTOL aircraft over conventional rotorcraft certified against CS-27 or CS-29. The increased safety regulations, specifically the single failure criteria, invoke engineering challenges that have not historically been addressed in conventional rotorcraft due to weight and complexity, among others. The rotorcraft industry will broadly benefit from new technology developed to comply with VTOL.2250(c) by guiding new designs towards fail-safe design concepts.

2. Historically, helicopter drive systems have been systems with multiple single points of failure, but have proven to be reliable devices. Where practical, failure modes are designed to progress in a manner which allows for detection and pilot action prior to a catastrophic event. Some failure modes, such as gearbox jams, have occurred with limited warning time due to latent crack growth in the gear rim. Gearbox jams are not common in helicopter drive systems and likely meet VTOL.2510(a) probabilistic failure criteria. Recent accidents caused by gearbox jams have inspired research in advanced fault detection as well as a desire to eliminate single load path designs in conventional rotorcraft.

3. Industry wide research into gear failures has produced design guidance for improved gear system safety. Gear system design practices, such as tooth design parameters and backup ratio, have been shown through simulation to produce crack propagation paths that can progress in an isolated manner. Testing has shown that crack growth rates can progress with enough detection time for pilots to be alerted of the failure and take appropriate emergency actions prior to the occurrence of a catastrophic event. Limited simulation work and data have been developed for the detection of cracks in rotor shaft systems, but field experience has shown that daily inspections will find rotor shaft cracks prior to a catastrophic event and it is likely that an onboard diagnostic system can detect these failures.

4. Multiple design concepts were presented for rotor shaft and epicyclic system concepts. These systems were selected because they were used commonly between the cross-shafted and non-shafted versions of the study quadrotor. These systems are commonly used on VTOL aircraft, although eVTOL concepts don't typically use epicyclic gear systems, yet. Motor system safety and reliability were also discussed; emphasizing the importance of further research in this area.

5. Multiple rotor shaft system design concepts are discussed in order to comply with VTOL.2250(c). However, it is not clear which rotor shaft concept would be the safest in practice. The baseline rotor shaft system includes a single load path, but associated in-service monitoring and daily inspections are intended to eliminate single failures. Future work is required to verify that rotor shaft failures may be reliably detected with adequate time for emergency procedures.

6. One alternate rotor shaft concept may be to include a stand-pipe and separate drive shaft, but this design still has single points of failure, requiring onboard diagnostics, similar to the baseline design. Another alternate rotor shaft system with one live rotor shaft, drive shaft, and three primary bearings was presented to eliminate single load paths, but it is unclear if this design will improve system safety since inspectability may be reduced.

7. The proposed epicyclic system builds off of the prior ultra-safe, high-ratio compound planetary transmission development. It is intended to segregate torque-split load paths and allow for easy fault detection using onboard diagnostic systems. Similar to the baseline rotor shaft system, the proposed epicyclic system requires future work to verify that the intended failure modes can be reliably detected with adequate time for emergency procedures.

8. Prior work discussed the need for motor reliability and fault detection improvements to comply with VTOL.2510(a). Motor configurations for adjacent industries utilize varying levels of fail-safety may be used to guide motor development for aviation. Motors are in development to increase fail-safety specifically for eVTOL aircraft and UAM. Motor failure rate data, in the primary propulsion environment, is limited and therefore failure rate prediction methodologies must be improved, accounting for wear out modes and common-cause failures. Additionally, means to detect and alert pilots and crew of impending failures must be established. Bearing failures, winding failures, and shaft failures, among others, must all be accounted for in the motor design with appropriate means of detection, which is likely difficult within the rotating magnetic field.

RECOMMENDATIONS

1. Research and development in the area of single failures in rotor shafts, epicyclic systems, and motors should continue. Historically, ultra-safe gear system research, configurations, and design guidance have aligned well with the enhanced safety objectives of SC-VTOL-01. Continued research in fail-safe design concepts and design guidance will benefit eVTOL and conventional rotorcraft, alike. Optimistically, continued research in these areas could translate to widespread adoption of VTOL.2250(c) into new rotorcraft designs certified against CS-29, or even smaller, CS-27 rotorcraft, in accordance with AIBN recommendations.

2. Further research to comply with VTOL.2250(c) single failure criteria within the rotating frame is recommended. Design concepts to meet the single failure criteria are

conceptualized, but limited, if any, publicly available information is available on VTOL.2250(c) compliant rotating systems. Publically available artifacts with examples should continue to be developed to aid industry in developing VTOL.2550(c) compliant drive and power systems.

3. Future work should investigate worldwide vertical flight activity to characterize critical failure modes and probability of such failures.

4. The rotor shaft and epicyclic system concepts presented herein should be further developed to determine if they are viable candidates for direct compliance with VTOL.2550(c), and SC-VTOL-01 more broadly. Simulation work should be performed for initial verification of detectable vs. latent failures. Full-scale seeded fault testing should be considered.

5. Future work should explore design elements that must be analyzed and potential requirements for seeded fault testing as accepted means of compliance with VTOL.2250(c). Specifically, the relationship between bearing races and gear heads in simple planetary systems have lead to catastrophic failures. Bearing and gear failure progressions in the proposed epicyclic design should be assessed and seeded fault testing should be performed to validate analytical predictions.

6. It is recommended that motor reliability and fault detection improvements to comply with VTOL.2510(a). It is recommended that adjacent industry research is performed and compared against the current state of aviation motor technology as it applies to both probabilistic, VTOL.2510(a), and single failure criteria, VTOL.2250(c).

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https://ntrs.nasa.gov/

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