VTUAV, Fire Scout Fatigue Usage Spectrum Development

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Abstract

The Fire Scout helicopter is the Vertical takeoff and landing Tactical Unmanned Aerial Vehicle (VTUAV). The Fire Scout is planned to be operated from USN FFG-7 frigates, Littoral Combat Ships (LCS), and land-based shelters. Prior to induction of the Fire Scout into service, a realistic usage spectrum is required to assess dynamic component fatigue lives. Ten broad mission profiles with various durations were used to develop a fatigue usage spectrum. It is assumed that 90% of missions will be conducted aboard ship and 10% from the land. The limits of Nz, velocity, altitude, and Angle of Bank (AOB) were established from V-n, V-h, and AOB-V envelopes. Each mission is composed of takeoff, hover, climb, level fight, maneuver, descent, and landing segments. Velocity, AOB, Nz, and torque levels were assigned to each maneuver occurrence in the mission profile. Maneuver duration and occurrences were computed for all maneuvers in each mission profile. Rotor start and stop, landings, and Ground-Air-Ground (GAG) cycles were established using recorded Anti-Submarine Warfare (ASW) mission data from various U.S. Navy helicopters. In this manner, the conservative fatigue usage spectrum was developed to calculate fatigue lives of VTUAV dynamic components and to determine service life.

1. Background

The Vertical takeoff and landing Tactical Unmanned Aerial Vehicle (VTUAV) is derived from the manned Fire Scout three-bladed helicopter, RQ-8A which in turn is based on the Schweizer 269 series. The complete VTUAV autonomous system is being developed by Northrop Grumman as MQ-8B Fire Scout, a four-bladed rotor helicopter. The airframe and rotor system are being manufactured by Schweizer Aircraft Corporation. The goal for VTUAV range is 110 nmi with endurance greater than 8 hours and a payload of 600 lb. The principle missions of VTUAV are Antisubmarine Warfare (ASW), Mine Warfare (MIW), and Anti-Surface Warfare (ASUW) from USN FFG-7 frigates, and LCS. To conduct its mission, the Fire Scout is equipped with electro-optical and infrared sensors. A laser designator is used to locate and track tactical targets for aircraft/ships to strike. Following a strike, the VTUAV can provide battle damage assessment.

VTUAV is a conventional helicopter with a single main rotor and a tail rotor at the end of the tail boom, **Figure 1 from Reference 1.** It has a fully articulated four-bladed rotor system with flapping, lead-lag, and pitch hinges. The main rotor blade collective and cyclic pitches are operated by a control system consisting of pitch horn, pitch link, and swashplate mechanism. The tail rotor is a two-bladed semi-rigid teetering rotor system. The skid landing gear is attached to the fuselage structure for vertical takeoff and landing, **Figure 1**.

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Figure 1. View of Fire Scout helicopter, Reference 1

According to Aeronautical Requirements (AR 56) of Helicopters, it is necessary to demonstrate structural integrity of the rotor blades, rotor hub assembly, rotor shaft, control system components, skid gear, and fuselage structure prior to operational evaluation, **Reference 2**. AR 56 (U.S. Navy) requirements are more demanding than the Federal Aviation Regulations (FAR) that certified the original 269 series helicopter. UAV's are often developed as technology demonstration vehicles with emphasis on command control software to substitute a human pilot for flying (takeoff, maneuvering, and landing). Once these objectives are achieved, the vehicle is often slated for Low Rate Initial Production (LRIP) without rigorous structural demonstration tests (static, fatigue, endurance and functional), **References 3 and 4**. The absence of proper development processes may result in unsafe aircraft, failed missions, loss of confidence, increased developmental cost, and operational risk. As one means to avoid future problems, the UAV certification process outlined in **References 3 and 4** was developed. Fatigue testing of the rotor hub, rotor blade, and many dynamic components is essential prior to induction into fleet service. To test these critical components and determine their fatigue life, it is necessary to know fatigue load levels and their frequency of occurrence for each maneuver within the flight envelope. The expected frequency of maneuver occurrences is called the usage spectrum. It is difficult to create maneuver occurrences and mission profiles of the new VTUAV without prior service experience. The typical usage spectrums for various helicopter types are outlined in **Reference 2**. The method to develop a usage spectrum using the recorded data is discussed in **References 5 and 6**. This paper delineates, the procedure used to develop the VTUAV fatigue usage spectrum using Concept of Operations (CONOPS) mission requirements and

Naval Flight Record (NAVFLIR) data of other Navy helicopters.

2. VTUAV System Training and Operational Environment

The first draft VTUAV system training and operational environment is discussed in **Reference 7**. The Fire Scout helicopter is an airborne component of the system with payload, data links, remote data terminals, Launch and Recovery System (LRS), and Tactical Communication System (TCS). The LRS can be located on the ground or on a ship within the range of a UAV. TCS is located anywhere on the network; physically it could be located together with the LRS or any place in the world. Communication and support equipment are required to communicate between the VTUAV, LRS and TCS, **Figure 2 from Reference 8**. In order to takeoff and land, the VTUAV is equipped with a precision Unmanned Common Automatic Recovery System (UCARS), **Reference 9**.

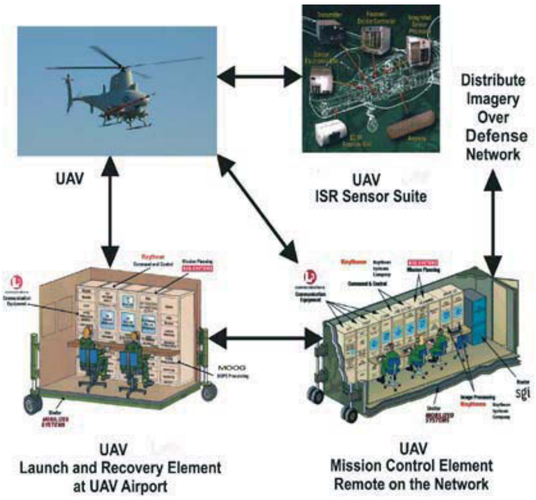


Figure 2. VTUAV training operational environment, Reference 8

3. Usage Spectrum Development

Helicopter types are classified based on their primary role, such as utility, cargo, troop transport, search and rescue (SAR), ASW, scout, crane, and armed. Each helicopter type has primary missions with varying weight, range, cargo, number of troops, internal stores, and external stores requirements. Mission profiles are defined with assumed gross weight, fuel, internal cargo, internal equipment, number of troops, altitude, velocity, AOB, and flight duration. Variations in each of these parameters result in different flight profiles. The basic mission profiles consist of maneuvers such as takeoff, hover, forward flight, sideward flight, rearward flight, sideslip, climb, turn, dive, pull-up, acceleration, deceleration, autorotation, and landing. Helicopters are designed with an assumed time in each of the maneuvers. Mission variations result in wide variations in their usage spectra. The variation in usage spectra leads to changes in the component retirement life.

3.1. Flight Envelope

The maneuvers in the usage spectrum, fatigue loads and their frequencies must be within flight envelope limitations. Flight envelope limitations are often a function of weight, vertical load factor, and velocity as shown in **Figure 3**. The VTUAV is limited to 2.7g and 128 knots at a maximum gross weight of 3,150 lb. For a typical gross weight of 2,900 lb, it is limited to vertical load factor of 3.0g and velocity of 139 knots, **Reference 10**. At present, the service ceiling of the VTUAV is 12,000 ft altitude with maximum forward velocity of 85 knots. However, velocity limitations are relaxed as altitude decreases from 12,000 ft to sea level; at sea level, it can fly with maximum speed of 130 knots, **Figure 4**. The VTUAV is limited to 30 degree AOB for a velocity range of 0 to 130 knots, **Figure 5**. The flight envelope is always limited to simultaneously satisfy all possible gross weight, load factor, velocity, and AOB configurations.

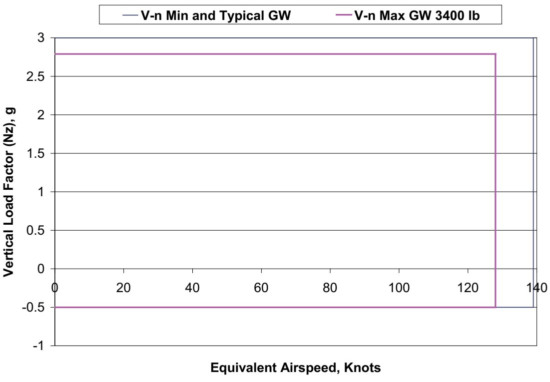


Figure 3. VTUAV V-n maneuver envelope

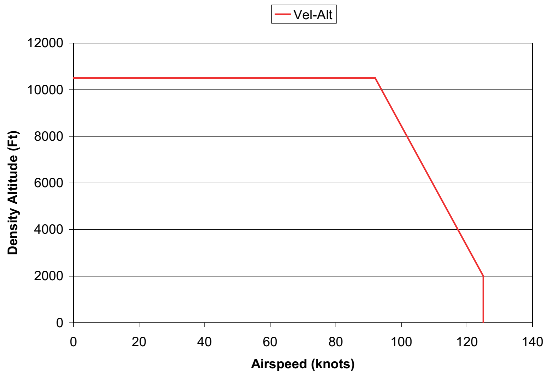


Figure 4. VTUAV velocity altitude envelope

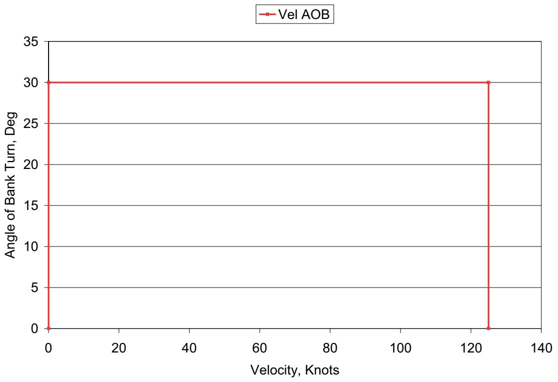


Figure 5. VTUAV velocity AOB envelope

The system identification technique uses mathematical model, flight test data, and a stitching technique to develop full flight envelope simulation. The transfer function between linear and angular rate and control positions is developed for each flight condition. Successful flights were conducted on the Fire Scout to validate the designs, **References 11 and 12**. However, the developmental flying vehicle is not subjected to operational flight envelope and is likely to exceed the flight envelope limit inadvertently. This will lead to an increase in components/structures load amplitude. To ensure UAV structural integrity, an automated flight envelope protection system may be necessary. The algorithm/model similar to the one discussed in **Reference 13** must be implemented to sense the flight parameters response/growth rate. For example, to limit V-n envelope, the expected Nz response can be represented by a linear model between the current value of Nz and pitch rate, **Reference 13**. The subtraction of the current Nz value from the envelope limit Nz is a margin that is used to lower future pitch rate in association with the feedback flight control system. The reduction in pitch rate will bring the Nz within the flight envelope. Details of the system can be found in **Reference 13**.

3.2. Flight Profile

The CONOPS document was used to derive missions shown in **Table 1** that will be performed by the VTUAV in the fleet service, **Reference 14**. Each mission provided in **Table 1** contains the likely payload, flight duration, range, and altitude Above Ground Level (AGL) at which most of the mission time will be spent. The 10 missions indicated in **Table 1** consist of Intelligence Surveillance and Reconnaissance (ISR) ASW, MIW, ASUW, and Functional Check Flights (FCF). For the Navy, 90% of the missions will be conducted from ship and 10% will be from shore. However, in the Army service, all VTUAV missions will be shore-based. The complete mission profile is shown in **Figure 6**. Each mission consists of engine start, vertical takeoff, hover, climb, level flight, turn, descent, and landing segments. After the engine start, a harpoon is released to set UAV free for takeoff; UCARS increases the power to liftoff the UAV to a hovering height of 30 ft. From hover, UAV climbs with a specified rate of climb to the designated cruise altitude for a forward flight. At a particular location, the VTUAV initiates the ASW mission that consists of continuous looping turns that look like a figure of 8 at the specified altitude. The UAV descends to another designated altitude and begins the same turn maneuver. The mission segment, climb-cruise-turn-cruise-descent-turn-cruise is repeated three times during this mission prior to the final descent, approach to hover, hover, and landing with UCARS.

1. Based on current draft CONOPS and assumed usage
2. Assume 90% sea and
3. Performance assumptions subjiected to change based on A/V perfro

Mission Title	% Sea/Shore Life	% Life Weighting Factor	% Total Life	Density Altitude (ft)	AGL (ft)	Range (nm)
1. ISR Mission (SEA)	50	0.9	45	5 to 10K	5 to 10K	25
2. SUW/SUW STOM/MIW/ASW (SEA)	20	0.9	18	10000	10000	110
3. ASW Relay (SEA)	5	0.9	4.5	15000	15000	110
4. Assault Support (SEA)	5	0.9	4.5	5000	5000	15
5. SUW Sector & NLOS (SEA)	5	0.9	4.5	10000	10000	40
6. MIW (SEA)	10	0.9	9	5000	3000	40
7. UCARS Waveoff (SEA)	5	0.9	4.5	30 - 1500	30 - 1500	0-2
8. Training/ISR Mission (SHORE)	94	0.1	9.4	5000	5000	10
9. FCF (SEA or SHORE)	3	0.1	0.3	14000	14000	10
10. Shore Waveoff (SHORE)	3	0.1	0.3	30-1500	30-1500	0-2
		TOTAL:	100			

Table 1. VTUAV Mission profile summary, Reference 14

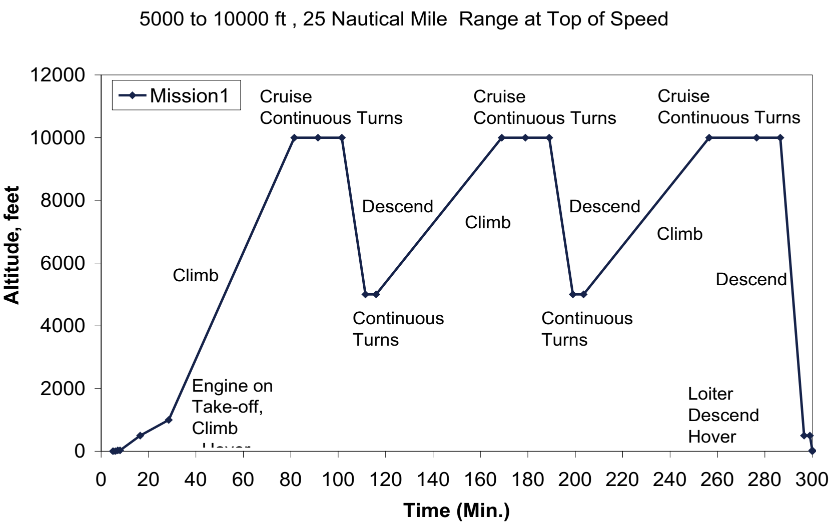


Figure 6. Sample mission profile

3.3. Launch and Recovery Profile

UCARS was developed by the Sierra Nevada Corporation, **Reference 9,** and uses a transponder mounted on the vehicle and a millimeter wave tracking system. UCARS equipment is installed on the Navy ship, **Figure 7 and Reference 7.** The various landing profiles consisting of descent, approach to hover, hover, and landing are considered while developing the usage spectrum.

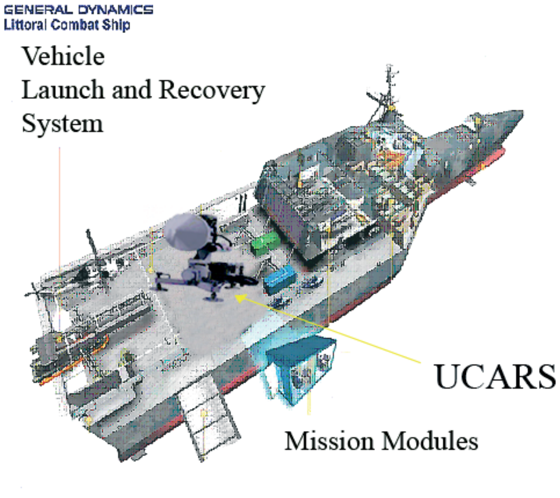


Figure 7. UCARS

3.4. Determination of Number of Flights, Rotor Start and Stop, Landings, and Ground-Air-Ground Cycles

Each flight flown by the Navy aircraft is classified according to Total Mission Requirement (TMR) codes. The codes are recorded by the pilot on NAVFLIR OPNAV Form 3710/4. TMR codes are three digit alphanumeric characters with the first character representing the flight purpose, the second character representing the general purpose and the third character representing the specific purpose. The first character denotes flight type such as training, support services, operations, contingency, combat, and exercise. The second character is a general purpose code and is used in conjunction with the specific purpose code to describe the detailed flight objectives. The third character, a specific purpose code is a number ranging from 1 to 10. In addition to TMR and flight hours, various landing types are also recorded on the NAVFLIR. The various landing types include vertical, rolling, Field Carrier Landing Practices (FCLP), and Touch and Go (T&G). Takeoff and landings are performed from the ship or shore.

ASW missions have been performed by Navy SH-2G, SH-3H, SH-60B, SH-60F, and SH-60R helicopters. The ASW mission flight duration distribution for these aircraft is shown in **Figure 10**. The average flight duration of 3.54 hours for previously conducted ASW missions is slightly higher than the criteria set at 2.77 hours. However, with the exclusion of UCARS wave-off, the average flight duration increases to 4.46 hours. That is in accordance with the requirement of longer flight durations for VTUAV missions, **Figure 10**. Further regression analysis of ASW total flight hours and total flights data reveals an average of 34 flights per 100 hours, **Figure 11**. This is very close to the present criteria of 36 flights per 100 hours.

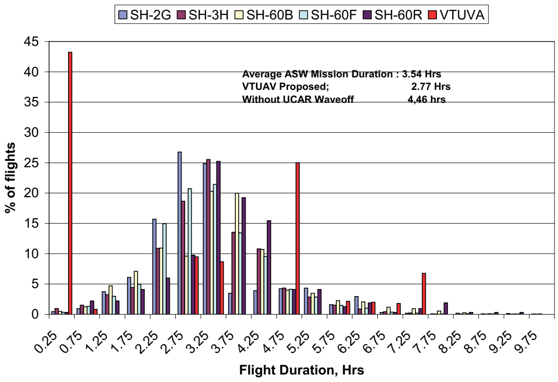


Figure 10. Flight hour duration distribution for 100 flights

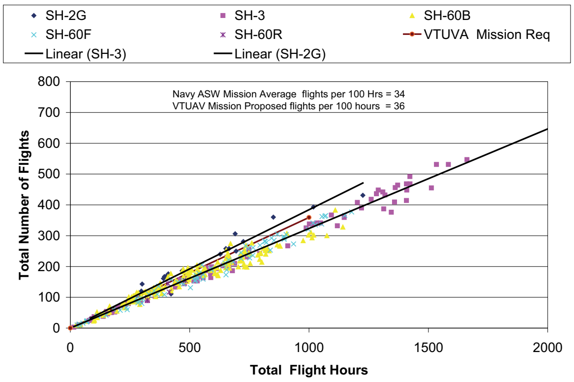


Figure 11. Determination of flights

The number of flights recorded on NAVFLIR can be used to estimate the number of rotor starts and stops for airborne flights. On many occasions, the rotor is started and stopped for maintenance actions and is not reported on the NAVFLIR, as NAVFLIR is filled out by the pilot only. To derive appropriate values, the H-3 recorded usage, indicated in **Figure 12**, was utilized. The average rotor start and stop are 120 per 100 hours with standard deviation of 40. The rotor start and stop are important as they determine the number of Centrifugal Force (CF) cycles and their variation from 0 to maximum value. The CF variation causes significant damage to rotor head components.

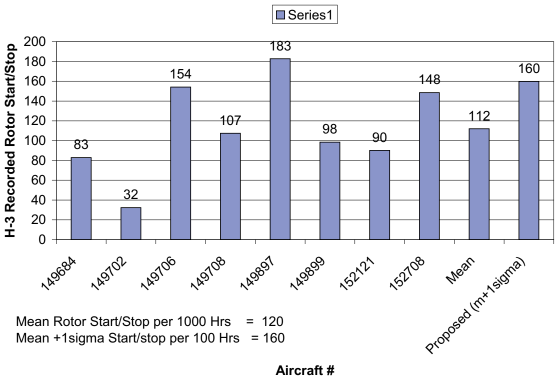


Figure 12. H-3 recorded rotor start and stop

The variation of stress/load from minimum to maximum during a flight is called GAG cycle. Therefore, GAG cycles are equal to the number of landings per 100 hours. The average landings for an ASW mission are 96 per 100 hours with a standard deviation of 42. To include the majority of helicopters, 223 (mean+ 3σ) GAG cycles per 100 hours are proposed. This number is composed of GAG cycles with and without rotor stops, **Figure 13**.

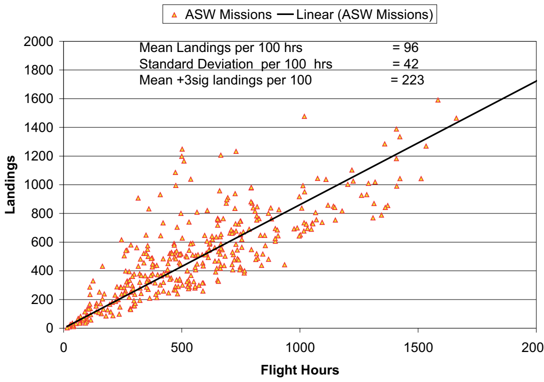


Figure 13. Total number of landings as function of total flight hours (GAG)

3.5. Maneuver Time Computations

The usage spectrum of any helicopter can be mapped to unique maneuvers by removing velocity, AOB, Nz, climb/descent rate, and power level prorating/splits as discussed in **Reference 17**. Once the percent time in each unique maneuver is computed, it is possible to further prorate/split the maneuver using the distribution of the parameter of interest within the unique maneuver to derive an actual fleet usage spectrum. High AOB turns, pull-ups, high speed level flight, and GAG conditions are damaging to most dynamic components, **References 6, and 15-17**.

When hovering, the helicopter is likely to perform maneuvers such as hover turns, sideward flight, rearward flight, control reversals, low speed forward flight, and acceleration from hover to forward flight, **Figure 14**. The climb segment consists of normal climb and full power climb. High speed forward flight generally involves sideslip due to cross winds and gust. To correct disturbances due to gust, control reversals are performed. A descent from a constant altitude mission may result in a pushover; the descent could be a partial power descent or normal descent. The high speed descent from high altitude to low altitude results in a deceleration. A rapid descent with a rate greater than 1,000 ft/min results in a dive. At the end of descent or dive, the pilot is likely to conduct a pull-up maneuver and climb to a specified altitude. These special maneuvers of short duration are performed while transiting from one flight segment to another. These maneuvers were introduced in all missions planned for the VTUAV. The number of their occurrences was utilized to derive the frequency of occurrence, while the typical maneuver durations were used to compute percent of time of each in the usage spectrum.

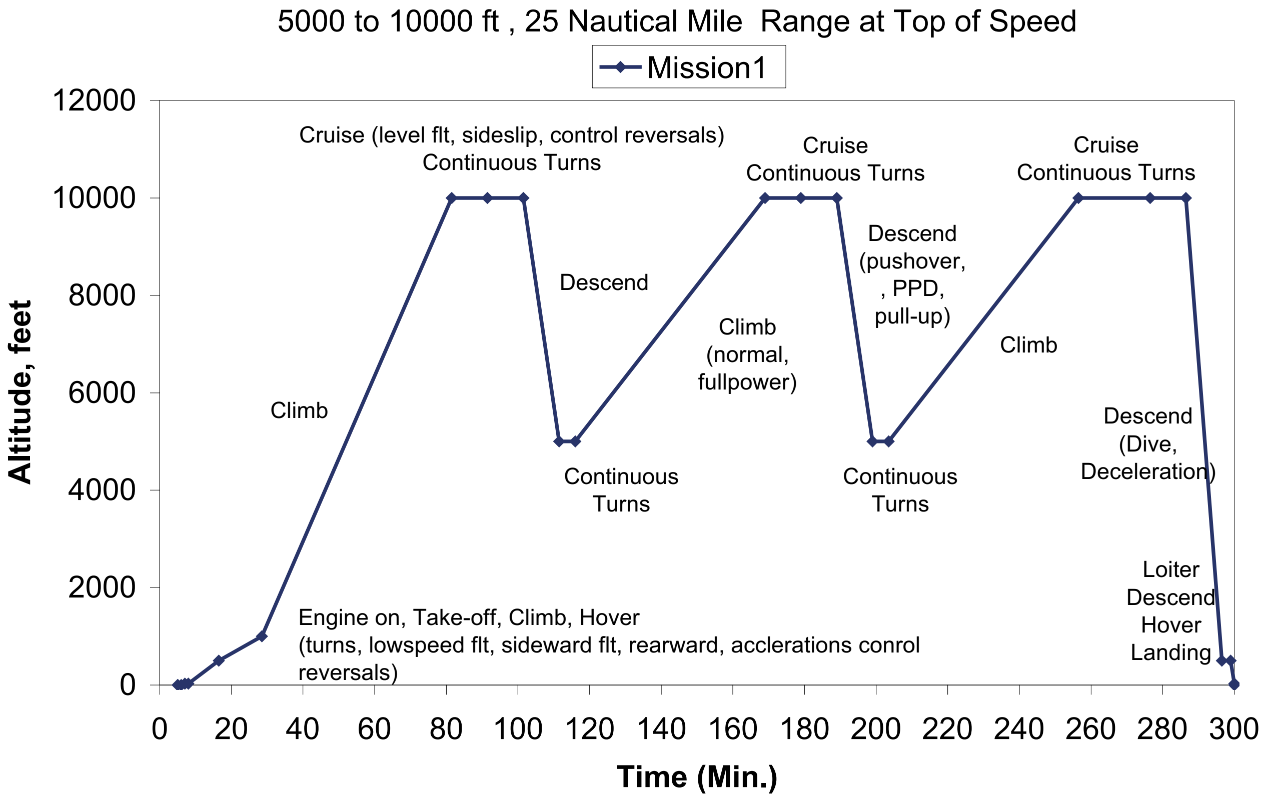


Figure 14. Mission profile with maneuver inserted

3.6. Functional Check Flight

An FCF is performed to determine whether the airframe, engine accessories, rotor system, and blades tracking are functioning according to set requirements. Therefore, they are generally conducted with major maintenance of the engine, transmission, rotor system, flight control system, etc. The FCF maneuvers are shown in **Table 2** and the flight profile of is shown in **Figure 15**. These flight check maneuvers ensure the airworthiness of the UAV during all flight conditions. The flight check maneuvers and their durations were utilized while developing the usage spectrum.

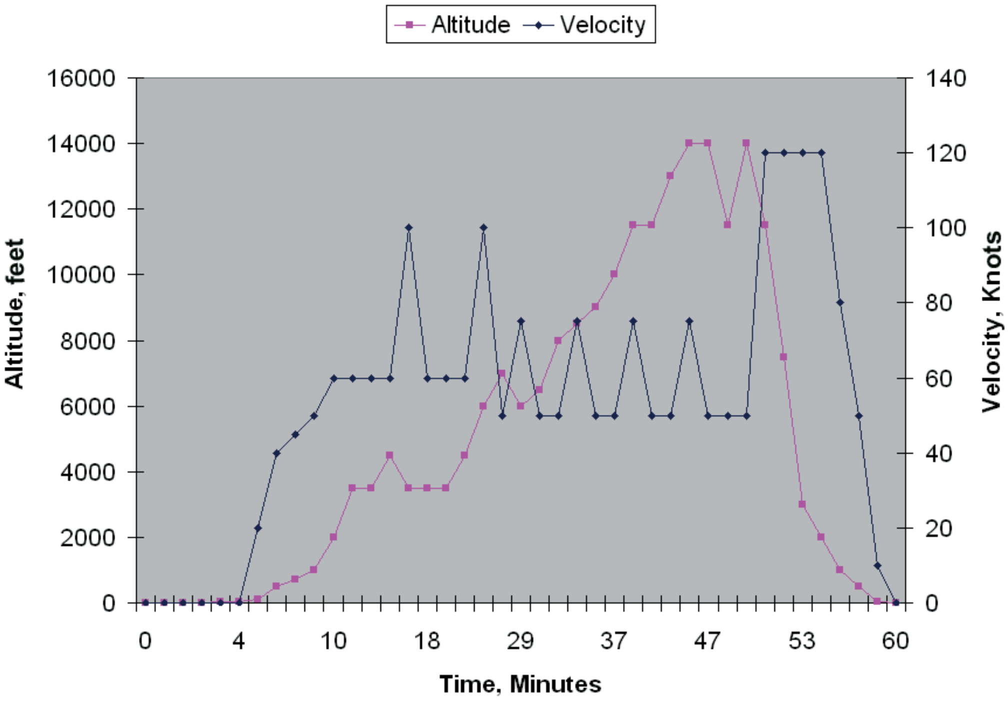
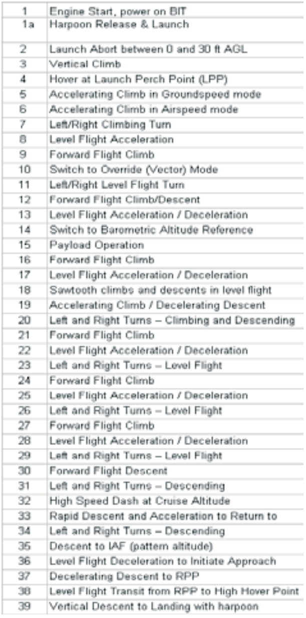


Figure 15. Mission profile of FCF, Reference 14



1	Engine Start, power on BIT
1a	Harpoon Release & Launch
2	Launch Abort between 0 and 30 ft AGL
3	Vertical Climb
4	Hover at Launch Perch Point (LPP)
5	Accelerating Climb in Groundspeed mode
6	Accelerating Climb in Airspeed mode
7	Left/Right Climbing Turn
8	Level Flight Acceleration
9	Forward Flight Climb
10	Switch to Override (Vector) Mode
11	Left/Right Level Flight Turn
12	Forward Flight Climb/Descent
13	Level Flight Acceleration / Deceleration
14	Switch to Barometric Altitude Reference
15	Payload Operation
16	Forward Flight Climb
17	Level Flight Acceleration / Deceleration
18	Sawtooth climbs and descents in level flight
19	Accelerating Climb / Decelerating Descent
20	Left and Right Turns – Climbing and Descending
21	Forward Flight Climb
22	Level Flight Acceleration / Deceleration
23	Left and Right Turns – Level Flight
24	Forward Flight Climb
25	Level Flight Acceleration / Deceleration
26	Left and Right Turns – Level Flight
27	Forward Flight Climb
28	Level Flight Acceleration / Deceleration
29	Left and Right Turns – Level Flight
30	Forward Flight Descent
31	Left and Right Turns – Descending
32	High Speed Dash at Cruise Altitude
33	Rapid Descent and Acceleration to Return to
34	Left and Right Turns – Descending
35	Descent to IAF (pattern altitude)
36	Level Flight Deceleration to Initiate Approach
37	Decelerating Descent to RPP
38	Level Flight Transit from RPP to High Hover Point
39	Vertical Descent to Landing with harpoon

Table 2. FCF maneuvers, Reference 15

3.7. Nz, Altitude, Velocity, and Power Prorating

From the CONOPS assumed mission profiles, the time spent at each altitude and velocity was analyzed to obtain the altitude and velocity utilization distribution indicated in **Figure 16**. The distribution helped to assign the time spent at each velocity in the usage spectrum. The altitude distribution was used to assign the time at various rate of climb and descent.

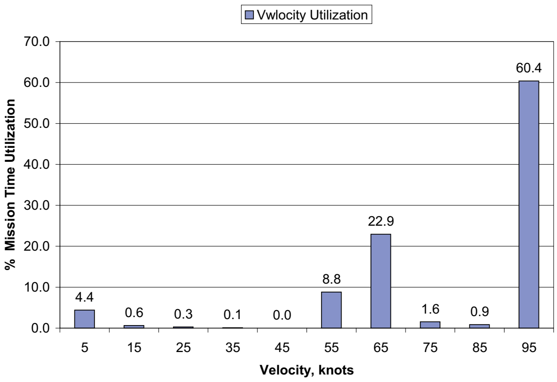


Figure 16. Velocity utilization

3.8. VTUAV Proposed Usage Spectrum

The proposed Navy VTUAV spectrum in a summarized form is displayed in **Figure 17a** and occurrences in **Figure 17b.**

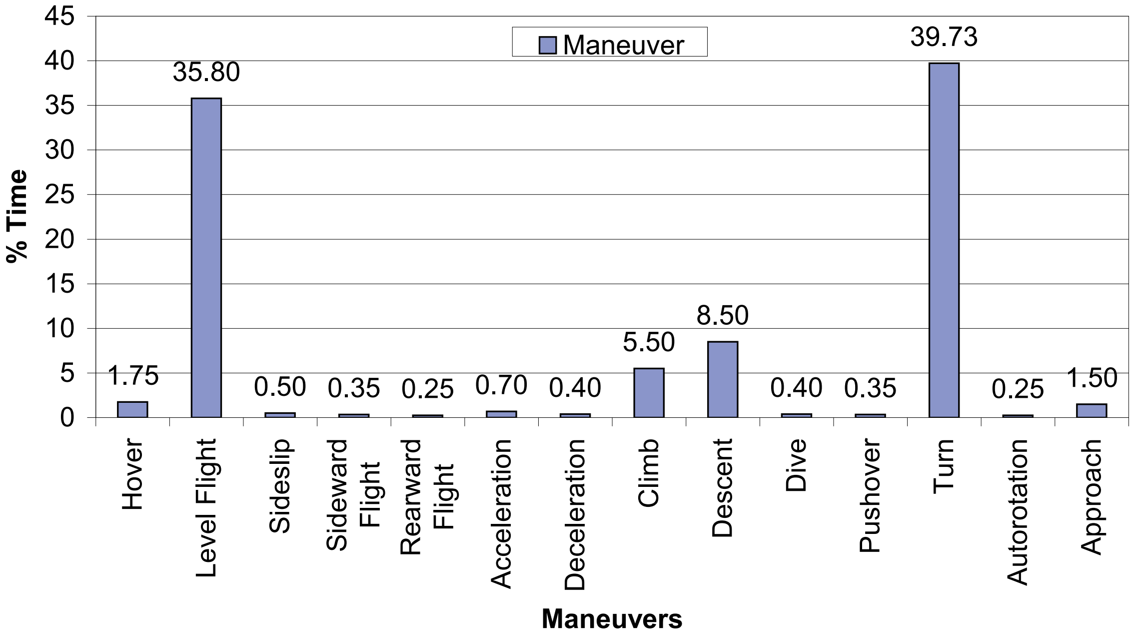


Figure 17a. Usage Spectrum percent time

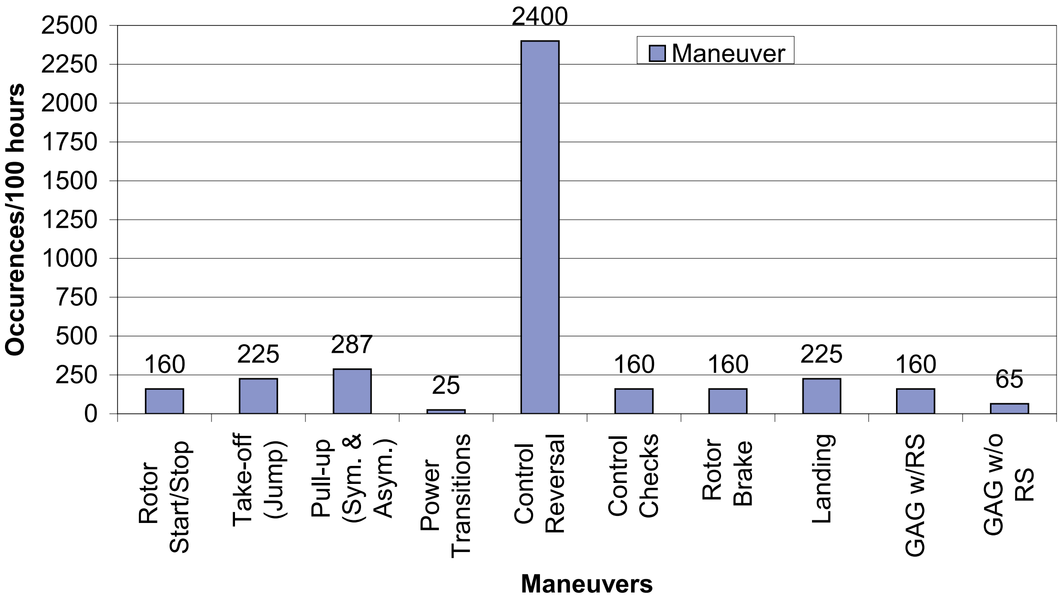


Figure 17b. Usage Spectrum percent occurrences

3.9. Comparison with Navy Rotary Wing Aircraft Spectrum

The recorded turn utilization of Navy helicopters is significantly higher than the original design, **Figure 18**. In addition, most of turn utilization is in a low AOB. The VTUAV-derived turn utilization is significantly higher than the present usage content in other Navy helicopters due to VTUAV mission requirements of continuous orbiting (turning) at a designated altitude. The pull-up occurrences are lower than the present Navy helicopters as all maneuvers are programmed in autopilot, **Figure 19**.

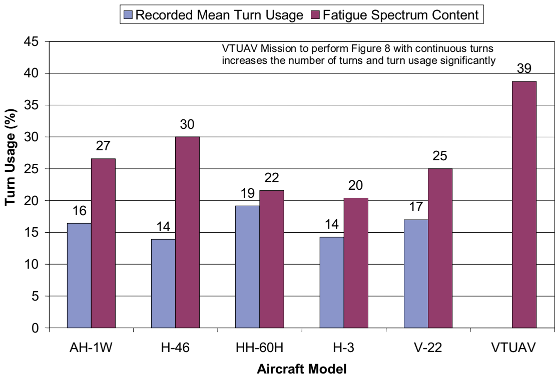


Figure 18. Turn usage

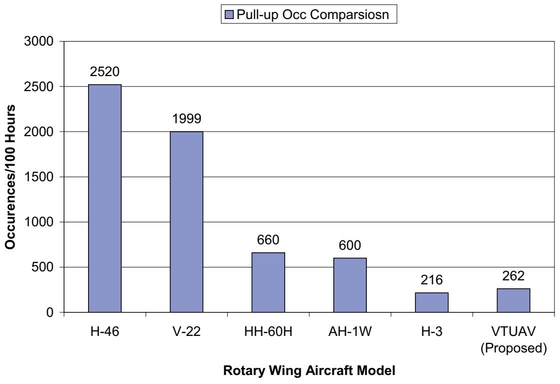


Figure 19. Pull-up

4. Conclusions

1. All mission requirements are properly translated into a conservative usage spectrum that is used to certify dynamic component structural integrity and fatigue life.
2. The usage spectrum development considers all maneuvers that are likely to be flown by the autopilot and remote operator.
3. The usage spectrum development considers VTUAV takeoff and landing profiles from ship and shore.

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