IMPROVING THE SAFETY MANAGEMENT SYSTEM THROUGH HFDM

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Abstract: Helicopter Flight Data Monitoring (HFDM) is an integral part of the service provider's safety management system. By capturing operational information about aircraft activities, the service provider can: identify safety hazards, initiate remedial action to maintain safety performance, facilitate monitoring and assessment of technical interactions between the crew and the aircraft, and facilitate continuous improvement of the safety management system. We wish to improve HFDM by providing aircraft metrics via automation of data download and reporting. Automation is achieved by formalizing the concept of a flight operation, exceedance monitoring and improving the HFDM architectural design to allow for the seamless movement of data. In the extreme, this model for HFDM provides protection of data even in the event of a mishap that would usually only available from crash survivable memory. This paper discusses the formalized concept of a flight operation, how regime recognition is used to support the function of an operation in order to improve the robustness of a HFDM program automated downloading and processing of data.

Key words: HFDM; regime recognition; HUMS; exceedance monitoring; automated reporting

Introduction: HFDM programs provide the data needed to proactively correct a safety issue [1]. However, a HFDM program can only be succed when the data is available for analysis. Data availability assumes that the data from a flight is downloaded, and then subsequently analyzed. In the advent of a mishap, the data from the flight might be lost. This data is invaluable for an accident investigation. HFDM systems do not require crash survivable memory or Aircraft Communication Addressing and Reporting Systems (ACARS), which could protect data, but adds considerable cost and weigh to a HFDM installation. Further more, promulgation of a HFDM system is cost sensitive, as it is not mandated on most helicopters.

Given this environment, a robust HFDM requirements were developed to:

- Assign data files associated with a flight operation such that at the end of the flight, those files can be downloaded for analysis in an automated way, and
- Provide automated reporting of events that can be identified as safety hazards which can be used as the basis for aggregation or trending, and
- Assist in triggering additional actions, such as crew contact, and

- Is low cost and weight, which is essential in order to make systems more prevalent in the industry. Cost and weight are drivers for the business case in most helicopter organizations, and
- Provide crash survivable data by transferring the data automatically in the event of a mishap.

The initial step to facility reporting requires the automated processing and downloading of appropriate data, which leads to the concept of an aircraft flight operation.

Aircraft Operation Concept: An aircraft operation is concerned with defining how data is assigned to a rotor turn or flight(s) and when it is appropriate to download that data. From power on, to rotor turn, through takeoffs/landings, mishap or hard landing, parameter and condition monitoring data needs to be associated with that operation (e.g. a flight). The operation is a fundamental concept and facilitates display and reporting of flight data, allowing:

- The ability to replay a flight from recorded aircraft states,
- Determine when component exceedances have occurred (over temp, over torque, etc), and
- Allow for a given operations to be associated with the data needed for the calculation of a rotor track and balance solution.

The definition of an operation must be robust enough that errors (loss of power, data not being downloaded) do not deter the ability to recover data from current or past operations. Fundamentally, an operation is associated with a flight or rotor turn. For example, if power is applied to the aircraft and then removed without the aircraft being started; those files that were created in anticipation of a flight are not an operation and are deleted.

Because data is typically downloaded at the end of every operation, there is continuity of data that represent both technical (aircraft system) and non-technical (pilot) parameters, which can be used by the safety management system or in an accident investigation. The flight operation consist of files associated with:

- Exceedances (operational limits defined by the original equipment manufacturer or service provider),
- Flight parameter data (latitude, longitude, altitude, velocities, accelerations, engine performance/torque/N1 (compressor RPM)/n2 (turbine RPM), airspeed, etc.),
- Mechanical diagnostics condition of rotating equipment/transmission, and Rotor Track and Balance (RTB) data, and
- Error logs.

Depending on the aircraft state at the end of the operations (e.g. normal flight vs. requirement for inspection to do an exceedance, or in the rare case of and accident/mishap), there will be different priorities on the data to be downloaded and how that data is downloaded. For example, for a normal flight, there is a period of time associated with aircraft shutdown. During shutdown, the pilot/crew chief is monitoring engine TOT temperature to ensure that lubrication will not coke. This is usually a two-minute period in which the operational data can easily be downloaded via Wi-Fi to tablet computer, smart phone/other portable device the pilot may have, or a local Wi-Fi base station. This data would include aircraft parameters data, condition indicators for mechanical diagnostics/RTB, and exceedance. Wi-Fi is the preferred download method as there is no cost associated with the bandwidth required for download. Wi-Fi can also establish a virtual private network (VPN) to ensure the security of the data. Alternatively, if no Wi-Fi is available and the aircraft state is nominal (e.g. no hard landing/inspection requirement or mishap), the files can be held locally in flash memory until Wi-Fi is available.

However, if the operation terminates with an operation exceedance, such as a hard landing, engine over temp/over torque, it is important that the parameter data (aircraft state) is downloaded by whatever means is available, such as local cellular modem using LTE (100 Mb/s download), or UMTS/HSPA (3G 7.2 Mb/s) or GSM/GPSR (2.5G 85.6 kb/s). If in the event of a mishap which causes loss of power, the HFDM should incorporate holdup power (such as an ultra-capacitor), and its own inertial measurement unit with GPS. An ultra-capacitor, in the event of power loss, can power the cellular modem. Considerations for an Inertial Navigation Unit (INU) and GPS should be made. This allows the HFDM unit to determine aircraft state independently of the aircraft avionics.

The advantage of this type of system is that: Implementing a cellular modem, Adding an ultra-capacitor holdup power, and an Internal INU/GPS for aircraft state does not greatly affect the bill of material cost or the system weight. The INU and GPS is desirable in a HFDM design as it reduces the number of aircraft interfaces needed to acquire parameter. Reducing aircraft interfaces reduces the cost and weight needed to for integration into the aircraft and greatly reduces reapplication cost. For retrofit, many aircraft have no Altitude and Heading Reference System (AHRS), so will require an INU anyway.

Because movement of data via cellular is rare (exceedances/hard landing/mishap do not happen often), the cost of the data plan associated with moving this data is low. Yet, because the data is transferred after the determination of a mishap/hard landing (within milliseconds), the data is protected even in the event of a mishap. A mishap may involve fire that could damage the HFDM persistent memory. By quickly downloading the data when a mishap is detected, the information needed for the investigation is protected. Additionally, the parameter data include positional information that can be used in locating the aircraft.

Most Type 27 Aircraft (defined by the FAA as airworthiness standards as rotorcraft up to 7,000 lb Maximum Takeoff Weight and 9 or fewer passengers) rarely fly over water for extended periods and will usually be within cellular connectivity. In the cases where the aircraft will operate in remote locations or over water, the HFDM can be equipped with a satellite modem for data transfer. Again, because the use of satellite data will be rare, the cost of the data plan will be low. As noted, the use of satellite or cellular modem only occurs when the operation is terminated due to a mishap/hard landing, or other regime that are of interest to the operator/owner of the helicopter.

Defining an Aircraft Operation: An operation is concerned with those conditions where a pilot/crew is in command of the aircraft and covers the data needed to reconstruct the pilots'/crews flight operation. The operation starts on rotor turn/power up, and reports

- The rotor turn time,
- The flight time,
- Flight parameters,
- Regime data,
- Exceedances,
- Mechanical diagnostics/RTB acquisition data (if equipped).

The operation ends on shutdown or due to a mishap/hard landing or similar condition. The type termination for the operation will define the data download priority.

The operation consists of files identified by date-time group and aircraft side number, which contain the data generated over the flight or rotor turn (ground operation). The flight operation consists of operational states that follow a set of defined functionality and rules needed to support HFDM, such as:

- Integral to the hardware file structure, the status of a flight operation files are associated by the files data structure location within persistent memory of the HFDM, such as:
    a. An active directory, which holds the current flight operation files,
    b. A transfer directory: those operations that are available for download, and
    c. An archive directory, which are those operations that have been downloaded off of the aircraft for analysis/visualization and reporting.
- If on power up there is an active operation (e.g. files in the active directory), these files are closed and then are scheduled for data transfer. An error is logged, as this suggest that the HFDM failed to close and transfer those files during the last active operation.
- A new operation is started when there is a valid time (from GPS). New flight operations files are created in the active directory.
- A major function of HFDM is to accrue time, such as power on time, rotor turn time and flight time.
    a. Rotor turn time is accrued when the main rotor RPM is greater than 10%.
    b. Flight time is time associated with flight regimes, typically torque > 30% (aircraft dependent). An important function of the regime recognition algorithm is to determine when and how the aircraft is flying.
- It is important to apply power to the radios (wireless communication) only when in appropriate regimes, such as: power on, rotor not turning, on shut down or when a mishap/hard landing is detected. A wireless connection need only be made when there are operations available in the Transfer directory.
- Rules for prioritizing which communication channel to use and which operational files to download.

   a. If Impact/Hard Landing is determined and no Wi-Fi connectivity (e.g. no external Wi-Fi detected), then cellular or satellite modem is used.
   b. For regimes which are associated with a mishaps, the parameter/aircraft state data is downloaded first. This may require just a few seconds, as data throughput of 3 Mb/s are typically observed.

- An operation is terminated when
   a. There is an active operation open from power up.
   b. The incremented rotor turn time is greater than zero, and the Regime allows active wireless communication, or a Mishap/Impact or Hard landing is detected.
- If an operations file transfers are complete, the operations files are move to the archive directory.

Incorporating these rules in software can be difficult. To reduce the complexity of the programing task, this can be implemented into a finite state machine. A sate machine is an abstracted construct that allows only a finite number of sates at any given time. The state machine transitions from one finite state to another state based on external inputs. The model of this state machine can be seen in Figure 1.

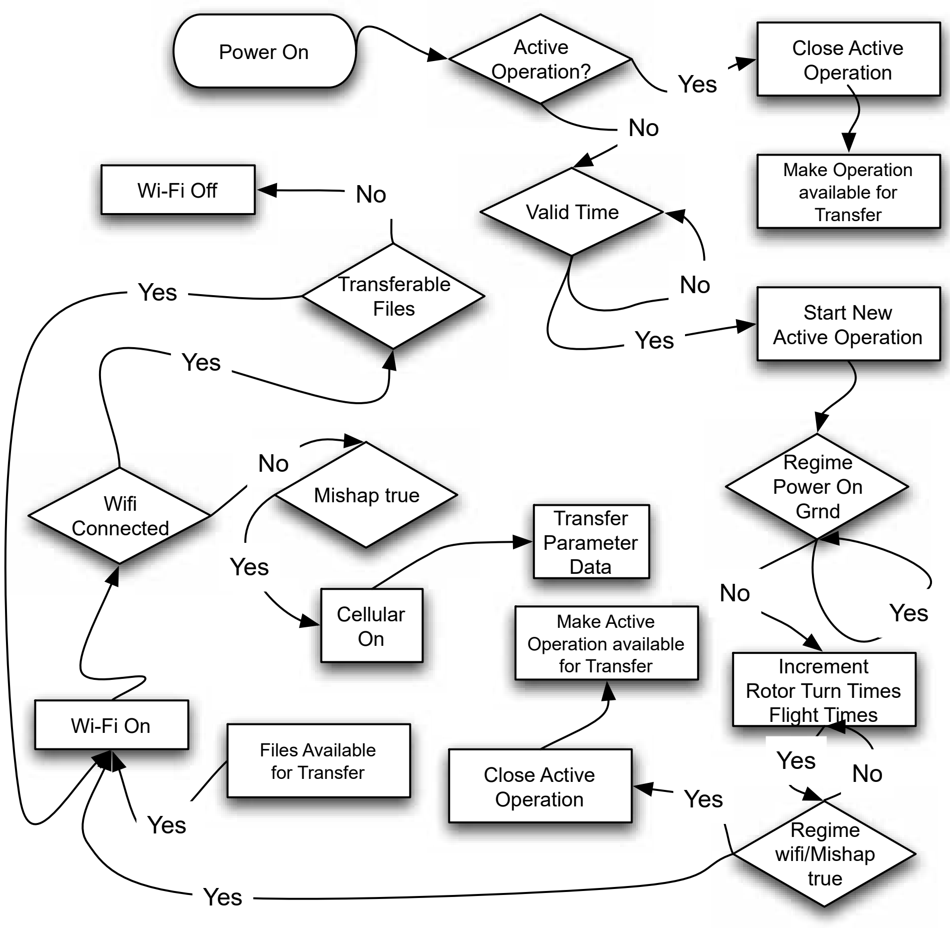

Figure 1 Operation Finite State Machine

For example, when power is applied, the state machine checks to see if there are files in the Active Operation directory. If false, the machine checks for a valid time. Once time is true, and new operation is stated, the regime being power on ground, etc.

Regime Recognition: An input into the state machine is regime. When to acquire data for mechanical diagnostics/RTB, determining when the aircraft is shutting down, or a mishap has occurred are all depended on knowing the aircraft regime. The general terms and requirements for Regime Recognition (RR) were developed in the FAA Advisory Circular “Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS)” [2]. RR in this application was defined more for loads monitoring rather than for aircraft state awareness. Similarly, in the “Aeronautical Design Standard Handbook for CBM Systems for US Army Aircraft Systems” [3], and in “Validation of FAA AC-29-2C MG-15 for Structural Usage Credits” [4], the primary usage of RR is for load monitoring.

The goal of RR used in this way is to extend the hours of life-limited structures or components. Life limited parts assume a worst-case usage spectrum. In practice, this results in an overly conservative life due to lack of real world usage knowledge. RR allows creation of the actual usage spectrum, which can then be used to re-life or update the life remaining on the part. While it is anticipated that RR for this application can be used for structural loads, the primary requirement for the project was to identify aircraft state. As noted, aircraft state supports a number of important HFDM related functions, including:

- Generation of flight statistics for HFDM reporting,
- Identifying and reporting high risk behavior: high angle of bank, rough approach, etc.,
- Determining the end of an operation for downloading of flight data, and
- Determine if the aircraft has had a hard landing/impact or crash.
- Provides an immediate time history of the operation,
- Determining when a mechanical diagnostics acquisition can be taken, and
- Associating a regime (ground, hover, 90, 120, 140 kts, etc.) for RTB acquisitions

To support these HFDM function, an easily configurable RR system allows:

- Identify when the rotor is turning, for the calculation of total rotor turn time for the given operation,
- Identify when the aircraft is flying, for the calculation of total flight time for the given operation,
- Determine when the aircraft in not flying or in ground operation, so that RF communications (Wi-Fi/Cellular Modem) can be powered to download data,
- Determine if the aircraft has suffered an event (mishap/hard landing) requiring an inspection/immediate action of the crew/maintenance team, and
- Determine when acquisitions for rotor track and balance/mechanical diagnostics can be performed.

RR Algorithm The RR application is based on mathematically rigorous methodology that is optimal in that sense that for a given probability of false alarm (e.g. stating the aircraft is in one regime, when it is in fact another regime), it maximizes the probability of correct classification. This algorithm is computationally simple to implement and configure. The algorithm is easily extended to encompass new regimes and/or new parameters. The RR algorithm uses a maximum likelihood estimator (MLE, see [5]) which assumes that input parameters are noisy. The algorithm weights the validity of a parameter by the information the parameter conveys (the inverse of variance is information). The output of the algorithm is the regime that is most likely, as a function of the *a priori* (e.g. configuration) parameter mean value and variance. This is conceptually different from algorithms using if/then/else search trees, which in effect are idealized by assuming no measurement or environmental noise.

The MLE is a quadratic classifier, which can accommodate nonlinear decision spaces. It takes the current set of measurements and calculates a normalized distance between the current measurements and a notional set of regimes. The regime that is closest statistically to the measurement is most likely. In this implementation, the MLE is structured as a multiple dimension hypothesis test, in which the aircraft parameters are used to test the hypothesis that the aircraft is in a given regime.

For example, one defines $P(H_i|\mathbf{z})$ as the probability that H_i was the true regime given a measured observation, $\mathbf{z}$. The correct hypothesis is the one corresponding to the largest probability of the *m* possible regimes. The decision rule will be to choose H_o if: $P(H_o|\mathbf{z}) > P(H_1|\mathbf{z}), P(H_2|\mathbf{z}), \ldots P(H_m|\mathbf{z})$, else choose the greatest $P(H_i|\mathbf{z})$. The null hypothesis $P(H_o|z)$, in this test, represent power on, rotor not turning.

In testing, this RR algorithm used six input parameters: yaw rate (degrees/second), Z acceleration (-1 G is normal to the earth), N2 (turbine) RPM, main rotor RPM, torque, and indicated airspeed. As noted, the null hypothesis was power on, rotor not turning. The 22 alternative hypothesis were:

Power On Aircraft, Rotors Turning Flight Idle (65%)	Regime 2
Power On Aircraft, Rotors Turning Flight RPM (100%)	Regime 3
Shutdown (Main Rotor > 10%, N2<10%)	Regime 4
Hover	Regime 5
Left Hover Turn	Regime 6
Right Hover Turn	Regime 7
Level Flight up to 0.3 Vne (39 Knots)	Regime 8
Level Flight up between 0.3 and 0.4 Vne	Regime 9
Level Flight up Between 0.4 and 0.5 Vne (60 Knots)	Regime 10
Level Flight up Between 0.5 and 0.6 Vne	Regime 11
Level Flight up Between 0.6 and 0.7 Vne	Regime 12
Level Flight up Between 0.7 and 0.8 Vne (100 Knots)	Regime 13
Level Flight up Between 0.8 and 0.9 Vne	Regime 14
Level Flight up Between 0.9 and 1.0 Vne	Regime 15
Decent	Regime 16

Climb	Regime 17
Autorotation	Regime 18
Level Left Turn:	Regime 19
Level Right Turn:	Regime 20
Pullout: 0.8 Gs	Regime 21
Pullouts: 3.0 Gs	Regime 22
Pushover: 0.2 Gs	Regime 23

Flight Test Example: A low cost/light weight HFDM system was installed on a Bell 206 Jet Ranger in the fourth quarter of 2016. The installation was conducted under an FAA 337 field approval and cleared for flight operations in the first quarter of 2017. Initial flight tests were done to: establish threshold for mechanical diagnostics, check RTB coefficients, and ensure the HFDM automated operation generation and downloading were functional. During the initial flight, 31 HFDM parameter data was collected, of which six parameters were used for regime recognition. An example of the flight path is given in Figure 2. The aircraft hovers, climbs, circles the airfield and lands.

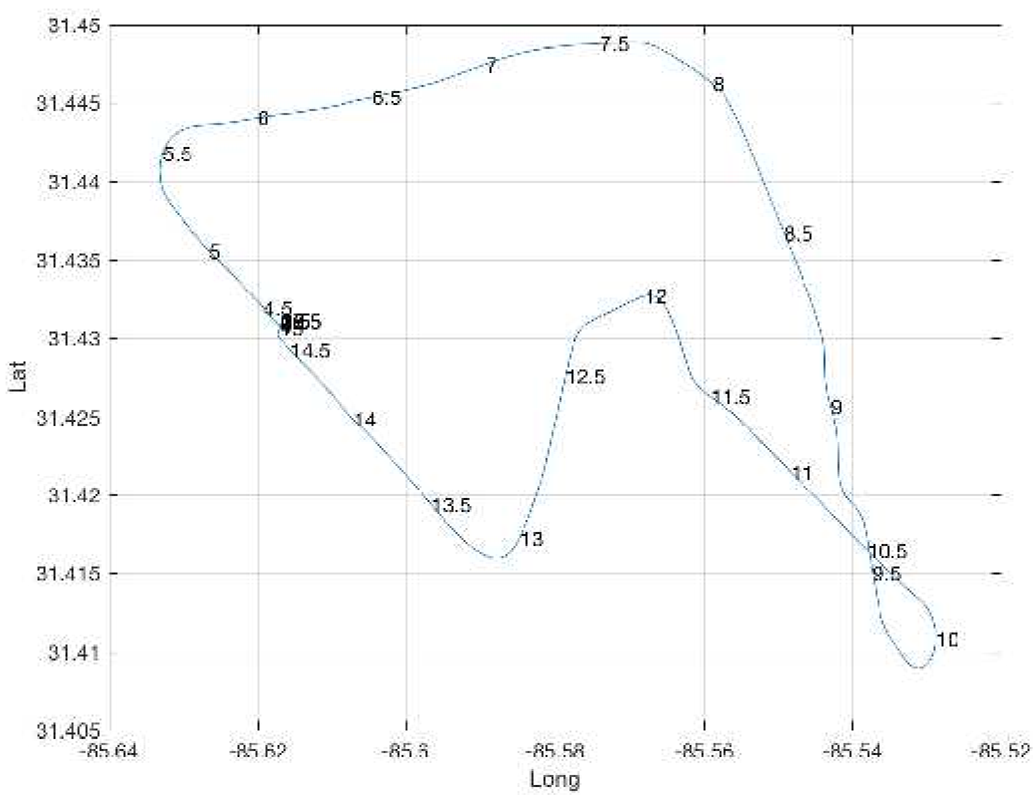

Figure 2 Example Test Flight

The times in minutes was plotted on the flight path to allow correlation with the flight parameters and regime indexes, Figure 3. The initial regime is 2, flight idle, transitioning to ground at 2:20. Note that the regime briefly goes to 17, indicating clime, then to regime 8 (low speed forward flight), before settling regime 3, ground 100%. From time 3:20 till 4:10, the aircraft is in hover (regime 5, 6, 7), and then toggles between hover and climb until 4:20. The aircraft climbs until time 6. From time 6 until time 14, the aircraft is in level flight, 70 to 100 Knots (regime 11, 12, and 13), performing right and left hand turns (see Figure 2). At time 14, the aircraft descends, hovers, goes to idle, and performs a shut down at time 17:25. The operation was successfully download and available for data analysis when the pilot returned to flight operations for debrief.

As noted, the function of this RR implementation is to provide input to the state machine. The state machine then determines when actions can be performed, such as: turn on the Wi-Fi, increment flight time, or perform and acquisition. As such, each regime is coded for what actions are be taken. This coding uses an integer representation of binary mask. For example, regime 2 (power on aircraft, rotor turning at 65%) increments rotor turn time, and allows Wi-Fi. The binary mask to represent this is 2. For regime 3 (ground, 100% main rotor RPM), rotor turn time is increments, and both mechanical diagnostics and RTB acquisitions are allowed, but Wi-Fi is off. The mask is 26. For hover (regime 5), which increments rotor turn time, flight time and allows mechanical diagnostics/RTB, the mask is 30. But for regimes 6 and 7 (left/right hand turn hover), only rotor turn time and flight time are incremented – the mask is 6.

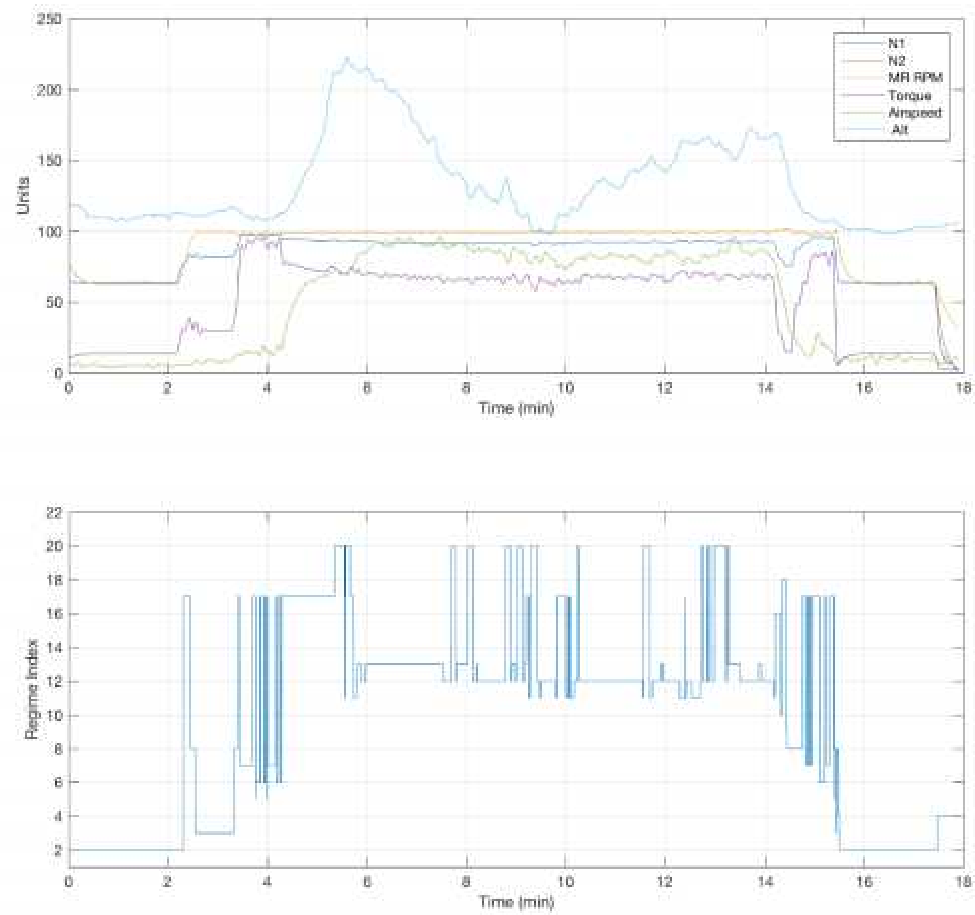

Figure 3 Flight Parameters and Regime Index

Other Functions: Flight Manual Exceedances. Automated exceedance processing is critical function of a HFMD system. Inflight occurrences require flight crew to submit a safety report and flight crews are sometimes not aware, or unwilling, to report an error. Exceedance monitoring is the most reliable method for monitoring flight crew compliance with operating limits and standard operating procedures. It captures all occurrences that take place during a flight, even those events in which the crew is unaware. Exceedance monitoring records quantifiable data that can be used to view trends. In that context, the crew's participation is a major component to provide the contextual information that is lacking in the data – to explain the issues around the event and allow insight into implementing control measures.

The HFDM exceedance monitoring function uses a hybrid system of internally derived inertial inputs, and data from a limited number of aircraft systems, both analog and digital. These parameters feed a configurable analysis engine designed to test for the operating limits as outlined by the equipment manufactures documentation. The analysis engine itself is based on the concept of simple and condition exceedance.

A simple exceendance is true if a measured parameter is greater than a given threshold, such as "the maximum operating pressure altitude is 20,000 ft". A condition exceedance is based on a simple exceedance that is conditioned on one or more other flight parameters. For example, "Vne 80 knots, when in takeoff power range of 85 to 100% torque". This exceedance is true if the condition of torque is greater than 85% is met while the IAS is greater than 80 knots. More than one exceedance can occur at a time. For example, if the torque is 101% for 6 seconds, and the airspeed is 84 IAS, both the maximum continuous power transient and the takeoff power range Vne would be exceeded.

Observation: During test flights, the HFDM system triggered the creation of new operation based on RR at aircraft startup, and correctly acquired mechanical diagnostic data in ground, hover and forward flight regime. The system also detected shutdown and automatically powered the Wi-Fi modem, downloaded data. This data was then automatically processed and available viewing by the pilot after the post flight debrief.

The RR incorrectly selected the climb regime when transitioning from Power On Aircraft, Rotors Turning Flight Idle (65%), regime 2, to Power On Aircraft, Rotors Turning Flight RPM (100%), regime 3. During the transition, the torque was higher than would be expected for regime 3. Its likely that adding an additional parameter, vertical rate (which available from the INU) will improve the discrimination of the RR algorithm for detecting climb and decent.

Operationally, it has been found that at some locations the Wi-Fi access points firewall blocks the transmission of data from the helicopter to the cloud based storage server. This is another reason for implementing cellular modem, which facilitate IoT by bypassing any firewall or other local security.

Conclusion: HFDM enhanced the safety and reliability of helicopters. The expense and weight of system makes it difficult for most Type 27 helicopter operators to make the business case and justify the installation. By reducing the cost/weight and automating the download and analysis, the business case is easier to make. This should expand the number of aircraft using HFDM. Overall, automation designed into the test system performed to expectation. Some additional configuration, such as adding vertical rate as a parameter to the RR algorithm, will improve the ability to discriminate during regime transitions. It is hoped that operators will find that the enhanced safety and reliability of HFDM equipped aircraft will justify the expense of installation.

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