# Formulation and Validation of an Aircraft Health Monitoring Tool (AHMT) for the MH-60R/S Fleet

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## ABSTRACT

The Aircraft Health Monitoring Tool was developed to compare the usage of an individual aircraft, or set of aircraft, to a baseline data set, e.g., a squadron or the entire MH-60 Fleet. The comparison allows maintainers and engineers to monitor how that aircraft was flown and its history of flight maneuvers compared to a baseline set of aircraft, rather than by considering only flight time or hours-in-regime. The tool identifies flight conditions and maneuvers based on those defined in the manufacturer's usage spectrum. To validate and assess the tool's accuracy, the output was compared manually against both flight test data and an established set of maneuver recognition results. The paper illustrates applications of the tool including trending analysis, outlier identification, and detailed usage analysis for both squadrons and individual aircraft.

**Keywords:** aircraft health and usage monitoring, HUMS, maneuver identification, validation.

## Introduction

Within the U.S. Navy, squadron-level maintenance is supported by automated detection and reporting of maintenance-related events such as high vibration levels, engine controller oscillations, flight control calibration issues, etc. To accomplish this, the Navy has developed and deployed an interactive flight data analysis, visualization and reporting tool called "Flightscope," providing the capability to process all MH-60 Health and Usage Monitoring Systems (HUMS) flight data and perform analyses across the entire Fleet over multiple years. Flightscope allows the user to display selected parametric data graphically and highlights selected events to see clearly what took place during a flight. Events of interest are defined using an embedded scripting language that operates on the HUMS data. This enables the identification of basic events, for example, one or both engines operating or main rotor engaged, as well as more complicated maneuvers such as autorotations.

The Aircraft Health Monitoring Tool (AHMT) has been developed to enable the application of Flightscope's maneuver identification and statistical analysis capabilities to fleet support and maintenance planning. The tool is used through Flightscope Explorer, an interactive web application that interfaces with Flightscope's database. The tool can be used to characterize the usage patterns of aircraft and to identify outliers in the fleet. This information can potentially be used to correlate material condition to individual aircraft usage and maneuver history. Other potential uses include fleet planning and asset positioning by identifying aircraft that have performed a significant number of maneuvers of interest such as Ground-Air-Ground cycles, or Autorotations. This may impact maintenance decisions such as inspections and future use of that aircraft. The information provided by AHMT allows the Navy to improve the management of aircraft and maximize availability.

It should be emphasized that AHMT focuses on aircraft usage in a way that may be actionably linked to maintenance guidance and deployment decisions and is *not* intended to guide component replacement times or perform structural regime recognition or component fatigue life tracking. Rather, AHMT seeks to characterize "how" an aircraft is flown.

## Maneuver Algorithm Selection and Implementation

The AHMT's aircraft maneuver algorithms were developed using a combination of sources that define maneuvers, including the aircraft manufacturer's usage spectrum, the HUMS manufacturer's usage manual, Navy maintenance and flight operations manuals, as well as internally developed maneuver definitions relevant to usage. To date, these algorithms can detect a total of 248 different maneuvers. The analysis results contain the identified maneuver name, start time, and duration. These results can be displayed individually in Flightscope's strip charts or aggregated across a large data set of many flights through Flightscope Explorer.

## Validation

The accuracy of the AHMT maneuver definitions was assessed using two separate validation data sets. AHMT analysis was run on both data sets and the AHMT results were compared to the expected results. This was accomplished by listing the AHMT results, and validation set's expected maneuvers side-by-side based on start time and comparing each maneuver's name/type, start time and duration. Maneuvers with above an 80% match to the expected results were deemed acceptable. There were some maneuvers that were not flown in either data set, such as Vertical Replenishment, so not all maneuvers were able to be validated. The results from these comparisons helped to identify areas of improvement for the next version of AHMT.

### Validation Data Set 1

The first validation data set came from a series of five test flights in which the pilot recorded specific maneuvers, with start and end times. The pilots recorded 143 maneuvers that had a comparable AHMT maneuver. Of these, there were 47 unique maneuvers. Each of the maneuvers in this data set were compared side-by-side and were also visually examined using the strip chart viewer in Flightscope, which allows the user to display selected parametric data graphically and clearly highlight maneuver start time and duration.

Table 1 shows a summary of the AHMT results next to the expected results for both validation data sets, with individual maneuvers grouped together. For example, Normal Take Off, Jump Take Off, and Rolling Take Off are grouped together under "Take Off." For each validation data set, the expected occurrence count and the AHMT occurrence count are listed. The "% Match" indicates the percent of AHMT maneuvers that were accurately matched to the expected maneuvers. For Validation Data Set 1, an exact match to what the pilot recorded was required to have an accurate match. From Table 1, it can be seen that AHMT correctly identifies most maneuvers, however, some maneuvers fell below the desired 80% Match criteria and require explanation. Maneuvers in the Approach group had a low matching because, although AHMT successfully identified an Approach occurred, the type of approach, i.e. Normal Approach or Rough Approach, was misclassified. This is due to slight variations in the ground speed criteria. As for the Control Reversal group, control reversal maneuvers can be performed in hover or during level flight, and the low matching for this group was due to the air speed criteria that separates hover from level flight. Differences in airspeed criteria also caused low matching for the Level Flight group, which is defined with speed bands, and for the Side Flight group, which was mistaken for hover in one case. These discrepancies will be addressed by adjusting each algorithm's criteria for the next version of AHMT.

*Table 1: AHMT comparison to both validation data sets, summarized by maneuver group.*

| | Validation Data Set 1 | | Validation Data Set 2 | | |
|---|---|---|---|---|---|
| **Maneuver Group** | **Expected Occurrence Count** | **% Match** | **Expected Occurrence Count** | **% Match** | **Legend** |
| Approach | 8 | 38% | 1448 | 68% | <60% |
| Autorotation | 9 | 100% | 1570 | 71% | 60%-80% |
| Climb | - | - | 5875 | 79% | >80% |
| Climb Turn | 13 | 85% | 2219 | 88% | |
| Control Reversal | 32 | 78% | - | - | |
| Descent | 2 | 100% | 1066 | 22% | |
| Ground Run | - | - | 6419 | 81% | |
| Hover | 5 | 80% | 17130 | 99% | |
| Hover Turn | 6 | 100% | - | - | |
| Landing | 30 | 97% | 1136 | 96% | |
| Level Flight | 6 | 67% | 41456 | 94% | |
| Pullup | 3 | 100% | 4046 | 84% | |
| Pushover | 2 | 100% | 3192 | 82% | |
| Rear Flight | 1 | 100% | 630 | 81% | |
| Rotor On/Off | - | - | 280 | 95% | |
| Side Flight | 4 | 75% | 1878 | 88% | |
| Take Off | 14 | 100% | 1137 | 97% | |
| Turn | 8 | 100% | 12552 | 93% | |

**Validation Data Set 2**
The second validation data set came from the results of a regime recognition software program that analyzed 123 flights. For this data set, the software identified 168 unique maneuvers that were comparable to AHMT with a total of 102,349 instances of those maneuvers. There was a significantly larger amount of data compared to Validation Set 1, so this validation relied mainly on the side-by-side comparison, with only a select number of maneuvers from each group manually viewed using Flightscope's strip charts.

Similar to Validation Data Set 1, differences in criteria for Approach type caused low matching for this group. As for the low matching in the Autorotation group, it was found that the AHMT definition for autorotation relied on a signal that frequently dropped out, causing AHMT to miss detections of the maneuver. Maneuvers in the Climb and Descent groups had low matching due to the differences in criteria, e.g., rate of climb/descent, torque setting. Improvements for the groups with low matching in either validation set will be incorporated into the next version of AHMT.

## Usage Studies

Given a date range and aircraft identification number, AHMT quickly calculates a percentile ranking of the target aircraft's total maneuver occurrences, total duration spent in each maneuver, percentage of flight time spent in each maneuver, or occurrences per flight hour, compared to a baseline data set. Fig. 1 shows a sample of the AHMT output using notional data that compares a target data set of 4 squadrons to the Fleet median. In each output, generated in seconds, the 248 maneuvers are listed, followed by the median value of the baseline, and the value and percentile ranking of the target data, with percentiles over 95% or under 5% highlighted in yellow and percentiles over 97.5% or under 2.5% highlighted in red. These percentiles are considered outliers and represent when the target aircraft usage is significantly more or less than the rest of the aircraft in the baseline. The tool can also generate plots of the distribution of aircraft in the baseline for each maneuver.

| | | Squadron 1 | | Squadron 2 | | Squadron 3 | | Squadron 4 | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Median (occ/100 hr) | Value (occ/100 hr) | Percentile | Value (occ/100 hr) | Percentile | Value (occ/100 hr) | Percentile | Value (occ/100 hr) | Percentile |
| Autorotation | 25.78 | 39.96 | 78 | 36.36 | 74 | 29.38 | 66 | 24.73 | 46 |
| Eng 1 On | 79.20 | 67.68 | 38 | 138.24 | 95 | 51.12 | 14 | 121.32 | 82 |
| Eng 2 On | 79.92 | 68.04 | 38 | 143.28 | 95 | 49.32 | 14 | 120.24 | 82 |
| Landing | 222.84 | 316.44 | 90 | 255.24 | 62 | 285.48 | 78 | 283.32 | 70 |
| Left Hover Turn | 944.28 | 1402.23 | 78 | 1318.20 | 70 | 1057.14 | 58 | 1962.33 | 98 |
| Right Hover Turn | 569.53 | 767.16 | 82 | 760.70 | 78 | 617.94 | 58 | 847.42 | 86 |
| Normal Approach To Hover | 153.00 | 223.20 | 86 | 183.60 | 82 | 182.52 | 78 | 153.00 | 50 |
| Rough Approach To Hover | 36.36 | 49.68 | 70 | 36.36 | 50 | 86.04 | 90 | 87.84 | 94 |
| Moderate Pullout | 70.20 | 127.44 | 86 | 70.20 | 50 | 107.28 | 74 | 61.92 | 38 |
| Normal Takeoff | 195.48 | 287.28 | 90 | 230.40 | 62 | 267.48 | 78 | 246.24 | 70 |
| Rolling Takeoff | 22.46 | 29.45 | 74 | 22.14 | 42 | 17.89 | 30 | 38.16 | 94 |
| Normal Landing | 208.80 | 285.48 | 94 | 243.72 | 66 | 273.96 | 78 | 217.08 | 58 |
| Taxi | 853.32 | 1173.52 | 94 | 991.26 | 82 | 929.46 | 70 | 858.66 | 54 |

*Fig. 1: Section of sample AHMT output.*

### Trending Analysis

The AHMT can also be used to visualize squadron to squadron differences, for example, between a training squadron and an operational squadron. Fig. 2 shows the occurrences per 100 flight hours of autorotations for 6 squadrons compared to the median value for the full Fleet over a 12-month period. As expected, most squadrons are consistent with the median value of autorotations, with a couple outliers. Squadrons A and F, which are training squadrons, experience on average 4 and 7 times as many autorotations per 100 flight hours than fleet median, respectively.  Fig. 3 shows the occurrences per 100 flight hours of landings of the same 6 squadrons compared to the median of the Romeo Fleet. Again, Squadrons A and F are slight outliers. This may be due to the training squadrons spending more time practicing take offs and landings.

### Outlier Identification

In the event where an aircraft is found to have an issue, e.g., a landing gear crack, it may be helpful to see if the aircraft has experienced any maneuvers relevant to that issue at a rate greater than the rest of the fleet. In this case the maneuver, High Descent Rate at Landing, may be of interest. Knowing the aircraft in question and the date the issue was discovered, a usage report can be generated to show not only the number of High Descent Rate at Landings the aircraft experienced leading up to the date the crack was discovered, but also how it compares to the rest of the fleet during this time. Fig. 4 shows a histogram of aircraft for this maneuver over a 12-month period. Most aircraft in the baseline, about 65%, have experienced less than 1 occurrences per 100 flight hours. This includes aircraft with no occurrences. The histogram also shows that 1.6% of aircraft have between 8 and 21 occurrences per 100 flight hours, indicating that these aircraft may be outliers.

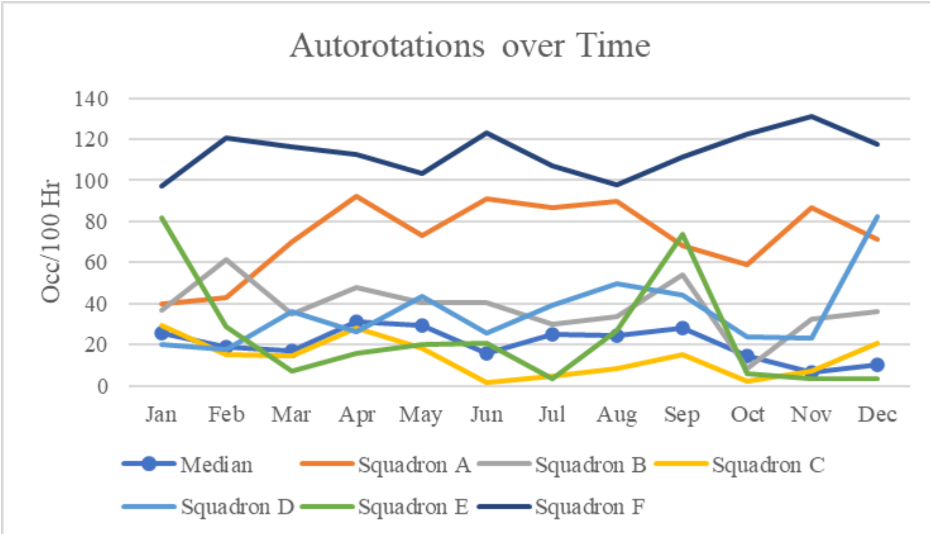



*Fig. 2: Trending over 12 months of Autorotation occurrences per 100 flight hours for the median of the fleet compared to 6 squadrons.*

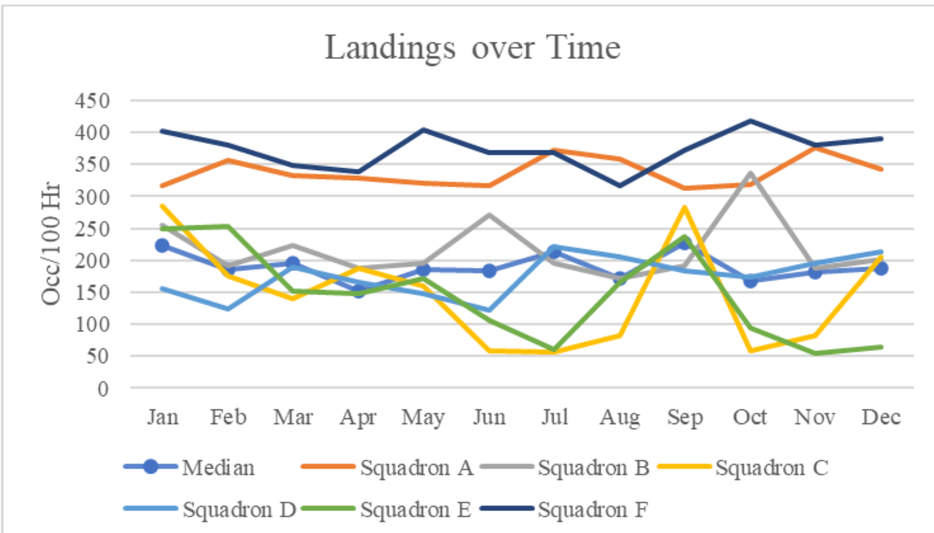



*Fig. 3: Trending over 12 months of Landing occurrences per 100 flight hours for the median of the fleet compared to 6 squadrons.*

**Usage Distributions**

Depending on the maneuver of interest, it may be useful to examine occurrences versus duration spent in maneuver. Fig. 5 contains four histograms generated by AHMT that show the distribution of hover maneuver occurrences, occurrences per flight hour, cumulative duration, and percentage of flight hours spent in hover, respectively. The data represents the Fleet over a 12-month period. Fig. 5*a* shows that about 20% of aircraft during this time had less than 500 hover occurrences. About 15% of aircraft experienced between 8 and 10 hover maneuvers per flight hour. In terms of cumulative duration, most aircraft had under 10 hours of hover maneuvers over the 12-month period, and none had more than 42 hours. From Fig. 5*d*, most aircraft spent under 10% of flight time in hover.

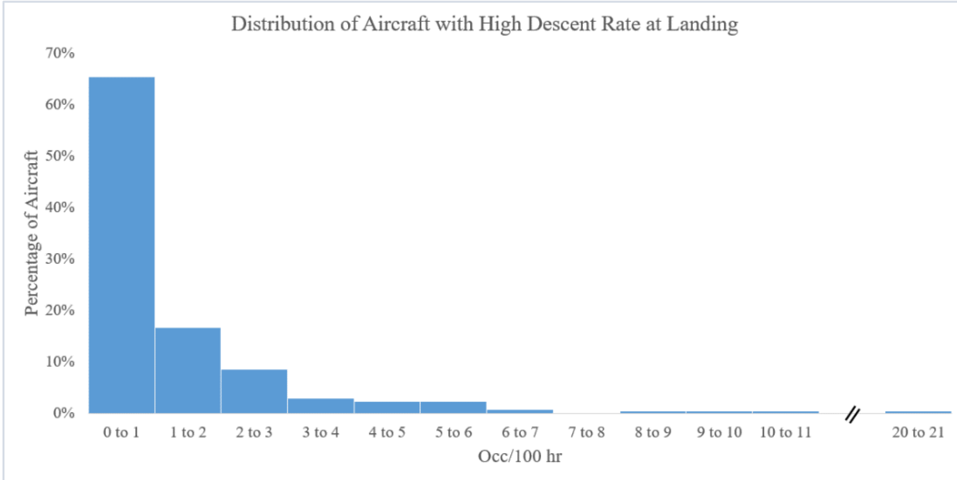
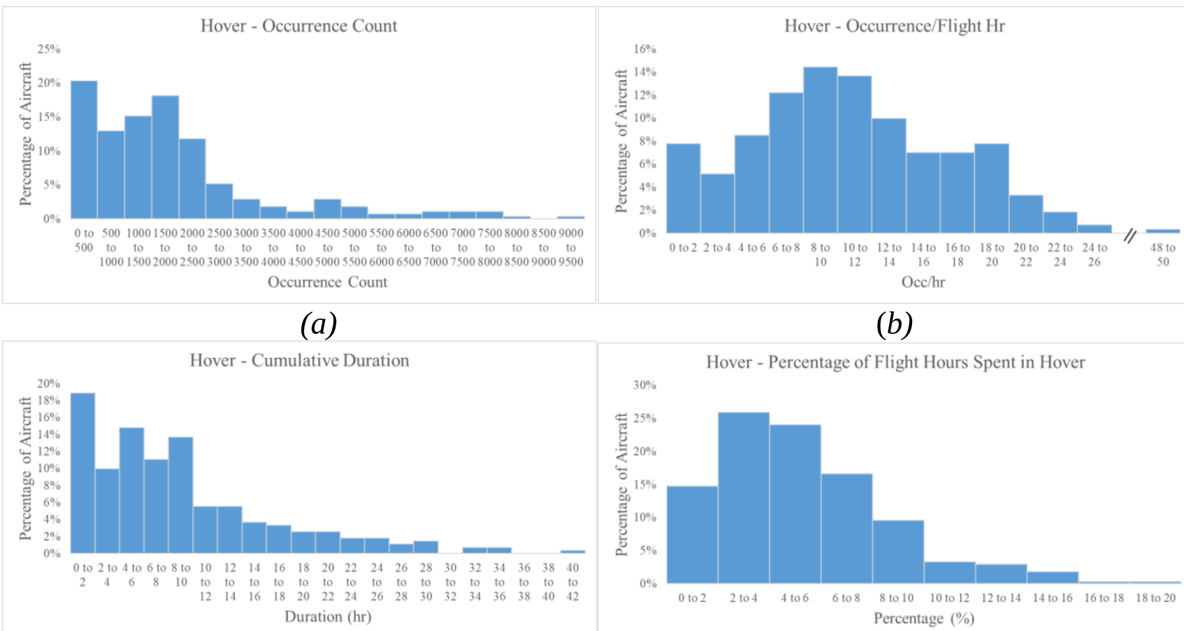



*Fig. 4: Distribution of High Descent Rate at Landing occurrences over 12-month period.*




*(a)* *(b)* *(c)* *(d)*

*Fig.5 a-d: Distribution of aircraft over 12-month period for Hover maneuver.*

## Summary

To better characterize the usage of the Navy's MH-60R/S Fleet, the AHMT was created, implemented and validated. Taking advantage of Flightscope's large database of aircraft parametric data, the tool can easily and quickly provide statistical analyses of one aircraft or a series of aircraft. Trending analysis can also be quickly generated to assist planning and maintenance. Usage studies can be carried out to help determine cause and effect analysis for relating maneuvers and failures. The AHMT is a useful tool for maintainers and engineers to monitor the overall health of aircraft in the US Naval Fleet.