Maneuver Regime Recognition Development and Verification For H-60 Structural Monitoring

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Abstract

The Navy has been developing its flight usage survey and structural monitoring capabilities for helicopter applications for many years. This paper describes the development and verification process used to establish structural usage monitoring capability for the H-60 series helicopter models presently in the Navy inventory. The paper discusses the approach used to acquire and establish a database of known flight maneuver data for the aircraft. The process of developing maneuver recognition criteria using the flight test database is described along with a discussion of the verification process used to substantiate the maneuver recognition logic and software. The paper presents some examples of the methods used in processing the flight test data to develop and define selected maneuver recognition criteria and parameter thresholds. The paper also includes a discussion of some of the problems, limitations and issues related to maneuver recognition criteria development and verification. Selected maneuver examples are used to illustrate some of the difficulties in maneuver identification. The paper concludes with some recommendations with regard to the development and verification of maneuver recognition criteria for application to other models.

Introduction

The Navy has been actively pursuing the development and implementation of structural monitoring capabilities for its rotary wing fleet for several years. The long term goal is to monitor and track the accumulation of fatigue damage for ach helicopter and tiltrotor model in the Navy inventory.

The V-22 Tiltrotor is currently entering service equipped with an on-board Health and Usage Monitoring System (HUMS) installed in each aircraft. This system includes, as part of its functionality, the capability to perform on-board recognition of the maneuvers flown during the flight. The data is stored and downloaded for post processing fatigue damage assessment. Since the development of this system the advancements in data storage capability have improved significantly and the Navy structural monitoring requirements for on-board systems have been simplified considerably. The present requirements for structural monitoring functionality simply require the acquisition of the raw parameter data needed to support maneuver recognition when the aircraft is operating. This raw parameter data is then stored in on-board computer memory, downloaded at the end of the flight and transmitted to NAVAIR for post-processing using ground based computer software to identify the maneuvers flown.

This paper describes the development and verification process used to substantiate the maneuver recognition algorithms for use with the H-60 models in the Navy inventory. The maneuver/regime recognition software discussed here will be used to identify maneuvers applicable to ground and flight operations for all H-60 variants to support usage identification and structural monitoring. In addition, the algorithms developed with this effort will also serve as the baseline starting point for the regime recognition software to be verified for the other helicopter models currently in the Navy inventory. The procedures and methods for verification described here for the H-60 models will apply to development of each follow –on model as well.

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Background

For H-60 maneuver recognition the V-22 maneuver/ regime recognition criteria was used as a baseline to write the H-60 regime recognition code. It was apparent from the start that some portions of the V-22 criteria would have to change due to control system and performance differences in the V-22 compared to the H-60. However, a large portion of the V-22 work could serve as a reasonable baseline with many areas of commonality. In particular, the helicopter mode maneuvers would be common. As a result, the regime recognition logic for many of the standard flight maneuvers like level flight, turns, climbs and dives could be transferable with simple threshold requirement changes to reflect differences in aircraft performance capability. So the V-22 criteria was coded and modified where necessary to address H-60 capabilities and performance. The details of some of these changes are addressed in detail later in the paper.

To validate and verify this H-60 regime recognition code, an H-60 flight test program was conducted to acquire known maneuvers for each aircraft operating regime. The maneuvers included in this program were those maneuvers typically flown in the qualification flight stress survey test program for the H-60 as well as various combinations of these maneuvers.

This data served as the baseline data to establish the individual maneuver recognition criteria for the H-60 as well as the verification database for validation of the final regime recognition code logic.

Flight Data Acquisition

The flight test maneuver matrix flown for the program was very large. It included basic maneuvers for each operating regime as well as combinations of maneuvers to evaluate regime recognition capability in the transition from one maneuver to the next. The overall maneuver matrix included 1200 maneuvers, combinations of maneuvers and aircraft ground operations. The actual maneuver matrix is too large to list in this paper. A sampling of the maneuvers is shown in Table (1) to illustrate the type of maneuver combinations considered.

The flight test program included 8 pilots to fly the required maneuvers. Each type of maneuver, hover, turn, climb etc. was flown by at least three of the pilots. Each pilot was also required to fly each maneuver multiple times so that both pilot variability and maneuver variability for each maneuver were included in the database.

Flight Date	Data Card Event No.	MANEUVER	Pilot
11/13/2000	54	low speed forward flight	1
4/9/2001	11	low speed forward flight	3
4/19/2001	22	low speed forward flight	5
5/18/2001	11	low speed forward flight	4
11/13/2000	56	low speed forward flight	1
4/9/2001	13	low speed forward flight	3
4/19/2001	24	low speed forward flight	5
5/18/2001	13	low speed forward flight	2
11/13/2000	58	low speed forward flight	1
4/9/2001	15	low speed forward flight	3
4/19/2001	26	low speed forward flight	5
5/18/2001	15	low speed forward flight	3
4/19/2001	17	low speed forward then vertical climb	2
9/6/2001	19	low speed forward then vertical climb	1
10/2/2001	15	low speed forward then vertical climb	4
5/16/2001	34	low speed forward then vertical climb	6
4/19/2001	18	low speed forward then vertical descent	2
5/16/2001	33	low speed forward then vertical descent	6
9/6/2001	20	low speed forward then vertical descent	1
4/19/2001	20	low speed forward then vertical descent	5
5/16/2001	35	low speed forward then vertical descent	6
11/13/2000	48	left sideward flight	1
4/9/2001	17	left sideward flight	3
4/19/2001	31	left sideward flight	5
5/16/2001	20	left sideward flight	4
5/18/2001	16	left sideward flight	2
10/2/2001	31	left sideward flight	4
11/13/2000	50	left sideward flight	1
4/9/2001	18	left sideward flight	3
4/19/2001	33	left sideward flight	5
5/18/2001	18	left sideward flight	2
9/6/2001	23	left sideward flight	1
10/2/2001	33	left sideward flight	4
11/30/2001	17	left sideward flight	6
4/9/2001	20	left sideward flight	3
5/18/2001	20	left sideward flight	5
10/2/2001	34	left sideward flight	4
9/6/2001	21	left sideward flight then vertical climb	1
10/2/2001	35	left sideward flight then vertical climb	4
5/16/2001	27	left sideward flight then vertical climb	2
9/6/2001	24	left sideward flight then vertical climb	1
9/6/2001	22	left sideward flight then vertical descent	1
10/2/2001	36	left sideward flight then vertical descent	4
5/16/2001	28	left sideward flight then vertical descent	2
9/6/2001	25	left sideward flight then vertical descent	1

Table 1: Flight Test Matrix Sample

Twenty five flights were flown to include all the required maneuvers and encompass the pilot to pilot variation required for the database. Each flight was done according to a sequenced flight card with the pilots and test engineer logging the estimated time each maneuver was flown in the flight maneuver sequence. The parameters recorded for each flight are listed in table (2).

#	Parameter
1	Flight Number
2	Real Time (seconds)
3	Weight on Wheels
4	Airspeed
5	Roll Attitude
6	Vertical Load Factor
7	Engine #1 Torque
8	Engine #2 Torque
9	Pitch rate
10	Yaw Rate
11	Vertical velocity
12	Pressure Altitude
13	Outside Air Temperature
15	Rotor Speed
15	Lateral acceleration
16	Longitudinal acceleration
17	Collective Stick Position
18	Longitudinal Stick Position
19	Lateral Stick Position
20	Pedal Position
21	Collective Stick Rate
22	Longitudinal Stick Rate
23	Lateral Stick Rate
24	Pedal Rate
25	Pitch Attitude
26	Heading
27	Roll rate
28	Radar Altitude
29	GPS longitudinal velocity
30	GPS lateral velocity
31	GPS vertical velocity
32	Doppler Drift Velocity
33	Doppler heading velocity
34	Doppler Vertical Velocity
35	Main Rotor Torque
36	Side Slip
37	Total Engine Torque

Table 2: Flight Test Parameters Recorded For Regime Recognition

Each flight lasted about 2.5 – 3 hours to acquire the data for the planned maneuver sequence on each flight card. The raw parameter data was recorded through out the flight, so both prime and non-prime data maneuvers were acquired for the entire flight for each of the 25 flights.

Several types of maneuver variation were also considered as part of the test program. Low speed and high speeds were evaluated, as well as various turn and climb rates. For Pull-ups, the test matrix included not only symmetric and rolling maneuvers but various techniques in flying the maneuver were also assessed. Table (3) lists the type of pull-ups flown with the various maneuver techniques identified. Approximately 130 pull-ups were flown to build the database. Combined maneuvers were also included in the matrix to assess maneuver transitions as well as single and multiple control axis inputs for reversals.

MANEUVER
symmetric pullouts (dive-through)
symmetric pullouts (inclined plane)
symmetric pullouts (level)
right rolling pullout (wings level dive)
right rolling pullout (inclined plane dive)
right rolling pullout (inclined plane level)
Right rolling pullout (wings level - level)
left rolling pullout (wings level dive)
left rolling pullout (inclined plane dive)
left rolling pullout (inclined plane level)
left rolling pullout (wings level - level)

Table 3: Types of Pull-ups Flown For the Known Maneuver Database

The net result of this testing is a very large database of known maneuvers for each maneuver type including speed, rate, power, flight techniques, maneuver severity levels, maneuver combinations and pilot variability.

Flight Data Evaluation

Initial flight data review

The initial review of the flight data required a very labor intensive manual evaluation of the flight time histories for selected parameters, to identify the exact location of each maneuver in the flight database. The pilot logged times were an aid in locating the proper segment of data as these times correlated reasonably well with the time parameter recorded with the rest of the parameter data. The time history review was still required however, to properly identify the actual start and stop time for each maneuver on the flight cards. Using these maneuver start and end times a master file was then created to include all of the known maneuvers in the flight test database.

Initially several complete flights were also selected for detailed comparison of the regime recognition output. This was done using the baseline V-22 regime recognition logic for both the prime and non-prime data. This was also done by manual review of the parameter time histories for selected flights. The time histories were checked to verify that the code was working properly with regard to maneuver identification against the criteria thresholds of the baseline code. This initially screening process quickly identified the criteria thresholds and regime logic issues which needed tailoring to fit the H-60 performance characteristics and control system differences from the V-22.

Maneuver/ Regime Recognition Development

Basic ground rules

The intent of the maneuver recognition process for the H-60 was twofold. First, the recognition criteria and logic should readily identify the maneuvers typically found in the fatigue spectrums used for fatigue life substantiation of each H-60 variant. Secondly, the regime recognition output should provide visibility to what the aircraft is actually doing in flight. This may seem like an obvious requirement but it bears mentioning because these two objectives are not necessarily always compatible. For example, the H-60 spectrums each include the hover regime. However, none of the spectrums address the more detailed breakdown of that regime into steady hover, vertical ascent or descent in a hover. Such detail is not significant in the overall fatigue damage assessment for component safe life determination. This level of detail however, is very useful in fully understanding how the aircraft is being flown in service. As a result, the H-60 regime recognition logic requires identification of the spectrum maneuvers to the maximum extent possible. Each spectrum maneuver is recognized consistent with the fidelity used in the spectrums. At the same time, the code should also identify the benign maneuvers as well to provide a complete picture of the aircraft usage.

The fatigue spectrums for the aircraft to some extent drive some of the regime recognition criteria thresholds. For example, climbs in the H-60 spectrums are broken out into various power levels --- maximum continuous power, intermediate power, and takeoff power. This breakdown drives the regime criteria for these maneuvers to include power thresholds to properly classify the maneuver into the appropriate spectrum range. Several operating regimes are subject to spectrum driven criteria thresholds. Some of these will be discussed in subsequent paragraphs in the paper.

The baseline V-22 regime recognition criteria also influenced the basic logic structure used for the H-60 recognition code. The V-22 regime recognition logic consists of several modules of recognition code. These include modules for, high speed flight, low speed flight, and hover as well as landing, takeoff and ground operations. The flight regime recognition modules transition from high speed to low speed at 50 knts and from low speed to hover at 15 knts. This basic logic structure is retained for the H-60 code. The primary reason for retaining this logic structure is that it allows for the development of regime recognition criteria of greater fidelity over each speed range. This increases the initial criteria development workload for the programmer. However, past experience with the V-22 program indicated the increased complexity of criteria was warranted to more accurately identify maneuvers in each speed range.

General criteria development approach

The scope of this paper does not permit an all encompassing discussion of the regime recognition development process, as it applies to each maneuver type for the H-60. As a result, the discussion here will be limited to describing the general process used in the development effort. One maneuver type example will then be presented to illustrate the approach used for much of the development work. This will be followed by a more focused discussion addressing some specific issues encountered in the development effort.

To define the recognition criteria thresholds for the various maneuvers, the known maneuver database was used to examine the range of variation for key parameters selected to identify each maneuver type. The following paragraphs will describe the approach used to define the criteria for the Quick Stop (QS) maneuver. This maneuver is a high pitch maneuver done to rapidly reduce aircraft speed. For purposes of clarity of presentation, only a small subset of the actual QS maneuver database will be presented in the figures shown. The process described however, has been applied to the full data set to define the criteria thresholds and logic used in the recognition code.

A general review of the data for the QS maneuvers indicated a drop in engine torque was common to each maneuver. Figure (1) shows the engine torque variation which is typical of these maneuvers. This characteristic made the engine torque parameter desirable for consideration in identifying the maneuver.

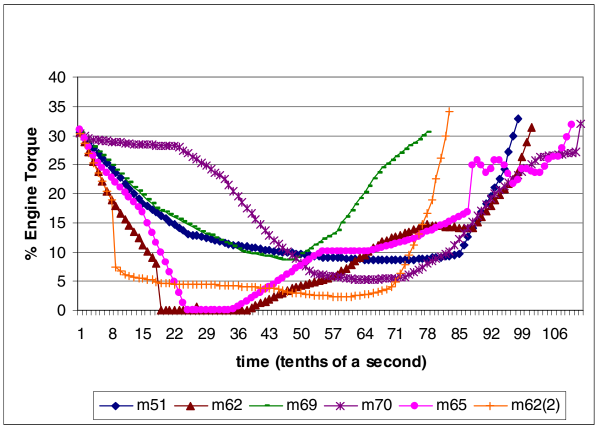

Figure (1): Percent Engine Torque vs. Time for a Typical Sample of Quick Stops

Considering the maneuvers shown in Figure (1) it is clear that in order to maintain continuity in identifying these maneuvers the engine torque threshold has to be approximately ≥15% engine torque. A lower value then this will cause discontinuous recognition of at least some of the maneuvers depending on how low the threshold is. However, using 15% engine torque as the threshold doesn't capture the full range of the maneuver from start to completion. The data indicates all of the maneuvers show a steady decrease in engine torque from about 28% engine torque to some lower sustained value and then a gradual increase to 25% as the maneuver eventually ends. The question is where in the steady decrease and increase of engine torque should the maneuver actually begin and end? Engine torque considerations alone may or may not adequately define those points in the maneuver

To address this question, a second parameter is considered to help locate the start and end of the maneuver. The parameter selected is collective stick position. Figure (2) shows the collective stick position time history for each of these QS maneuvers. This data shows a distinct drop in collective at the beginning of the maneuver around 25-30% stick position that matches up well with the engine torque change as one might expect, and provides a good reference for defining the start of the maneuver. However, the end point is less clear. The collective position variation at the end of the maneuver is anywhere from 25% to about 48% as the engine torque increases. (This variation is actually even greater when considering the entire QS flight database).

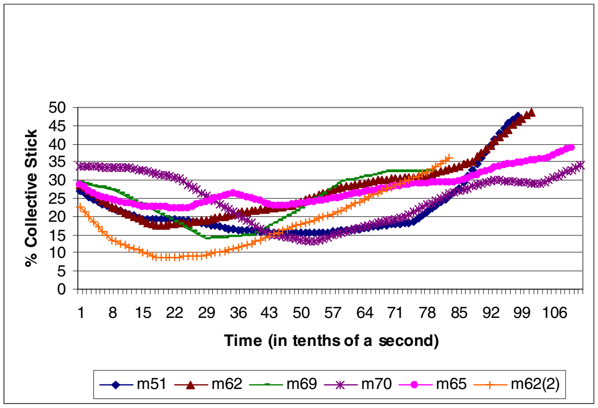

Figure (2) Collective Position Change for Sample Quick Stops

Based on these trends it was decided that a collective stick position threshold in conjunction with engine torque criteria could be used to identify the start of the QS maneuvers but the combined criteria was not appropriate to define the end of the maneuver. A second level criteria was defined using only engine torque increase to set the maneuver endpoint. The second level criteria is considered acceptable given the constraint that a QS maneuver has been found. In essence the second level is a constrained set of logic that says, a QS exists and the maneuver ends when the engine torque comes up above 25 -30% engine torque for the data shown in figure (1). The actual value selected involves some engineering judgment as to how maneuver m65 is to be handled beyond the 25% value as the data flattens out briefly.

A third parameter, aircraft pitch angle, also is significant in the identification of the QS maneuvers. Figure (3) shows the aircraft pitch angle variation for the sample data. There is a distinct pitch angle increase when the maneuver begins and a threshold level of about 10 degrees seems appropriate for the data shown. Again the end point using this parameter is not readily obvious. The pitch angle drops off for one maneuver very distinctly but the sustained values for the other maneuvers provide no end point indication. Review of all the QS data in fact showed that in many cases QS maneuvers occurred and simply transitioned into steep approaches. This third parameter may seem to be redundant criteria. However, it is a valuable means of distinguishing QS maneuvers from autorotations and autorotation recoveries as discussed later in the paper.

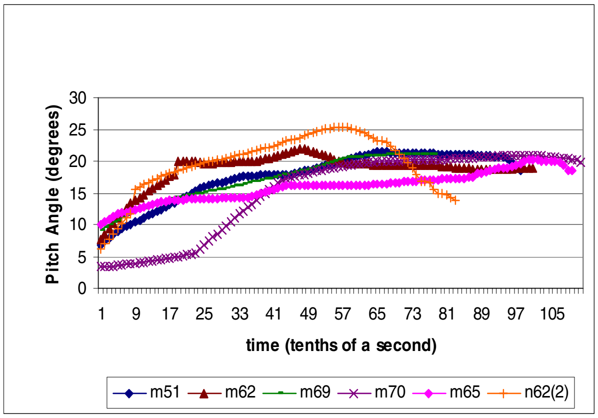

Figure (3): Pitch Variation for Sample Quick Stops

Review of all the QS data showed that the combined criteria for percent engine torque and collective position coupled with aircraft pitch angle could effectively define the start of the maneuver but the second level engine torque criteria alone was most effective in identifying the end point.

Not all maneuver types are this complex nor do they require multiple levels of criteria to fully recognize the maneuvers. The more transient the maneuver the more it seemed to require increasing levels of logic complexity. In addition, the greater the parameter overlap became for several types of maneuvers, the more the level of complexity increased to maintain separation. This will be addressed in more detail in subsequent paragraphs.

A good portion of the threshold criteria is actually set quite simply based on the way the flight stress survey maneuvers are flown. The idea being to set thresholds that will provide direct correspondence to or at least be broad enough to encompass the flight stress survey range for the maneuver. The following paragraph discusses some maneuvers which fit this scenario.

Flight stress survey and level flight influence

For the H-60, the maneuver criteria for climbs, dives, hover turns, sideslips, rolling takeoffs and landings are examples of maneuvers which utilize relatively simple parameter threshold criteria based on flight stress survey ranges. The criteria for rate of climb (ROC) and power levels for climbs is driven by flight stress survey levels. Similarly, the hover turn rates and side slip thresholds flown in the flight stress survey were used to set the criteria for these maneuvers in the recognition code.

Rolling takeoffs and landings are typically done in flight load surveys to define the upper bounds of usage (highest loadings). As a result this to some degree necessitates keeping the minimum ground speed for identifying these rolling maneuvers on the high side of the flight test database range. The intent in each regime identification is to insure that the maneuvers identified correspond to the flight stress survey maneuvers flown to acquire component loads for component life determination.

To some extent the minimum threshold criteria for some maneuvers is also driven simply by the upper and lower bounds of level flight. The ROC thresholds to identify ascents and descents are examples of this. ROC values above 500 fpm and below -500 fpm define the start of these maneuvers. These thresholds are also applicable to the thresholds seen for partial power descents and approaches as flown in the flight stress surveys.

The angle of bank (AOB) threshold criteria for turns is also set based on upper and lower bounds of level flight. For the H-60 this threshold is set at 10 degrees (AOB). However, to satisfy the fatigue spectrum breakdown for turns at 30, 45 and 60 degrees AOB the regime recognition code tags each turn with the maximum AOB seen during the maneuver. The maximum values are then conservatively grouped around the three spectrum reference points for component damage tracking purposes.

The transient maneuvers are more difficult to define as was mentioned earlier. The fatigue spectrum and flight stress survey dictate some parameter threshold criteria, or at least the approximate range of that criteria, but that is typically not sufficient to identify these maneuvers. Two examples of this are described below.

For pull-up maneuvers the vertical load factor (NZ) levels in the spectrums are 1.5 and 2 G's. These spectrum entries however, include pull-ups flown over a range of NZ values in the flight stress survey. As a result, the NZ threshold for pull-ups in the code is set at 1.3 G's to encompass what was flown in the flight stress survey. However, this is only one of several parameters needed to identify this type maneuver. This will be discussed in more detail in subsequent paragraphs.

The control reversal criteria consists of several parameters, stick position magnitude, peak to peak criteria and response time for the peak to peak stick motion to identify reversals in each control axis. The thresholds defined for this type maneuver is heavily influenced by the flight stress survey flight techniques. The range of stick magnitudes and response times for peak to peak stick travel seen in the maneuvers flown in establishing the known maneuver database were used to define the threshold criteria for regime recognition. However, the pilots flew these maneuvers consistent with flight stress survey, and handling qualities aircraft qualification methods. For regime recognition purposes only the reversals corresponding to flight stress survey techniques were used to develop and define the reversal criteria. This was done again to ensure that reversals recognized with the code are consistent with the reversal loads used in the fatigue spectrum.

Specific Maneuver Recognition Issues

During this regime recognition development process several significant issues became apparent that significantly affected both the threshold criteria and the logic used to properly recognize some of the flight maneuvers. Some of these issues and the problems encountered are described below. The actions taken to improve the recognition logic and criteria are also described.

Transient maneuver duration

The V-22 regime recognition code for identifying pull-ups and pushovers relied on NZ and aircraft pitch rate parameters to identify these maneuvers. Evaluation of that logic during the V-22 development effort indicated the need to perform some additional post processing of the monitoring system output to identify these maneuvers in their entirety. This post processing requirement was driven by the programs cutoff date for software drops for the monitoring system. For the H-60 program the plan was to incorporate changes in the V-22 recognition criteria to eliminate the need for a second post processing step to recognize these maneuvers.

Initial review of all of the pull-ups and pushovers in the database indicated each pull-up and pushover was recognized by the baseline V-22 criteria. However, evaluation of the flight data time histories showed portions of several maneuvers were not being included as part of the maneuver. To correct this, the pitch angle parameter was added to the recognition criteria for both pull-up and pushover maneuvers. This three parameter criteria became the baseline for the H-60 recognition code.

The three parameter criteria improved the recognition but did not totally solve the problem. Figure (4) shows a typical example for a symmetrical pull-up. The 3 parameter criteria (level 1 criteria in the figure) was correctly identifying the start of the maneuver and most of its duration but was consistently cutting the maneuver short of the end point. In this case the goal was to capture as much of the duration of the maneuver above 1.3 G's as possible, or at least to the point of peak pitch angle if possible and preferably a little longer as shown by the maneuver time history. It was apparent in the review that adding another parameter, roll angle --- would help improve the recognition for rolling pull-ups to some degree, but this addition provided no improvement to the symmetrical maneuvers. Evaluation of criteria threshold changes for the existing three parameters could not produce the desired result either.

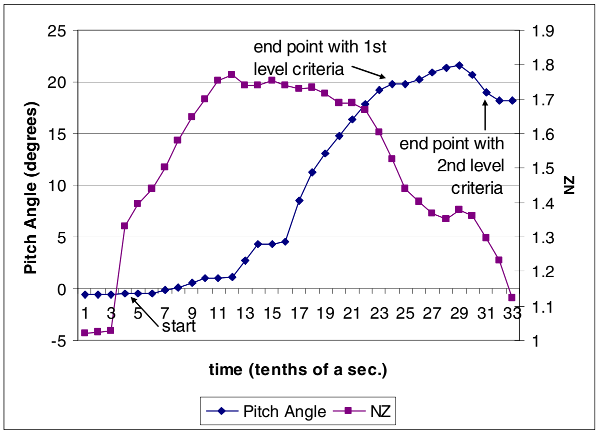

Figure (4): Typical Symmetric Pull-up

The problem was eventually solved by introducing a second level recognition logic in the code. This second level code can only be applied once the pull-up has initially been identified by the level 1 criteria. The second level criteria uses only NZ and aircraft pitch angle parameters to identify the remainder of the maneuver. The logic evaluates the pitch angle change over time and continues the pull-up as long as pitch angle exceeds a second level threshold after peek pitch has been detected. The level 2 logic recognition improvement is shown in figure (4).

The pushover recognition logic experienced the same problem as the pull-up criteria. The baseline logic used a three parameter (NZ, pitch rate and pitch angle) criteria to identify the maneuver. Figure (5) shows the typical result for a symmetrical pushover with the three parameter (level 1) logic and thresholds. The start of the maneuver is again reliably detected but the end of the maneuver was lost. The goal here was to capture as much of the NZ < .95 part of the maneuver, as long as the pitch angle remained in its downward direction. However in this case, as the logic phased out the pitch rate parameter a new parameter had to be considered. The ROC parameter had to be considered with various thresholds for ROC and NZ to distinguish the end of the pushover. The addition of ROC was needed to cover aircraft transitions to a descent/dive, level flight and in some cases even ascent. Figure (5) shows the typical result obtained with the second level logic/criteria to identify the last portion of the maneuver.

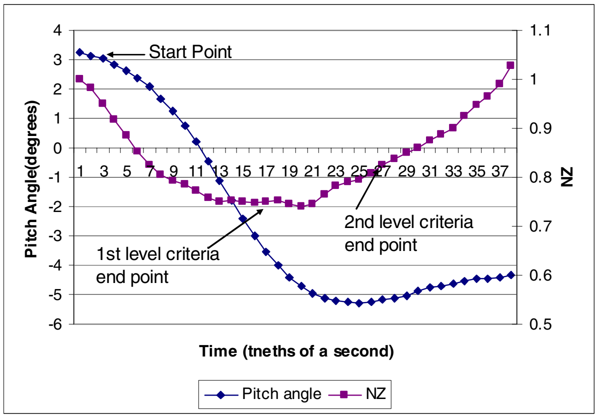

Figure (5): Typical symmetric Pushover

These results emphasized the importance of detailed review of the flight time histories for the maneuvers to ensure that the full maneuver duration is captured by the recognition criteria.

Maneuver criteria overlap

Defining unique recognition criteria that will reliably find the desired maneuver can sometimes be a significant problem. This is due in some cases to criteria overlap ---- two or more maneuver types falling into the same range of operation for the selected parameter(s). When this occurs, it may result in improper recognition of the maneuver type in many cases if not properly considered in the regime recognition development process. The following section discusses one major example of this for the H-60 regime criteria development.

Figure (6) is the plot of a typical autorotation taken from the maneuver data file. The key characteristic of the autorotation is its very low engine torque values for most of the maneuver. At first glance it seems the most difficult issue here is simply to define the criteria threshold level to begin and end the maneuver. To do that all of the autorotations in the file were compared for engine torque magnitude during the steady portion of the maneuver. That assessment indicated that a threshold value of 17% engine torque would be required to assure continuity of all autorotations flown as shown by heavy dashed line in figure (6). This value also seemed reasonable to define the start and end of the maneuver. However, it became apparent rather quickly when comparing engine torque values for some of the other maneuver types, that there was a potential criteria overlap problem. Figure (7) is a plot showing some of the low engine torque maneuvers from the database.

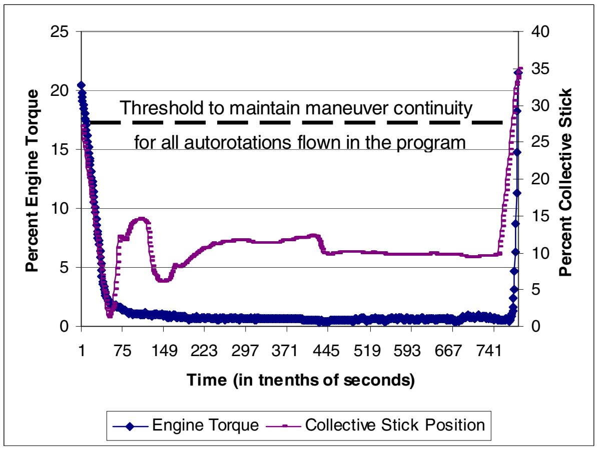

Figure (6): Typical Autorotation

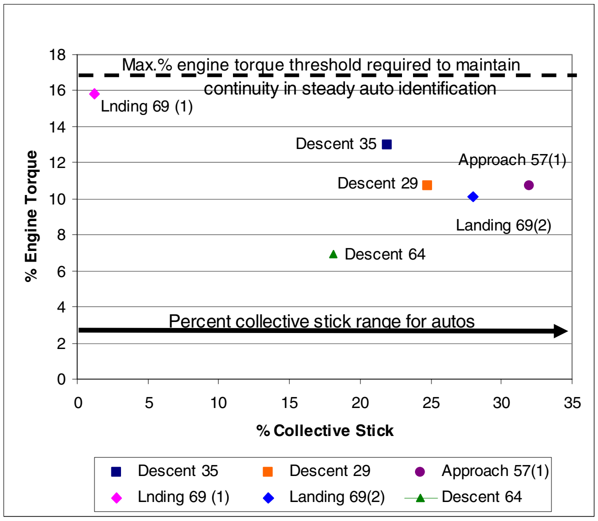

Figure (7): Percent Engine Torque and Collective Stick Position Minimums for Various Maneuvers

To avoid the overlap recognition problem it was obvious additional parameters would have to be considered to identify autorotations uniquely. To do this, the collective control stick position was chosen as a likely parameter to identify autorotations uniquely. Every autorotation in the database showed the characteristic dip in collective stick as shown in figure (6). However, as the assessment continued it was obvious that the task to find a unique criteria for autos would be far more difficult. The collective position at the start of the auto was very descriptive but through the steady portion of the maneuver and near the end of the maneuver collective positions could be very high as the heavy black arrow indicates in figure (7).

The final solution was again to resort to a two level criteria for the autorotation criteria and logic. The level 1 criteria uses percent engine torques and collective stick position to identify the start of the maneuver. The collective stick threshold was set at 16%. This threshold allows some separation from the lowest descent point found in the database (descent 64 at a collective position of 18%). Beyond the start of the autorotation the level 2 autorotation criteria opens the constraints on collective stick position to allow the maneuver to be recognized to its completion. Conflict with the other low engine torque maneuvers at this point is avoided by limiting the level 2 criteria to apply to autorotation recognition only (i.e. the aircraft is in autorotation and the end of the maneuver must be identified).

The above approach, while effective for eliminating conflict with other in-flight maneuvers, is not sufficient however, to eliminate potential conflict with landings as shown in figure (7). To address this issue, the modular construction of the regime recognition logic proved very useful. The separate landing module allowed the use of a different set of thresholds for autorotation landings. As a result, it was a simple matter of defining a new percent engine torque threshold below the lowest landing values in combination with a collective criteria to maintain recognition separation. This approach seems acceptable since true autorotation landings will fall below the normal landing minimum values for the engine torque parameter. (There were no true autorotation landings in the database to actually demonstrate this).

One major hurdle still remained however, in defining a unique criteria for recognizing autorotations. The QS maneuvers discussed earlier look very much like autorotation recoveries. The autorotation criteria could not be refined sufficiently to avoid erroneous identification of quick stops as autos. The solution here was found by considering the uniqueness of the sequence of the maneuver parameters for each maneuver type.

All of the quick stops showed very high pitch angles and low engine torques at the beginning of the maneuver and actually through the entire maneuver, as figures (1) and (3) indicate. The autorotation high pitch values occur in the final portion of the recovery from the auto. This sequence consideration for aircraft pitch allows the use of logic to identify quick stops by checking for the occurrence of an autorotation prior to the high pitch low torque condition. If the autorotation was found the logic gives priority to the autorotation to run to completion as an auto recovery. If no autorotation preceded the data combination identifying a quick stop, the quick stop identification is given priority. There is a risk in this approach, if an autorotation actually begins in a very high pitch condition. None of the autorotations in the database showed this characteristic. In fact there is a good 10 degree pitch margin between the quick stop maneuvers and the start of autorotations. As a result, it seems unlikely that this will be a problem in-service.

Maneuver Recognition Limitations

The H-60 maneuver recognition code has some limitations in what maneuvers are recognized. The following paragraphs discuss some of these limitations and their impact on the final results.

Hover side and rearward flight

Figure (8) is a diagram illustrating the criteria used to identify hover, side flight and rearward flight. Recognition of these maneuvers is based on monitoring the parameters--- aircraft heading and ground track, and determining the angle between those two values. (Ground track is determined from GPS forward and lateral directional components). The present H-60 code uses this logic to identify these maneuvers in the low speed module (between 50 and 15 knts). This logic is not part of the hover module logic (less than 15 knts). As a result, the hover module will only indicate hover as the identified maneuver in these conditions. This limitation results from the fact that in the true hovers done to build the flight test database, it was found that the aircraft motion was not steady enough to preclude short duration transitions in and out of sideward flight and rearward flight. Based on the transient nature of the reference parameters in this very low speed environment the recognition logic was simplified to allow for only hover in the hover module with one exception. If sideward or rearward flight begins in the low speed module and transitions into the hover module speed range the maneuver can continue as long as the parameter threshold requirements are met. However, sideward flight or rearward flight can not initiate in the hover module. This was deemed a limitation that could be acceptable for the H-60 since these maneuvers are non-damaging as well.

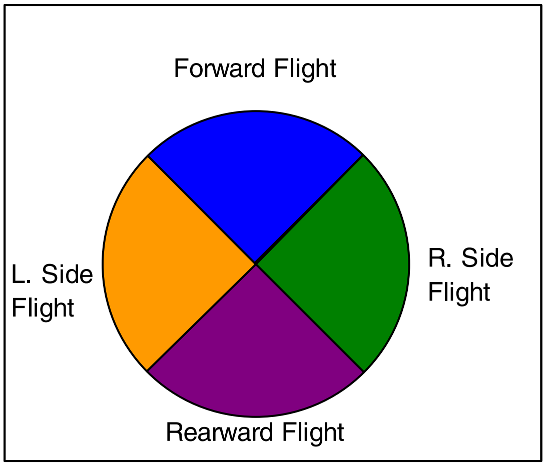

Figure (8): Low Speed Flight Quadrants

In addition, sideward and rearward flight identification is limited to the level flight parameter ranges. Once the ROC thresholds for ascent and descent are crossed the ascent and descent regimes are given priority in the recognition logic. The rationale for accepting this simplification in the logic is that this will produce the more conservative results in fatigue damage assessment for the H-60.

Accelerations/ decelerations

Accelerations and decelerations of the aircraft are only identified when the aircraft is operating within the level flight parameter ranges. Once the aircraft exceeds the ascent or descent thresholds on ROC the ascent or descent maneuver identification is given priority in the logic structure. This simplification was made since the ascent or descent maneuver identified will also include the maximum airspeed attained during the maneuver. As a result, visibility to the aircraft acceleration or deceleration is in effect not lost in the overall flight maneuvering sequence. More importantly however, it was deemed more conservative to give the ascent and descent regimes priority as time spent in these regimes will be mapped to climbs and partial power descents which typically result in higher damage rates for H-60 components. This is also more consistent in relating accelerations and decelerations recognized by the code to the accelerations and decelerations flown during the flight stress survey qualifying the aircraft.

Pull-ups

The pull-up criteria identifies this maneuver for NZ values $\geq$ 1.3 G's. The selection of this threshold is based on the H-60 fatigue spectrum pull-ups at 1.5 and 2.0 G's. The 1.5 G maneuver uses the highest load from pull-ups flown in a load factor range around this value. The 1.3 G threshold covers the low end of that range and insures that all significant pull-ups are identified. Pull-ups below that NZ threshold will be identified as ascents or climbs. Using an Nz threshold lower than 1.3 runs the risk of overlap in other maneuver types.

Evasive maneuvers

The flight test program flew several types of evasive maneuvers. Table (4) lists the various types of maneuvers which were included in the database. Review and evaluation of the parameter time histories for these maneuvers indicated that most of them had no unique characteristics to distinguish them uniquely with direct multi-parameter threshold criteria and logic. Quick Stops were the exception to this finding. Each of these other evasive maneuvers is simply the combination of several standard maneuver types expected with helicopter operations.

It may be possible to construct some pattern recognition criteria using the recognized maneuver sequence for these evasive maneuvers to identify them uniquely. However, that evaluation has not yet been initiated.

MANEUVER
Quick Stop
Quick Stop To Side Flare
Bunt
Roll
Mask/Unmask
Buttonhook
Course Reversal

Table 4: Evasive Training Maneuvers

Results

Flight data acquisition

The overall process of flying known maneuvers and establishing a database of useful data to define the recognition criteria had its own limitations. The pilots were very consistent in the data produced. Approximately 98 % of the data acquired was usable. On occasion, some of the maneuvers flown would show some deviation resulting in a different maneuver then that specified by the flight card. Some examples of this included;

1. A symmetrical pull-up would be done and the aircraft would experience some roll producing instead, a rolling pull-up.

2. Accelerations and decelerations were done over the full airspeed range in one airspeed sweep and in the process the aircraft might begin to ascend or descend. This would cause the recognized maneuver to transition to ascent or descent type maneuvers.

3. To control airspeeds in maximum decelerations the pilots occasionally would pull the nose of the aircraft up almost to the point of a quick stop and in the process build a rate of descent that would transition into a descent maneuver.

In general, almost all the maneuvers of each maneuver type were found to be very representative. For maneuvers where this was not the case, the "rouge" maneuver was quite obvious among the total population of common maneuvers. When this occurred the "rouge" maneuver was tagged as unrepresentative.

Maneuver recognition code performance

Ideally the process for development and verification of regime recognition code would be to construct the code based on known set of maneuvers and then validate its performance using another set of known maneuver data. This program had no such luxury and it did not seem prudent to subdivide the database to accomplish that. Priority was given to acquiring as many known maneuvers as possible, including as many factors as possible that might cause variation in those maneuvers, to develop a code robust enough to identify each maneuver. As a result, the true test of success here is the capability to recognize all the known maneuvers in the database correctly.

This goal was successfully achieved. The recognition code recognizes the prime maneuvers in the master file within the limitations of the code, as described earlier. In addition, manual checks of the maneuvers by reviewing parameter time histories indicated the code effectively identified the complete maneuver duration as required.

Additional checks of non-prime maneuvers within flights were also made to evaluate the recognition code performance. For example, in many cases while performing dedicated pull-ups the pilots would naturally follow that with a pushover. Non-prime takeoffs, landings, approaches could also be checked in each flight. These maneuvers are also readily identified by the code. Manual review of parameter time histories against the maneuver sequence identified by the code for selected flights in their entirety also confirmed the adequacy of code's capability. In addition, the functions of the code in retaining the maneuver description parameters (i.e. NZ, roll angle, air speed, ROC pitch angle etc.) were also readily verified.

The master file of known maneuvers was immensely useful in this overall verification process. Initially it provided an easy means of locating and evaluating the characteristics of each maneuver, to establish recognition criteria boundaries. It also permitted easy comparison of common type maneuvers. Over plotting of maneuvers to look for trends and unique characteristics for identification was also easily done using this data file. The ability to easily compare common types of maneuvers also allowed for quick identification of maneuvers that may not have been flown representatively as discussed previously. The master file also permitted easy identification of the effects of code changes across the whole range of maneuver types to identify criteria overlap and interactions.

To further enhance the accuracy and reliability of the code consideration is being given to taking the known maneuvers from one of the H-60 qualification flight stress surveys and processing the data through the code. This would provide valuable results to insure that the maneuvers recognized by the code are consistent with the maneuvers used to assess component fatigue damage. However, that effort has not yet been initiated.

The hope is that this code will be sufficiently robust as a result of this development process, to handle any variations found in the fleet and still return reliable results in identifying aircraft usage.

Conclusions

1. The dedicated known flight maneuver database provided good quality maneuvers to develop the criteria and logic to establish maneuver recognition capability for H-60 variants.

2. Creation of a master file of known maneuvers;

    a. Permitted easy and thorough comparison of common maneuver types to define maneuver recognition criteria,

    b. Facilitated quick identification of criteria threshold and logic deficiencies,

    c. Provided a reliable means of assessing criteria overlap and interactions for various maneuver types and

    d. Provided a simple means of overall assessment of regime recognition code performance and verification for fleet use.

3. Maneuver recognition criteria must be defined and evaluated very carefully to insure that the total duration of transient maneuvers is completely captured in the recognition process.

4. Maneuver criteria overlap must be checked closely when developing the recognition code to insure erroneous recognition of maneuvers does not occur.

5. A modular code structure based on aircraft speed transition points provided increased flexibility and recognition fidelity in defining recognition criteria.

6. Some code capability limitations may occur. Those limitations must be understood and handled conservatively based on the aircraft model to be monitored.