Maneuver Recognition Verification & Validation Using Visualization

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Abstract

In this paper, maneuver recognition verification and validation is discussed and described using flight load surveys, dedicated flights, and the visualization technique. Recorded flight parameters are used to create visualizations with commercially available flight simulation code. Each maneuver is validated by three complementary approaches to provide evidence to certifying authorities (NAVAIR, U.S. Army Aviation, FAA and EASA) that the developed Regime Recognition (RR) algorithm recognizes each maneuver appropriately. Thus, RR can be used to monitor individual rotorcraft usage, develop fleet aircraft usage spectrums, and compute serialized component fatigue life for Condition Based Maintenance (CBM).

Keywords: maneuver, regime recognition, visualization, verification, validation, recognition, usage

Introduction

Pilots fly rotorcraft using collective, cyclic and rudder pedal flight controls. During a flight, they perform various maneuvers such as rotor start, take-off, hover, climb, level-flight, turn, pull-up, descent, control-reversals, and landing. Typically, there are 300-350 unique maneuvers at various velocities, climb/descent rates, bank angle, torque levels, headings, sideslip angle, and vertical accelerations. The maneuver recognition algorithm is normally based on 20-30 flight parameter variations. The unique time variations of these parameters within a finite duration define a regime, Refs. 1-2. A skilled aeromechanics engineer is able to identify these maneuvers by studying the graphical presentation of time histories. The US Navy's standard approach used for the last 20 years is to conduct dedicated (scripted) flight tests in which a group of pilots perform a set of maneuvers following the same flight card sequence, Ref. 1. The maneuvers recognized by the RR algorithm are matched to the flight card maneuvers sequentially for verification and validation. However, if RR recognized maneuvers differ from the flight card listed maneuvers, and contain additional and transient maneuvers, it becomes difficult to assure the certifying authority of the high reliability of RR verification using only dedicated flights.

The current rule based RR verification using dedicated flights is labor intensive, costly, and still heavily relied on engineering judgment. The US Navy is evaluating the technical feasibility of utilizing visualization technique based on 3-D flight simulation as an effective way to enhance RR validation and reduce uncertainty associated with rule-based system. The visualization of flight time history at various speeds and angles will facilitate thorough examination of transient responses and additional maneuvers. By comparing the data side-by-side, the visualization tools will help improving the accuracy of the embedded logics in RR algorithm. With advances of microprocessor technology, the current onboard Health and Usage Monitoring System (HUMS) records flight parameters data for post processing on the ground. Reference 3 describes the use of HUMS data for Military Flight Operations Quality Assurance (MFOQA) for flight visualization and pilot debriefing. The complete visualization of rotorcraft maneuvers and the flight parameter magnitudes along with the output from rule based RR is presented herein to demonstrate its capability to enhance the RR algorithm verification and validation.

Regime Recognition Verification and Validation

A general approach for software Verification and Validation (V&V) process is described in Reference 4. Various RR developments for different aircraft platforms are outlined to some extent in Refs 5-11. However, most existing RR programs are proprietary and thus the specific details and processes are usually not known. The US Navy primary utilizes the data gathered from a combination of flight loads survey and dedicated (scripted) flight tests for RR development and V&V. The authors in Ref. 2 have presented a detailed maneuver-by-maneuver identification approach. Maneuver state flow charts are also created to show how changes to parameters result in a progression from one regime to another as the rotorcraft is in motion. The parameter variation ranges and parameter thresholds are specified to initiate and conclude each maneuver. These flight parameters and control-stick positions are utilized to develop RR algorithm logics and rule set to identify the programmed maneuvers. Matching with the scripted maneuvers could then validate the algorithm. The RR development and V&V processes are now discussed further in the following sections.

Rotorcraft flight load survey

Flight Load Survey (FLS) is conducted to record flight parameters and flight loads for life limited dynamic components, control systems, landing gear components, and airframe structures. Loads data are used to compute component damage rates per hour for maneuvers within the usage spectrum. Thus, for a fleet aircraft, it is necessary to recognize and match the proper loads with the original maneuvers of FLS flights using RR algorithm.

A production representative aircraft is instrumented with slip rings, acceleration and strain gages to measure rotating components loads for FLS. Note that when the fleet

configuration changes significantly over time due to additional payloads, installation of equipment or armaments, FLS will need to be repeated. Since the high sampling frequency loads data ranging from 25Hz to 4 MHz would require a large amount of storage, the FLS maneuvers data are record as discrete events of 60 to 300 seconds duration within each flight. This constraint introduces difficulty in recognizing maneuvers for RR algorithm that is based on the lead or lag of one parameter threshold magnitude with respect to other parameter magnitude. There also may be limitation for the maximum parameter value during FLS that may not exist in the service aircraft. In such a situation, the maximum allowable values of the parameters should be adjusted and incorporated into the RR algorithm. The maneuvers not flown during the flight load survey need to be validated with other techniques.

Dedicated (scripted) flight tests

Dedicated (scripted) flights are conducted using rotorcraft installed with telemetry system but without instrumentation to measure rotating component loads. These aircraft also have Health & Usage Monitoring System (HUMS) on-aboard. The system is checked for Electromagnetic Interference (EMI) and its influence on the parameter measurements. The velocity and vertical acceleration transducers are more accurate in the telemetry package as compared to HUMS. Furthermore, the sampling rate and filter characteristics are superior in the telemetry system as compared to the HUMS recording. FLS, HUMS and telemetry systems record similar basic flight parameters (including velocity, altitude, attitudes, attitude rates, accelerations, and control positions). As a result, it is possible to cross-reference the earlier measured loads with these parameters. HUMS recorded flight parameter time histories are verified using the telemetry measurements. The significant differences in parameter values shall be resolved as the difference in parameter magnitudes influences the regime recognition.

To conduct dedicated flights, maneuver sequence cards for the pilots to follow are constructed. There are typically four main types of cards. The first card type repeats the same maneuver at least three times. The second card type conducts each maneuver after a period of level flight. The third type of card consists of the maneuvers of a flight profile in the order of rotor start, taxi, take-off, climb, level flight maneuvers, descent, landing approach, landing, and rotor stop. The fourth card type consists of mixed maneuvers. Turn and sideslip maneuvers have a specified target angle of bank (AOB) and sideslip angle, respectively. Level flights have a specified maximum velocity. Take-off and landing are generally specified as vertical or running/rolling. Take-off power levels are occasionally indicated as Maximum Continuous Power (MCP) or Take–Off Power (TOP) level. To account for the difference in pilot techniques, a group of 15 to 20 pilots is usually needed to fly at least 15 to 20 dedicated flights for RR V&V. With sample size greater than 17, the 90% confidence interval on mean decreases significantly, Ref. 13. However, due to lack of aircraft/pilot availability and limited resources, the US Navy was only able to utilize eleven pilots flying ten dedicated flights for H-60 and ten pilots for eleven dedicated flights for H-53.

Each pilot is provided with the maneuver sequence flight cards and instructed to fly the maneuvers according to the specification with respect to the velocity, AOB, and Nz level on the card. Pilot is also instructed to use discrete indicator to signal and record the start and end of a maneuver. This information is required to match flight card with the RR output.

An illustration of the maneuver V&V process for FLS and dedicated flights are shown in Table 1. Each maneuver in the flight card is matched with the recognized regime in sequence. In addition, the maneuver recognition is verified using the parameter time histories. If the maneuver recognized in the regime output is other than the pilot reported, the parameter time histories are critically examined to declare it as a surrogate maneuver or unrecognized. The details about surrogate maneuvers can be found in Ref. 2.

Each flight card maneuver is assigned a status of recognized, surrogate recognition, or unrecognized. The reason for surrogate and unrecognized recognitions is provided and any parameter that does not meet the RR incorporated criteria is also identified. A complete database is created for all maneuvers flown during the FLS and dedicated flights. This database contains the status of each maneuver flown by various US Navy helicopters such as H-60, H-53, and V-22. The agreement between the rotary wing maneuvers flown and recognized by the RR program should be greater than 90% for each regime and greater than 95% overall. The regimes with less than 90% recognition with respect to flight card should be investigated to identify the discrepancy. Such discrepancies could be due to pilot technique, surrogate maneuver, or RR criteria. For example, sideslip recognition in Table 2 is 60% only. The close examination of sideslip angle during the regime revealed it's less than 5 degrees. Using visualization of the maneuver, it clearly reveals that the rotorcraft performs a level flight with negligible sideslip angle thus RR recognition is appropriate. Once the RR software has been validated & verified, it's used to analyze and develop U.S. Navy fleet usage spectrum, component fatigue life, and reliability as discussed in Refs. 12-16.

Table 1: Maneuver Verification and Validation Process

Flt #	Maneuver Id	Time	Duration	Maneuver RR name	Maneuver on flt.card name
1	1	358.15		Rotor start	1. Rotor Engagement
1	6	694.15	5	Turn Taxi Right	
1	5	778.15	29	Taxi	
1	2	778.15		Normal Takeoff	5. Normal takeoff
1	14	853.15	14	Climb Hover	
1	28	998.15	50	Level Flight @0.6vh	
1	240	1048.15	118	Full Power climb twin engine	6/7/8/ Twin engine climb
1	27	1230.15	5	Level Flight @0.4vh	
1	233	1235.15	8	Part Pow er Descent	
1	27	1243.15	77	Level Flight @0.4vh	9/10 Level flight
1	230	1320.15	3	Normal Descent @0.4vh	
1	27	1323.15	16	Level Flight @0.4vh	
1	37	1339.15	35	Right sideslip @0.4vh	11. Right sideslip
1	228	1655.15	2	Climbing Turn Right @0.7vh	
1	79	1657.15	14	Angle Bank 10-25 right turn @0.7vh	
1	276	1669.15		Later RVSL @V>0.3vh	16. Lateral doublet
1	28	1671.15	2	Level Flight @0.6vh	
1	274	1672.15		Collect Ctrl RVSL @V >0.3vh	22. Collective doublet
1	231	1673.15	1	Normal Descent @0.7vh	
1	27	2422.15	15	Level Flight @0.4vh	
1	27	2515.15	8	Level Flight @0.4vh	
1	69	2523.15	5	Angle Bank < 25-35 left turn @0.4vh	27 Left Turn
1	27	2567.15	7	Level Flight @0.4vh	
1	237	2574.15	1	Normal Ascent @0.4vh	
1	72	2590.15	27	Angle Bank 25-35 right turn @0.4vh	28. Right Turn
1	27	2617.15	7	Level Flight @0.4vh	
1	237	2765.15	1	Normal Ascent @0.4vh	
1	240	2766.15	13	Full Power climb twin engine	31. Normal acceleration
1	28	2779.15	1	Level Flight @0.6vh	
1	28	3222.15	1	Level Flight @0.6vh	
1	231	3223.15	3	Normal Descent @0.7vh	38. Normal deceleration
1	28	3226.15	2	Level Flight @0.6vh	
1	27	3542.15	5	Level Flight @0.4vh	
1	210	3550.15	1	Ascending Pushover @0.4vh	43. Symmetric pushover
1	288	3552.15	1	Maximum Rate Acceleration	
1	126	4787.15	2	Cyclic pull-up @0.7vh)	51. Symmetric pullout
1	29	4896.15	2	Level Flight @0.75vh	
1	142	4933.15	15	Asymmetric Pullup to left @0.7vh	57. Left rolling pullout
1	265	5413.15		Tw in Engine Pow er to Auto at 0.4vh	
1	251	5413.15	1	Auto Rotation Pushover @80 Knots	
1	242	5414.15	11	Stab Auto Flight @50 Knots	61a. Autorotation
1	274	5668.15		Collect Ctrl RVSL @V>0.3vh	
1	233	5669.15	3	Part Power Descent	62. Partial power descent
1	12	5828.15	3	Low Speed Descent	
1	216	5834.15	29	Dive @0.4vh	65. Power dive
1	27	5860.15	3	Level Flight @0.4vh	
1	12	7044.15	2	Low Speed Descent	71a Rough approach
1	293	7136.15		Normal Landing	71b. Normal landing
1	294	7485.15		Rotor Stop	75. Rotor shutdown

Table 2: H-60 Percent Recognized

No	Regime	Flown (a)	Recognized (b)	Reliability(c)
1	Rotor start	7	7	100%
2	Taxi & taxi Turns	7	7	100%
3	Vert. & Rolling Take-off	17	17	100%
4	Hover	44	44	100%
5	Hover Rt/LT Turns	16	16	100%
6	Climb	5	5	100%
7	Max Pow er Climb	12	12	100%
8	Sidew ard Lt/Rt	26	26	100%
9	Rearw ard	14	14	100%
10	Sideslip (Rt/Lt)	5	3	60%
11	Long./Lat/Yaw /Coll. Control Reversal	51	51	100%
12	Right Turns at various AOB and Speed	41	41	100%
13	Left Turns at various AOB and Speed	42	42	100%
14	Level flight at various speed	16	16	100%
15	Symmetric Pull-up	11	11	100%
16	Asymmetric (Lt/Rt)	29	28	97%
17	Pushover	14	14	100%
18	Acceleration (Norma/Max rate)	3	3	100%
19	Deceleration (Normal/Max rate)	16	13	81%
20	Normal/Partial Pow er Descent	16	15	94%
21	Dive	1	1	100%
22	Autorotation & Auto Turns	15	15	100%
23	Pow er Transitions	8	8	100%
24	Vertical/Rolling Landings	15	15	100%
25	Rotor Stop	7	7	100%
	Overall	438	431	98%
	(a) No. of Events Flow n by Pilot			
	(b) No. of Events Recognized in comparison w ith Pilot card			
	(c) % Recognized in Comparison w ith Pilot Card			

Rotorcraft simulation software and flight training simulator

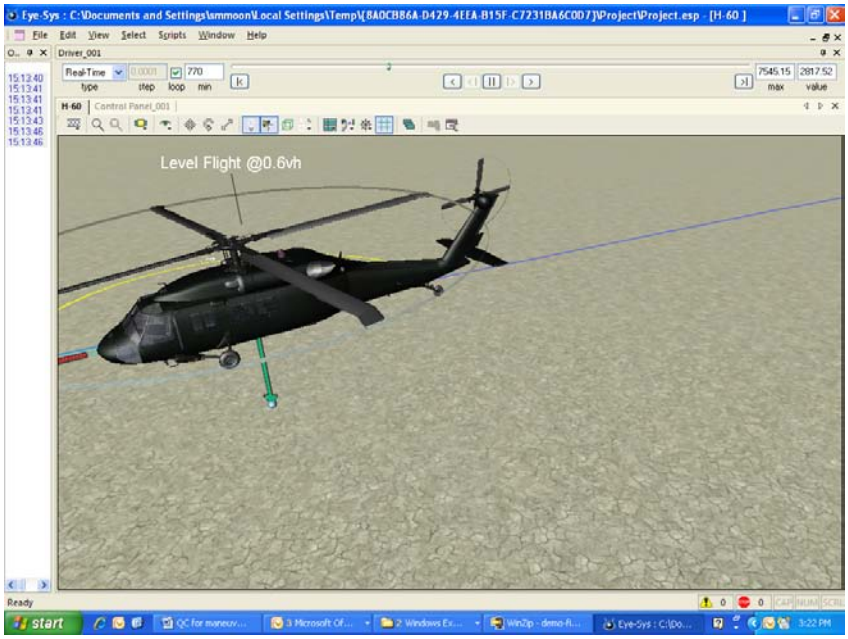
The mathematical helicopter flight simulation programs (GENHEL, COPTER, 2CGHAS, UMARC, UMARC/B FLIGHTLAB, COMRAD) developed by aircraft manufacturers and research organizations can be used to generate flight parameter time histories. The mathematical models incorporate all aerodynamic, dynamic, control, and inertia of helicopters. The flight control stick positions are input into the program to simulate each maneuver. The program output consists of aircraft attitudes, accelerations, and rates time histories. These parameter time histories are input to the RR algorithm and the output is compared with the simulated regimes.

Another potential approach is to utilize a flight training simulator level D/type 7. It is typically a 6-DOF system including pitch, roll, yaw, and three accelerations. The simulator is developed based on various mathematical models that incorporate the stability derivatives derived from the flight test data of specific aircraft. The 6-DOF motion simulator is validated using the flight data for each maneuver control input. FAA, EASA, and Military Agencies certify the simulators. The recertification of pilot training simulator hardware and software is required every two years to maintain currency and address any flight training changes. Since the flight time history for each maneuver can be simulated consistently with the recorded flight control system inputs (collective, cyclic, and pedal positions, pitch, roll, yaw, and accelerations), the flight simulator could be used to provide an independent means to V&V the RR algorithm. It is also a more cost effective way to study the effects of various pilot techniques or newly introduced maneuvers/tactics. However, the level D flight simulators are costly to develop and maintain, thus inexpensive and simple 3-D visualization tools are needed to understand the rotorcraft motion and to enhance RR V&V.

Maneuver Visualization

Computer-based visualization is a powerful tool used to understand large sets of time-dependent flight-test data. An animation is generated in which the dataset can be “played back” and observed. An operator can view the animation at various play back speeds and angles to gain insight into particular quantities of interest. Annotations or dynamically changing graphics may be added to the animation to improve the understanding of data quantities that cannot be observed easily or directly.

In this work, we used the Eye-Sys graphics toolset (Interactive Data Visualization Inc., Lexington, SC) to visualize flight test data. This software is well suited for engineering applications, which require 3-D visualization. Tools for plotting and manipulating raw input data as well as generating animations are included. The play back interface allows the user to conveniently scroll through data and play back sections of interest, Visualization 1.



Visualization 1: H-60 3-D visual model of the Eye-Sys graphic interface

HUMS Flight Parameter Data

The flight test dataset was in the form of a file containing more than 2 hours of continuously collected data, representing 26 different quantities. The specific data quantities used to drive the visualization included: Pitch, Roll, Heading, Radar Altitude, Airspeed and Nz. Ideally, longitude and latitude would have been available; however, these quantities had not been collected during the flight test. Instead, we estimated the latitude and longitude quantities and added these to the dataset. The estimates were formed by time integrating the airspeed to estimate the incremental distance traveled during each time interval. These distances were then applied in the direction given by the heading quantity.

A second file contained the results of a flight maneuver/regime recognition algorithm that had been run on the HUMS recorded data. These results consisted of the names of the recognized regimes along with the timestamps of the beginning and end of each maneuver/regime. This file comprised a second input dataset for the visualization.

Visualization

Using Eye-Sys, a basic virtual world was established containing a simple ground plane, sky, and light source. A solid model of an H-60 Helicopter was inserted into the world model. The flight test data file was linked to the model, thereby enabling its data to drive the 3-D animation. The flight test timestamp quantity was identified as the time base for the animation. Pitch, Roll, and Heading quantities were configured as Euler angles that controlled the attitude of the H-60 model during the animation. Similarly, the radar altitude, along with the estimated latitude and longitude were configured to control the 3-D position of the H-60. This basic configuration allowed the animated H-60 model to

mimic the rigid body motions of the actual aircraft. An operator can quickly gain insight into the basic flight dynamics by playing back the animation.

Augmented Data Display

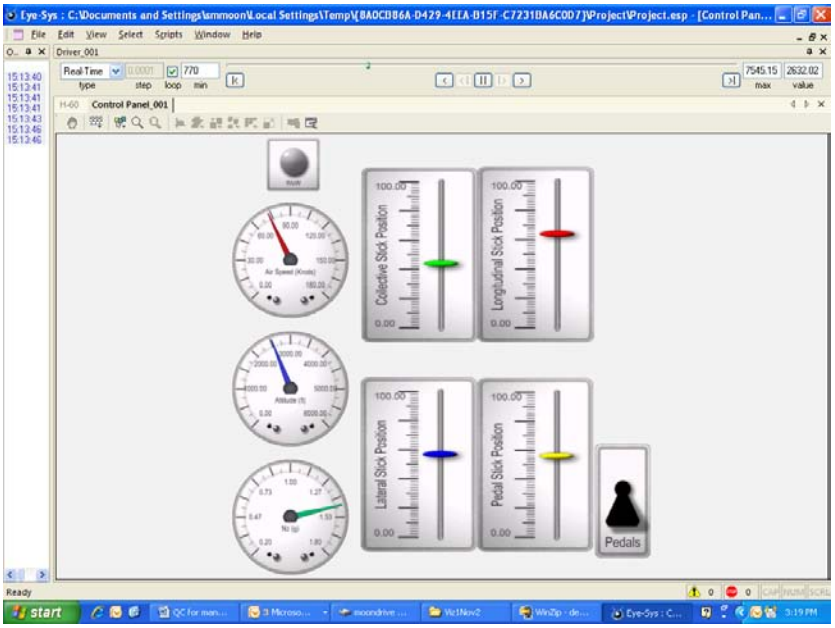
Some of the flight data quantities cannot be readily visualized by simply observing the solid body motions of the aircraft. Examples include airspeed and Nz. To augment the visualization, two arrows representing these vector quantities were added to the animation, Visualization 1. The airspeed arrow emanated from the front of the aircraft pointing in the forward direction. The Nz arrow emanated from the bottom of the aircraft pointing in the downward direction (relative to the airframe). The lengths of these arrows were dynamically adjusted a way that its length was proportional to the respective data quantity at all times. An observer can readily comprehend changes in airspeed and Nz by observing the changes in length of these arrows.

The entire 3-D path of the aircraft (i.e., latitude, longitude and radar altitude) was presented as a multisegmented line element in the animation. The H-60 model therefore moves along this line from beginning to end as the animation progresses. Presenting the entire segmented line allows the observer to better comprehend the aggressiveness of turns, climbs, or dives.

Although the attitude and heading of the H-60 model mimics that of the actual aircraft, it is sometimes helpful to present a quantitative means of visualizing these quantities in the animation. To this end, we implemented a dynamically adjustable graphic that depicts the attitude as Euler angle arcs with numeric angle values, Visualization 1. This aids the observer in perceiving small changes in attitude, and in correctly identifying the absolute values of the Euler angles.

Cockpit Control Panel

The cockpit instrument panel in Visualization 2 consists of an altimeter, speedometer, vertical acceleration indicator, collective, longitudinal, lateral, rudder control stick positions. The flight test data file is linked to instrument needles and control stick positions to drive the cockpit animation as shown in Visualization 2. The instruments, control stick positions, and solid rotorcraft animation are synchronized. The control stick position graduated scale varies from 0 to 100% displaying the values of control position in percentage during the various maneuvers of the solid rotorcraft visualization model.



Visualization 2: Cockpit display

Flight Maneuver/Regime

The flight maneuver/regime data file was linked to the animation. Eye-Sys was configured to identify which maneuver/regime corresponds to any instance in the animation. This was done by correlating the animation time base with the timestamps within the maneuver/regime data file. The name of the maneuver/regime was then presented in the animation as a line of text displayed above the aircraft. The observer can then simultaneously observe the motion of the aircraft and the identified flight maneuver/regime, Visualization 1.

V&V of Maneuvers in the Usage Spectrum Using Visualization

1. Rotor Start and Stop

Rotor start and stop is easiest maneuver to visualize. The helicopter is stationary with the engine on and the rotor brake released, the clutch engages the transmission system consisting of shaft and main gearbox. The rotor shaft initiates main rotor rotations as shown in Visualization 1 with the RR program recognition label.



Visualization 3: Rotor start

2. Taxi and Taxi Turns

Taxi is visualized as the rotorcraft wheels move on runway/surface with velocity greater than 20 knots. The change in heading while taxing confirms taxi turns.

3. Take-off

Take-off is visualized by showing the weight-off-wheels from the ground with the rotor rotating along with identification coming from the RR simultaneously, Visualization 4. The timestamps for the visualization action and the RR simultaneously confirm algorithm recognition. In a simulator or rotorcraft cockpit, the pilot initiates the take-off with an increase in the collective and longitudinal stick positions as shown in Fig. 2. This leads to an increase of torque, radar altitude, climb rate, and pitch attitude as indicated in Fig. 3. The changes in altitude and positive pitch attitude along with control positions can be observed during visualization. This validates the take-off recognition. The swat switch on the cross bar and the increase in percentage of torque are positive indication of take-off for a helicopter equipped with skid gear. The simulators validate the maneuver by comparing the aircrafts six degrees of freedom response for same control stick position variation.

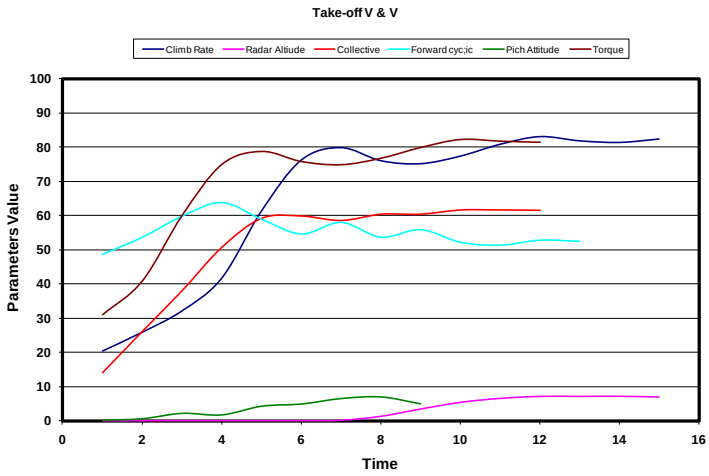
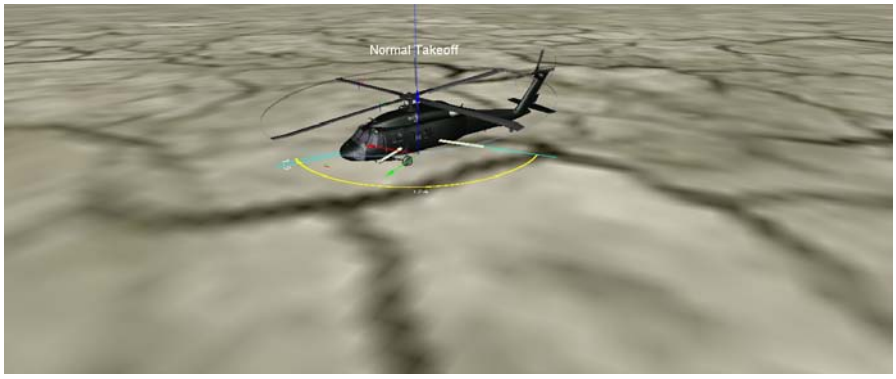


Figure 1: Stick positions and flight parameters during take-off



Visualization 4: Take off

4. Hover

The maneuver in Visualization 5 shows a rotorcraft leaving the ground with altitude increasing. The rotorcraft reaches an altitude and is steady with the rotor rotating and output from regime recognition indicating it is in steady hover. The collective stick position is almost constant, providing the torque required to hover at the given gross weight and altitude. The rudder pedal position is constant indicating the heading in the direction shown in Visualization 5 and Fig. 2. The recognized hover satisfies ADS-33C flying quality and simulation requirements specified in Refs. 17-21. The minimum duration of ADS-33C simulation is 30 seconds. The recognized hover duration is 38 seconds. The hovering altitude tolerances of ADS-33 simulation are +/- 3 feet for desired maneuvering and +/- 5 feet for adequate maneuvering are satisfied. The forward velocity is almost zero indicating on the spot hovering. The longitudinal stick position is nearly constant revealing a rotor disc/plane perpendicular to rotor shaft. The hovering altitude varied from 6 to 10 feet. It also correlated the flight card maneuver flown as shown in Table 1. Thus, recognition is verified and validated using three approaches: visualization, simulation, and flight card.

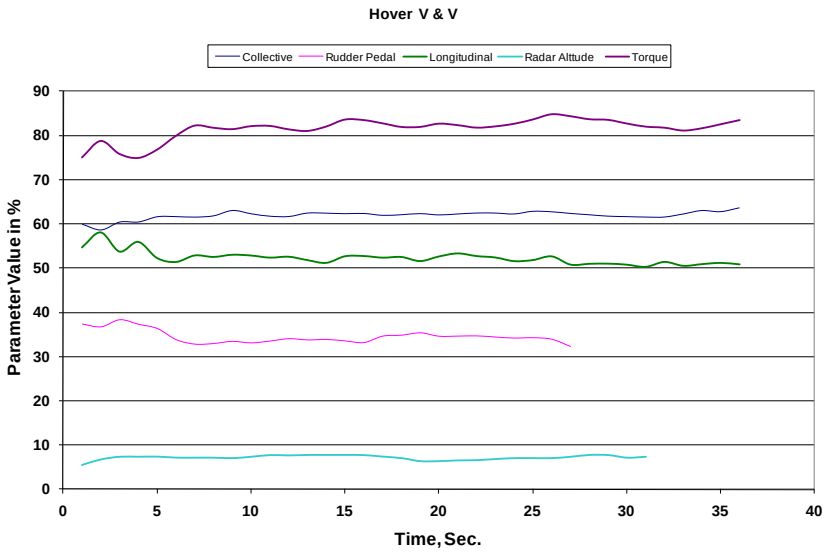
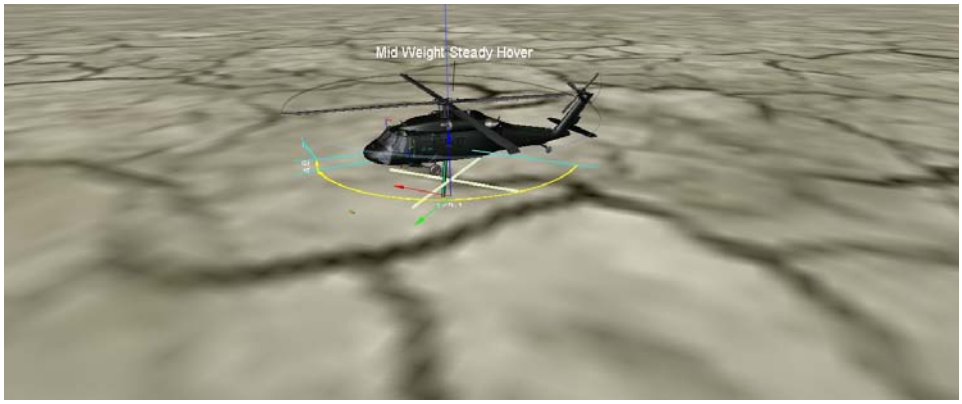


Figure 2: Stick positions and flight parameter variation during take-off



Visualization 5: Hover

5. Hover Turn

A hover turn is initiated with an increase in rudder pedal position during simulation as well as the rotorcraft flight. Once the yaw rate is initiated, pedal position is held constant as shown is Fig. 3. Visualization 6 and Fig. 4 show the rotorcraft heading changing as hover turn progresses at fixed altitude, which is sustained with invariable collective, stick position, and torque, Fig. 3. The longitudinal stick position is maintained at initial value in absence of cross wind. Hover turns also satisfied flying quality compliance of > +/-6 six degree change in heading. Hover turn of six second duration also satisfies ADS-33 compliance of less than 15 second.

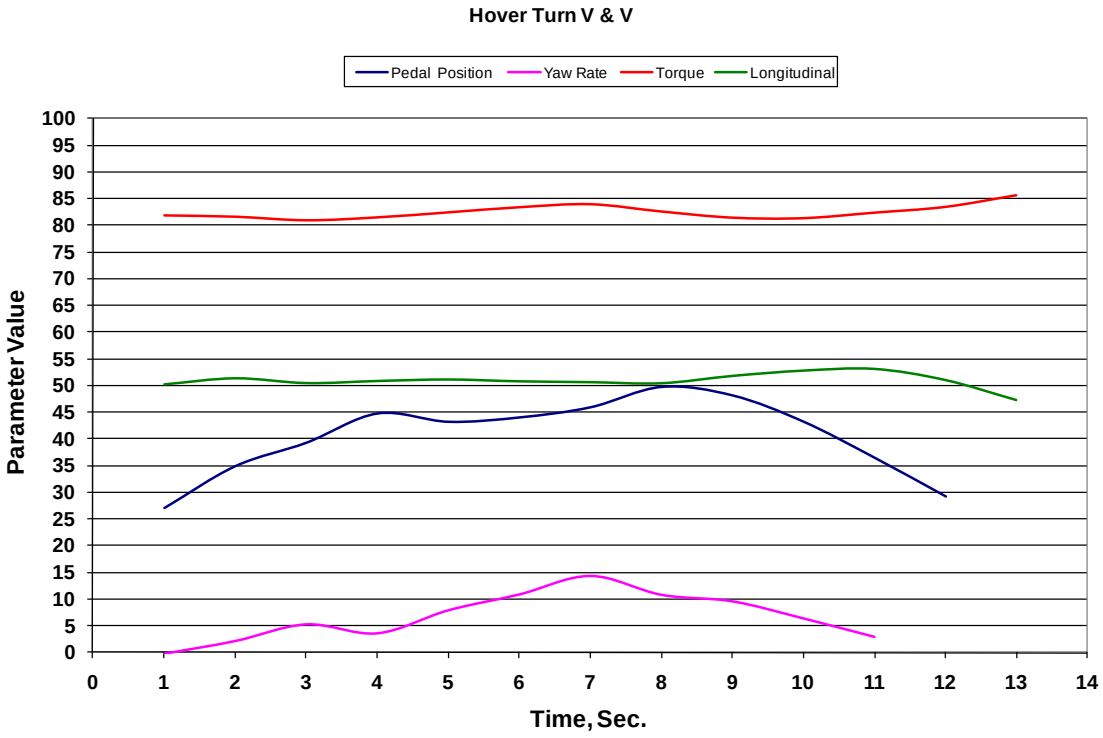
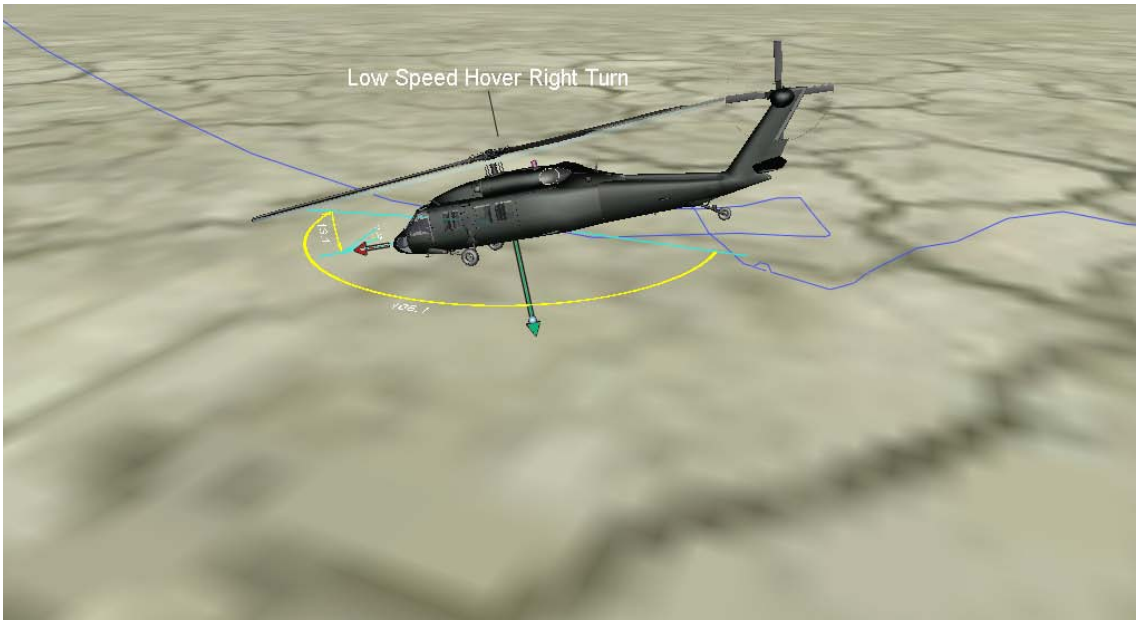


Figure 3: Control Stick positions during hover turn



Visualization 6: Hover turn

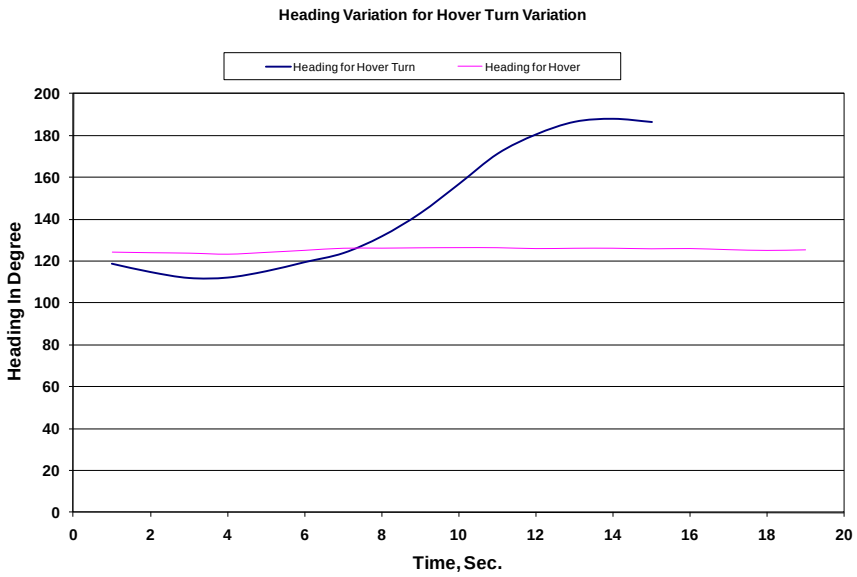
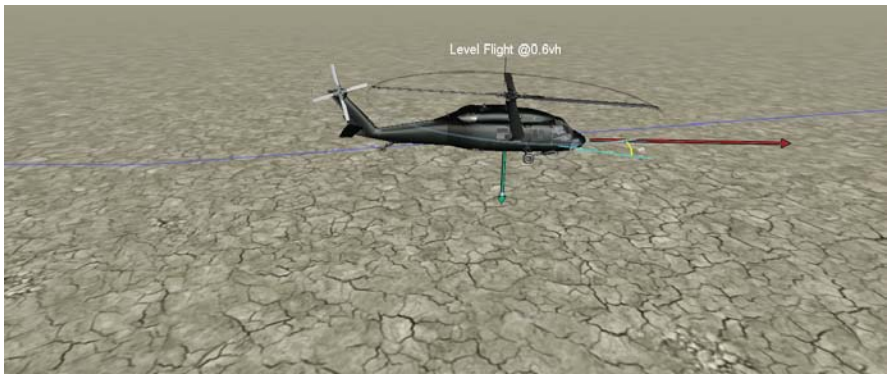


Figure 4: Heading and torque variation during hover turn

6. Forward Level Flight

The forward level motion of Visualization 7 shows a helicopter moving with various speeds having pitch down, small roll and yaw attitudes as expected by rotorcraft trim equations. In addition, an almost constant altitude with no vertical up or down motion of rotorcraft indicates the nature of forward flight. The RR program reorganizes this behavior as level flight. An additional 15 level flight events were conducted in dedicated flights with various velocities as shown in Table 3 and the RR output matches flight card sequence of level flight at various velocities. This verifies and validates the RR recognition of level flight.



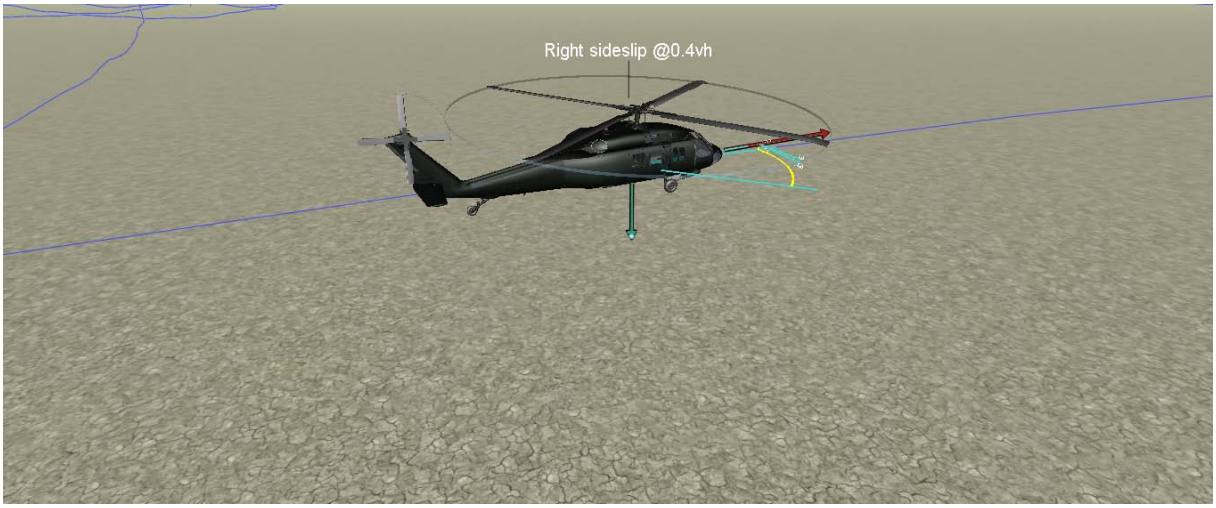
Visualization 7: Forward level flight

Table 3: Multiple level flight events in a flight at various velocities

RR id	Time	Duration	Regime	Event	Pilot Recorded Maneuver
27	1879.3	13	Level Flight @0.4vh	9	Level Flight, 45 knots
230	1892.28	9	Normal Descent @0.4vh		
27	1901.28	11	Level Flight @0.4vh		
27	2051.3	10	Level Flight @0.4vh	10	Level Flight, 60 knots
28	2061.28	3	Level Flight @0.6vh		
231	2120.28	10	Normal Descent @0.7vh		
28	2130.3	12	Level Flight @0.6vh	11	Level Flight, 75 knots
27	2142.28	10	Level Flight @0.4vh		
28	2152.3	22	Level Flight @0.6vh	12	Level Flight, 90 knots
231	2174.28	32	Normal Descent @0.7vh		
28	2206.28	1	Level Flight @0.6vh		
28	2422.28	8	Level Flight @0.6vh		
29	2430.3	8	Level Flight @0.75vh	14	Level Flight, 105 knots
231	2438.28	6	Normal Descent @0.7vh		
30	2494.28	29	Level Flight @0.85vh		
232	2523.28	4	Normal Descent @0.9vh		
30	2527.3	31	Level Flight @0.85vh	15	Level Flight, 120 knots
232	2558.28	10	Normal Descent @0.9vh		
30	2568.28	30	Level Flight @0.85vh		
30	2736.28	9	Level Flight @0.85vh		
31	2745.3	42	Level Flight @0.95vh	17	Level Flight, 135 knots
30	2787.28	4	Level Flight @0.85vh		
31	2791.28	45	Level Flight @0.95vh		
31	2969.28	8	Level Flight @0.95vh		
32	2977.3	14	Level Flight @1.05vh	18	Level Flight, 150 knots
31	2991.28	9	Level Flight @0.95vh		

7/8/9. Sideslip, Sideward and Rearward Flight

The RR program indicates sideslip recognition stamp on Visualization 8, however the visualization is difficult as it is perpendicular to y-direction in two dimensional XZ plane of the screen. The sideslip occurs during high-speed level flight where as a sideward maneuver is conducted from hover in low speed. The rearward visualization shows the helicopter nose pointing forward where as helicopter motion is backward with small speed.



Visualization 8: Sideward Sideslip

10. Acceleration

Acceleration is visualized as an increase in velocity within a small duration. The RR label appears at the same time on the Visualization 9. The maximum acceleration occurs at lower speed compared to higher speed as expected according to aeromechanics principle, as shown in Figure 5.



Visualization 9: Acceleration

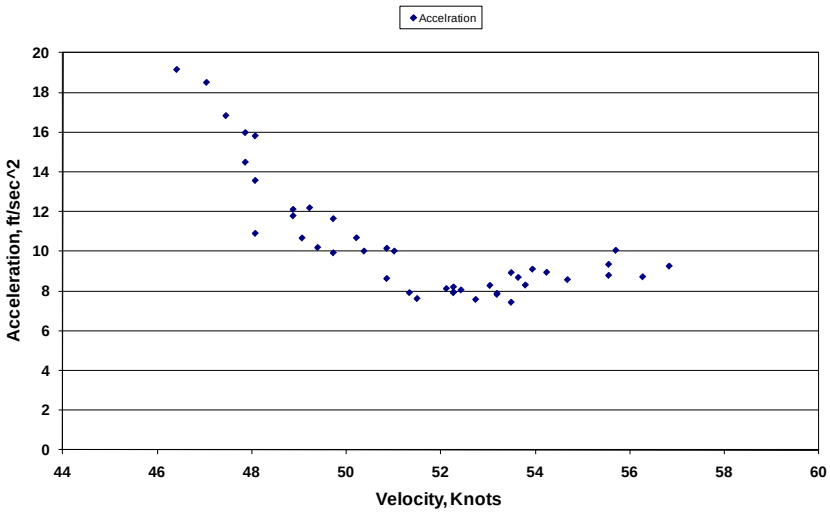


Figure 5: Acceleration as a function of velocity

11. Max Power Climb

The developed regime recognition identified the full power climb that matches the flight card sequence maneuver, Table 1. For further validation, the incremental power required to climb was calculated using the aeromechanics principle and compared with recorded incremental power variation with climb rate, Figure 6. The excellent correlation between predicted incremental power, flight data, and recognition of full power during the same time period makes the RR recognition reliable. To insure consistent recognition, the RR was tested with flight test data where fifteen full power climb events were conducted in a flight. The RR exactly recognized the full climb in the output in the sequence as flown in the flight as shown in Table 4. Further validation and verification is provided by the maneuver in Visualization 10 that clearly shows the rotorcraft rapidly climbing with an increasing rate of climb.

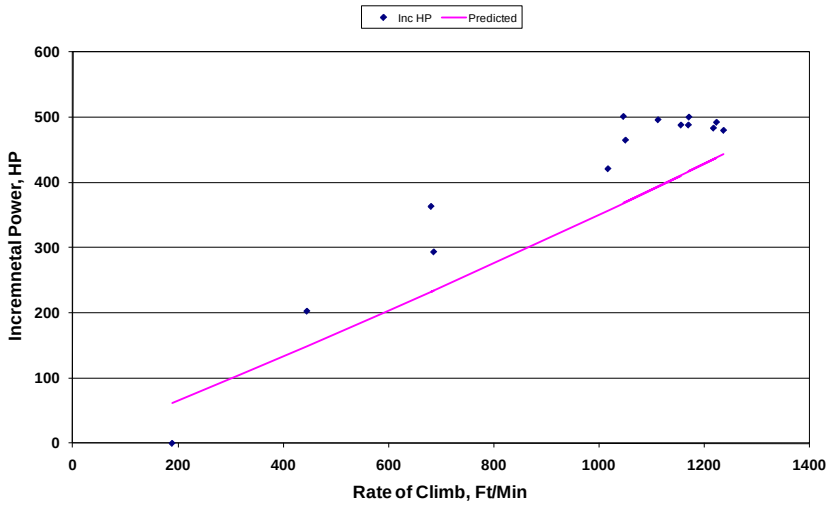


Figure 6: Incremental power variation during full power climb

Table 4: Multiple full power climb events in a flight

RR id	Time	Duration	Regime	Event	Maneuver
28	686	23	Level Flight @0.6vh		
27	709	23	Level Flight @0.4vh		
240	732	43	Full Power climb twin engine	1	Climb MCP
237	775	11	Normal Ascent @0.4vh		
27	831	13	Level Flight @0.4vh		
240	844	35	Full Power climb twin engine	2	Climb MCP
230	951	3	Normal Descent @0.4vh		
27	954	12	Level Flight @0.4vh		
240	966	36	Full Power climb twin engine	3	Climb MCP
237	1002	19	Normal Ascent @0.4vh		
28	1116	35	Level Flight @0.6vh		
27	1151	24	Level Flight @0.4vh		
240	1175	39	Full Power climb twin engine	4	Climb MCP
29	1284	5	Level Flight @0.75vh		
28	1289	21	Level Flight @0.6vh		
240	1310	29	Full Power climb twin engine	5	Climb MCP
238	1339	9	Normal Ascent @0.7vh		
231	1397	7	Normal Descent @0.7vh		
28	1404	8	Level Flight @0.6vh		
240	1412	42	Full Power climb twin engine	6	Climb MCP
29	1515	11	Level Flight @0.75vh		
240	1526	39	Full Power climb twin engine	7	Climb MCP
238	1565	11	Normal Ascent @0.7vh		
238	2598	11	Normal Ascent @0.7vh		
240	2609	45	Full Power climb twin engine	15	Climb MCP
30	2863	1	Level Flight @0.85vh		
240	2864	10	Full Power climb twin engine	16	Climb MCP
239	2874	1	Normal Ascent @.0.9vh		
30	2875	4	Level Flight @0.85vh		



Visualization 10: Maximum power climb

12. Symmetrical Pull-up

The recognized symmetric pull-up was analyzed to verify its authenticity. The longitudinal and collective stick position variation used to perform the symmetrical pull-up was plotted and compared with available variation of these parameters from the simulator and flight test data presented in Ref. 22. Also, the rotorcraft's vertical acceleration, pitch rate and roll rate response variation resemble the one provided in Ref. 22. Visualization 11 shows the descending rotorcraft being pulled up resulting in a

significant increase in vertical load factor vector length and digital value indicated on cockpit accelerometer dial with no associated roll attitude. Multiple pull-ups, shown in Table 5, were conducted by dedicated flight and recognized by RR in the same sequence. This verifies and validates RR of symmetrical pull-up.

Table 5: Multiple Pull-up events in a flight

RR id	Time	Duration	Regime	Event	Maneuver
238	2929	4	Normal Ascent @0.7vh		
232	2933	3	Normal Descent @0.9vh		
119	2936	3	Symmetric Pull-up @0.9vh	1	Symmetric Pull-up
232	2939	3	Normal Descent @0.9vh		
30	2994	2	Level Flight @0.85vh		
232	2996	13	Normal Descent @0.9vh		
119	3009	2	Symmetric Pull-up @0.9vh	2	Symmetric Pull-up
232	3011	8	Normal Descent @0.9vh		
30	3019	35	Level Flight @0.85vh		
30	3302	18	Level Flight @0.85vh		
29	3320	16	Level Flight @0.75vh		
118	3336	8	Symmetric Pullup @0.7vh	3	Rolling Pull-up
279	3344	2	Normal Deceleration		
238	3409	9	Normal Ascent @0.7vh		
30	3418	1	Level Flight @0.85vh		
119	3419	5	Symmetric Pullup @0.9vh	4	Rolling Pull-up



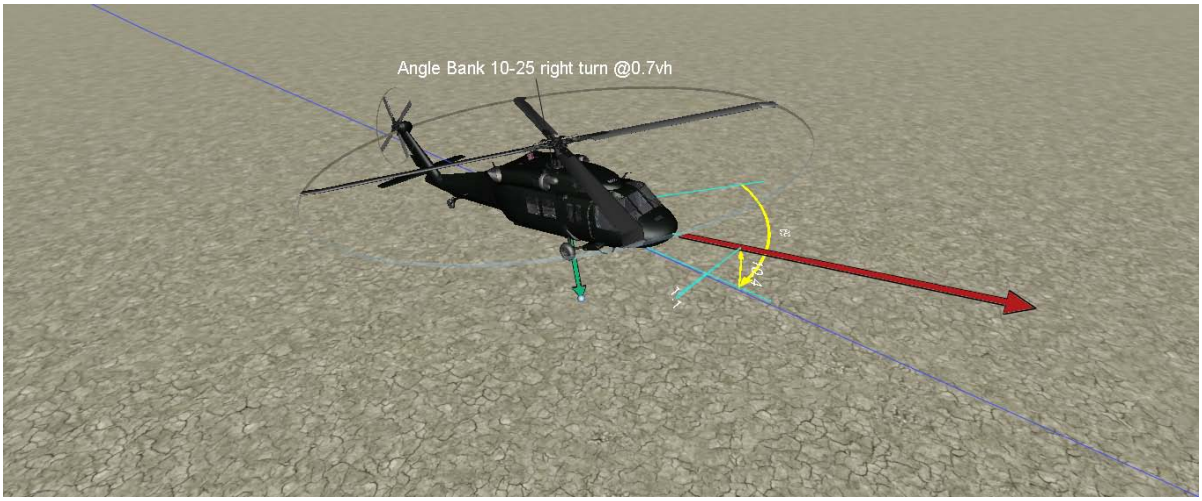
Visualization 11: Symmetric pull-up

13. Turns

The dedicated flight containing 33 right and left turn events at various bank angles and velocity were conducted and matched to RR output to validate the turn recognition as shown in Table 6. Also, Visualization 12 clearly shows a rotorcraft turning and the RR stamp displaying AOB turn at the same time leading to V&V of a Turn.

Table 6: Multiple turns in a flight

RR id	Time	Duration	Regime	Event	Maneuver
73	1603.24	30	Angle Bank 25-35 right turn, @0.7vh	1	Right Turn, 30 Deg.
29	1633.24	5	Level Flight @0.75vh		
28	2373.24	161	Level Flight @0.6vh		
76	2534.24	10	Angle Bank 10-25 left turn, @0.7vh	4	Left Turn, 30 Deg.
30	2562.24	159	Level Flight @0.85vh		
29	2721.24	15	Level Flight @0.75vh		
70	2869.24	20	Angle Bank 25-35 left turn @0.7vh	5	Left Turn, 45 Deg.
30	3034.24	28	Level Flight @0.85vh		
80	3062.24	23	Angle Bank 10-25 right turn @0.9vh	6	Right Turn, 20 Deg.
30	3094.24	2	Level Flight @0.85vh		
27	3161.24	20	Level Flight @0.4vh		
39	3181.24	17	Angle Bank < -50 left turn @0.4vh	9	Left Turn, 60 Deg
28	3201.25	6.99	Level Flight @0.6vh		
42	3229.24	18	Angle Bank > 50 right turn @0.4vh	10	Right Turn, 60 Deg.
73	4838.24	26	Angle Bank 25-35 right turn @0.7vh	33	Right Turn, 45 Deg



Visualization 12: Angle of bank turn

14. Deceleration

Deceleration is visualized as significant decrease in velocity within a short duration. The RR label appears at same time on the visualization. The maximum deceleration occurs at lower speed compared to higher speed as expected according to aeromechanics principle, as shown in Fig. 7.

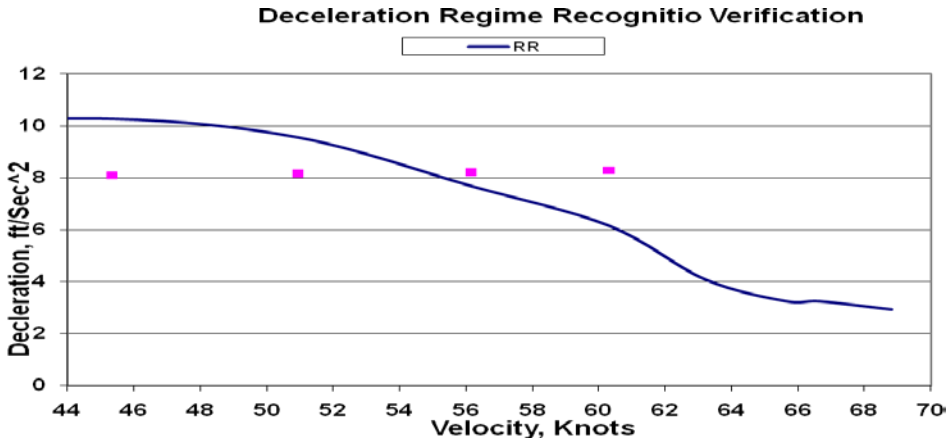


Figure 7: Deceleration

15. Partial Power Descent

The developed regime recognition identified the partial power descent that is confirmed by flight card sequence entries, Table 1. The decrease in incremental power required to descend was determined using the aeromechanics principle and compared with recorded incremental power reduction, Fig. 8. The excellent correlations between calculated power, flight data, and recognition of partial descent during the same time period make the RR recognition reliable. To insure the recognition reliability RR was tested with flight test data where multiple (15) partial descent events were conducted in a flight. The RR exactly recognized the partial descents in the flight card sequence as shown in Table 7. The maneuver in Visualization 13 depicts the motion and helps verify the partial power descent.

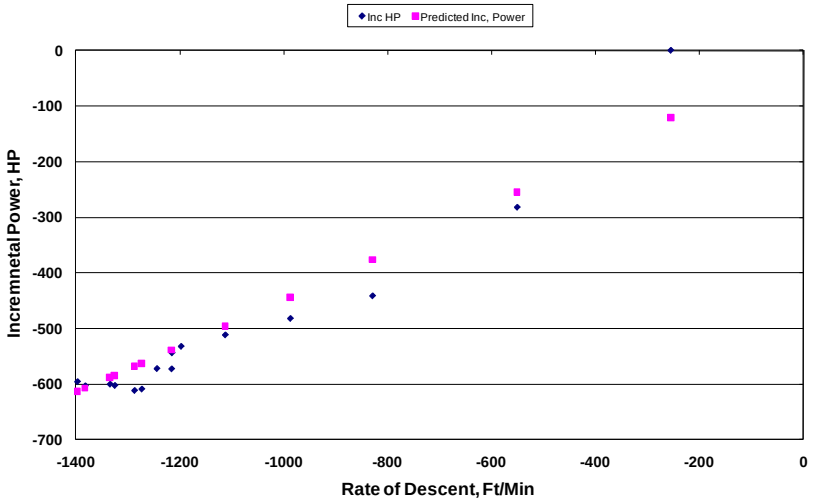
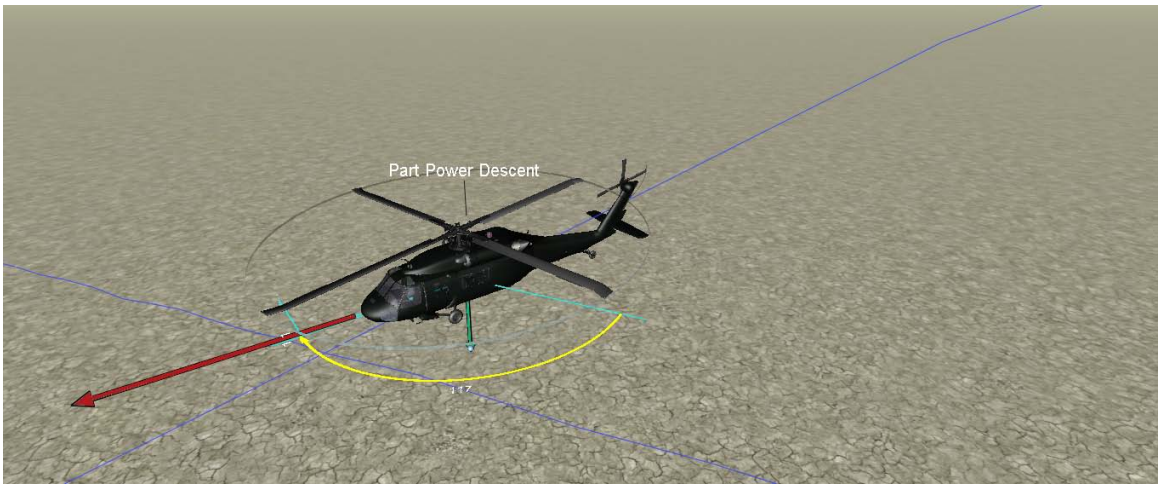


Figure 8: Incremental power reduction to descent

Table 7: Multiple partial power descent in a flight

RR id	Time	Duration	Regime	Event	Maneuver
114	3894	0 2.00	Descending Ang Bank 10-25 right	vh	
233	3896	17	Part Power Descent	1	PPD
27	3913	4	Level Flight @0.4vh		
240	3917	81	Full Power climb twin engine		
238	3998	6	Normal Ascent @0.7vh		
28	4004	18	Level Flight @0.6vh		
234	4022	21	High Speed Part Power Descent	2	PPD
28	4043	2	Level Flight @0.6vh		
234	4045	16	High Speed Part Power Descent	3	PPD
231	4061	1	Normal Descent @0.7vh		
28	4062	46	Level Flight @0.6vh		
231	4353	2	Normal Descent @0.7vh		
234	4355	22	High Speed Part Power Descent	4	PPD
231	4377	1	Normal Descent @0.7vh		
29	4378	3	Level Flight @0.75vh		
28	4505	1	Level Flight @0.6vh		
234	4506	8	High Speed Part Power Descent	5	PPD
28	4619	6	Level Flight @0.6vh		
231	4625	19	Normal Descent @0.7vh		
234	4644	9	High Speed Part Power Descent	6	PPD
231	4653	1	Normal Descent @0.7vh		
29	4739	2	Level Flight @0.75vh		
234	4741	5	High Speed Part Power Descent	7	PPD
231	4746	2	Normal Descent @0.7vh		
29	4794	1	Level Flight @0.75vh		
28	4795	1	Level Flight @0.6vh		
234	4796	41	High Speed Part Power Descent	8	PPD
231	4837	19	Normal Descent @0.7vh		
28	4911	5	Level Flight @0.6vh		
234	4916	28	High Speed Part Power Descent	9	PPD
29	5127	1	Level Flight @0.75vh		
28	5128	3	Level Flight @0.6vh		
234	5131	29	High Speed Part Power Descent	10	PPD
29	5160	4	Level Flight @0.75vh		
28	5164	22	Level Flight @0.6vh		
29	5246	30	Level Flight @0.75vh		
234	5276	13	High Speed Part Power Descent	11	PPD
28	5289	3	Level Flight @0.6vh		



Visualization 13: Partial Power Descent

16. Autorotation

Autorotation is performed in the event of engine failure, thus power/torque from the engine is zero or almost zero during the autorotation training. This significantly reduces rotor speed within couple of seconds. The rotor is in windmilling action due to the high rate of descent where the airflow is from bottom of rotor disc to top. The change in potential energy is equal to the power required for autorotation and safe landing.

Thus, autorotation is recognized using very low threshold torque and high rate of descent. The variation of aeromechanics predicted and measured rate of descent is shown in Figure 9. The good correlation between predicted and measured rate descent and torque indicates the threshold used to identify autorotation and auto recoveries are appropriate. Twelve dedicated flights each having five autorotations were run through the RR program. The program identified all the autorotations as shown in Table 8. The autorotation durations were significant compared to auto recovery, thereby verifying and validating the RR. Visualization 14 shows a rapid descent rate and recovery with RR indicating an autorotation.

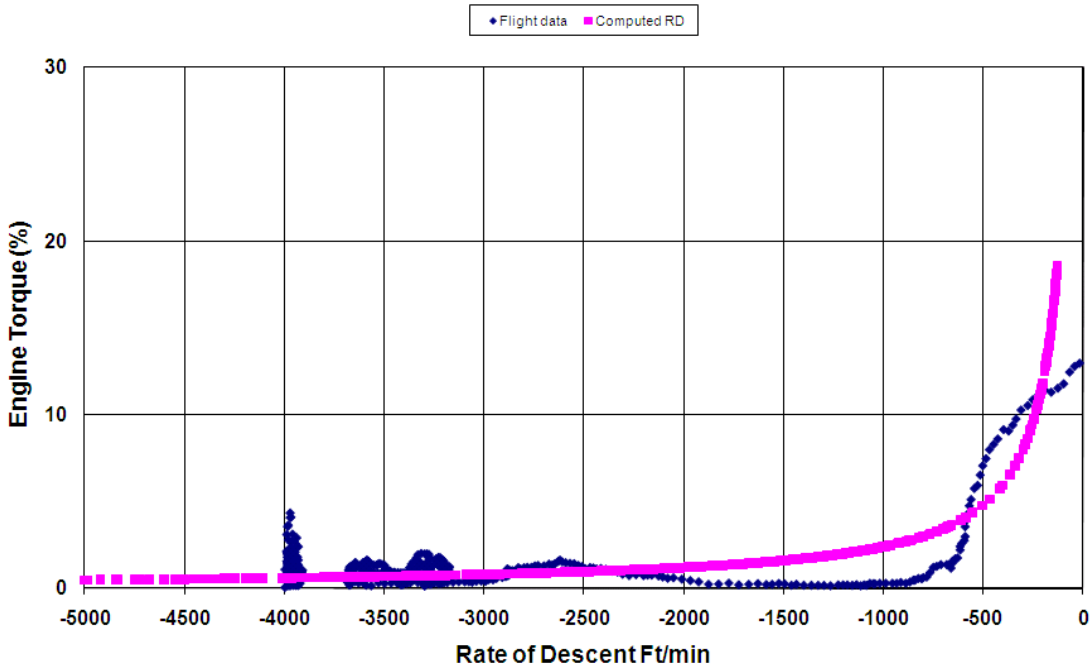
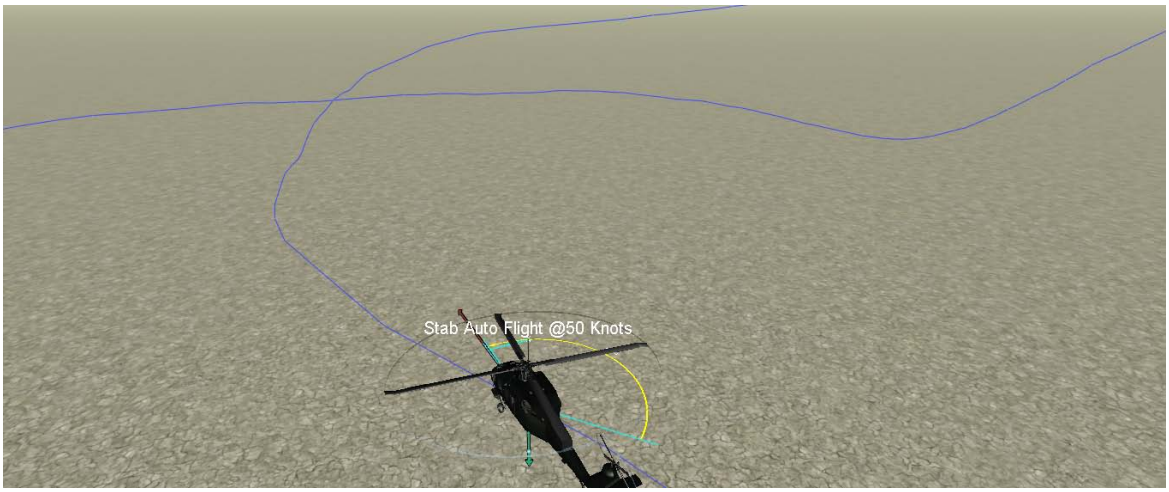


Figure 9: Engine Torque Variation with Rate of Descent

Table 8: Multiple autorotations in the flights

Autorotation and Auto Recovery Durations (Seconds)

Flight #	Auto 1	Auto Rec. 1	Auto 2	Auto Rec. 2	Auto 3	Auto Rec. 3	Auto 4	Auto Rec. 4	Auto 5	Auto Rec. 5	Total auto	Total auto recovery
1	27.10	3.05	29.00	2.00	18.00	10.00	10.00	20.00	27.73	2.02	**111.83**	**37.07**
2	36.00	1.00	32.70	2.10	32.00	0.00	25.19	3.03	25.57	2.00	**151.46**	**8.13**
3	24.57	0.00	24.55	0.00	24.38	1.00	21.00	2.00	21.27	0.00	**115.77**	**3.00**
4	26.60	1.05	22.00	1.00	22.57	1.03	18.00	2.00	19.00	2.00	**108.17**	**7.08**
5	34.77	4.13	35.00	1.00	34.00	4.00	34.60	1.05	31.65	2.05	**170.02**	**12.23**
6	32.57	2.05	27.00	4.00	29.00	6.00	28.00	2.00	18.00	9.00	**134.57**	**23.05**
7	25.00	10.00	34.69	0.00	22.00	6.00	29.07	2.00	17.00	10.00	**127.76**	**28.00**
8	32.00	0.00	33.00	0.00	27.00	1.00	26.58	3.12	3.17	0.00	**121.75**	**4.12**
9	29.75	1.00	26.00	4.00	28.02	2.00	21.00	3.00	24.05	4.00	**128.82**	**14.00**
10	31.95	3.00	31.02	1.00	26.00	2.00	27.47	0.00	28.00	0.00	**144.44**	**6.00**
11	27.74	2.09	26.00	0.00	29.00	3.00	26.66	2.07	24.00	4.00	**133.40**	**11.16**
12	26.65	0.00	25.00	3.00	22.00	2.00	27.58	1.02	24.08	2.00	**125.31**	**8.02**

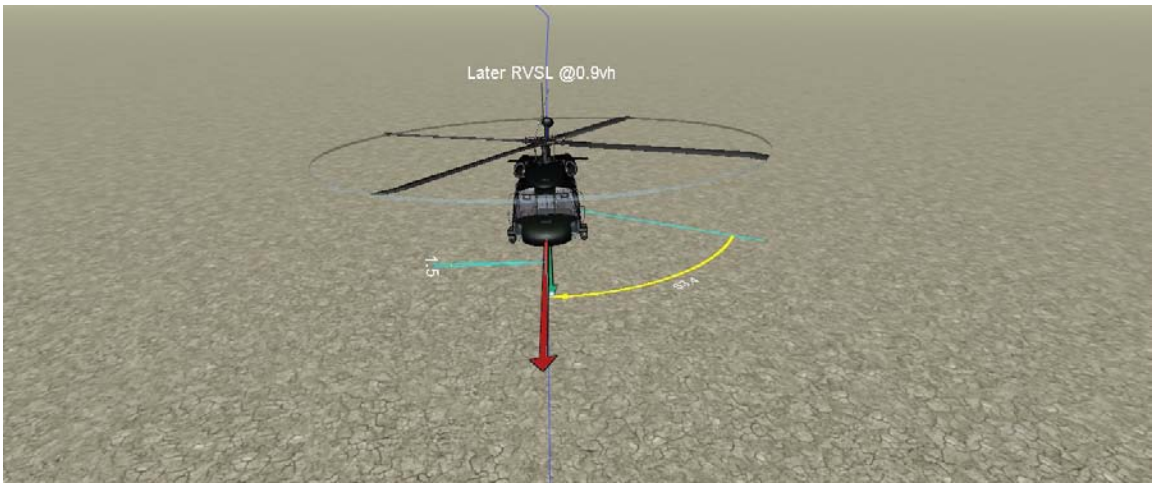


Visualization 14: Autorotation

17. Control Reversal

The control reversals algorithm recognized all reversals (longitudinal, lateral, collective and pedals) in dedicated and flight load survey flights. However, they contained flying quality control reversal pulses conducted during the flight load survey. Control reversals conducted prior to rotor start and stops were also recognized. This resulted in more than expected control reversals in the fleet flight data. Thus, the control reversal logic was revised to remove control pulses resulting in an average 35-40% reduction in control reversals. The removal of control reversal prior rotor start shows significant decrease in control on the ground. It shall be noted that control reversals on the ground prior to rotor start are not damaging to dynamic components. Visualization 2 shows the control panel

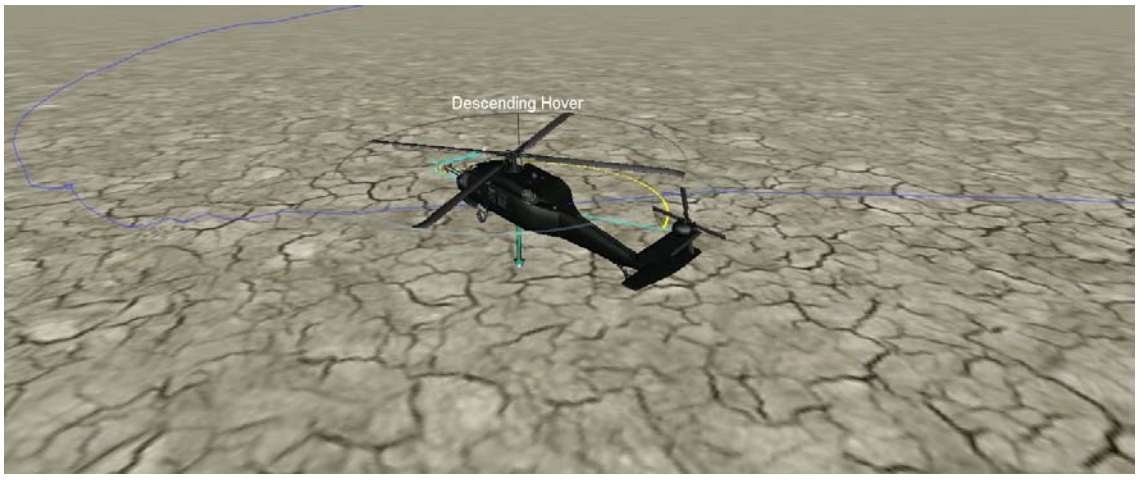
with longitudinal, lateral, collective and stick positions and the indicators on them provide actual control stick positions during the flight. The visualization provides rapid change in control stick position about its current mean position and RR recognizes the control reversal during the same time, Visualization 15. This verifies and validates control reversal algorithm.



Visualization 15: Control Reversal

18. Approach

The approach is initiated approximately 300 feet above ground level by lowering the collective stick to initiate descent. The reduction of aft cyclic stick reduces forward speed. The rotorcraft starts descending, leading to hover, and eventual landing as shown in Visualization 16 and Fig. 1.



Visualization 16: Approach

19. Landings

Visualization 17 shows rotorcraft wheels touching the ground at the same time RR recognizes it as landing. The recognized landings are also validated by comparing the

landings on the flights cards, Table 1. The landings for flights without flights cards were validated using Naval Flight Record (NAVFLIR). The NAVFLIR records flight hours and different types of landings for all United States Navy fixed and rotary wing aircraft. The ten recognized landings are shown in Table 9. For the same flight, ten landing were reported on the NAVFLIR. The short duration take-off to landing pair were associated with low average radar altitude. These findings were used to classify 32,000 flight-hours of data from 100 rotorcraft into take-off and landing cycles (Ground Air Ground) of different severities.



Visualization 17: Landing

Table 9: Take off/Landing Cycle Duration

	Take-off Time, Sec	Landing Time, Sec	Take-off/Landing Cycle Duration, Sec	Radar Altitude (ft)
1	704	1071	368	90
2	2240	5228	2988	3833
3	5514	5560	46	17
4	5590	5631	41	12
5	5649	5678	29	9
6	5759	5784	25	8
7	5803	5845	42	32
8	5854	5882	28	18
9	5893	5941	48	40
10	5991	6123	132	394

Conclusions

1. The HUMS recorded parameters are successfully utilized to develop H-60 3-D Visual animation with commercially available Eye-Sys visualization code.
2. The complete maneuver is visualized along with regime recognition output and is used for verification and validation of maneuver/regime recognition program.
3. The cockpit display animation was created that provides the current control stick positions, speed, altitude, and vertical acceleration and helps verify the regime recognition.
4. The developed regime recognition program is successfully validated using dedicated flights, flight load survey flights, and is used to analyze fleet data.

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