CH-46 Blade Stall During the Conduct of Dynamic Component Upgrade and Fuselage Strain Survey Tests

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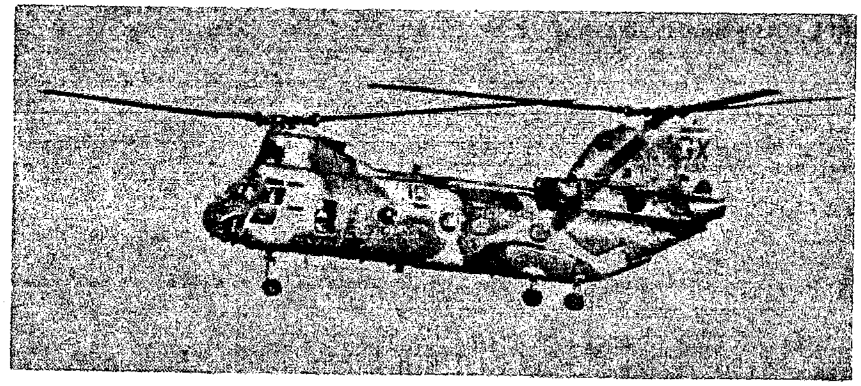


INTRODUCTION

This paper examines an in-flight blade stall occurrence during the conduct of Aircraft Testing conducted at Naval Air Warfare Center, Patuxent River MD. It gives a background of the testing, a short synopsis of the events leading up to the stall event, a brief description of the event itself, a description of the initial team response, follow on actions, lessons learned, and team recommendations.

BACKGROUND

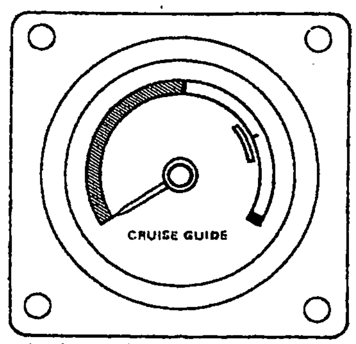
The H-46 Sea Knight has been in service since the early 1960's. There are high time aircraft in the current inventory that have accumulated close to 12,000 flight hours. The airframe is currently cleared to 12,500 flight hours. At current and forecast usage rates there exists a shortfall of aircraft for the Marine medium lift and the Navy vertical replenishment (VERTREP) missions until follow on aircraft are procured. It will take an extension of aircraft useful life to 20,000 flight hours to address this shortfall. The Dynamic Component Upgrade (DCU) was developed to address life extension of the rotor and drive systems. Boeing Helicopters (BHC) was contracted to design, manufacture, and test the new rotor and drive system components. The basic design of the new rotor and drive system is the same as the current system with the inclusion of numerous improvements and the manufacture of dynamic components with PH 13-8Mo stainless steel vice the 17-4PH stainless steel. The scope of testing planned by Boeing was considered insufficient by Naval Air Systems Command (NAVAIR 4.3.3). As a result, NAVAIR tasked Naval Air Warfare Center-Aircraft Division (NAWC-AD) to complete the necessary testing and provide airborne data tapes to Boeing to calculate fatigue lives. After the program was initiated, the question of fuselage fatigue life was raised. As a result, NAVAIR tasked NAWC-AD to instrument critical fuselage components and to process all fuselage data to present to a third party (Aerostructures) to calculate fuselage fatigue lives. The testing was completed in May of 1997 and encompassed a series of engineering and mission aircraft maneuvers conducted during a varied matrix of loading conditions, density altitudes, and flight conditions.

Project Status Prior to Stall Episode

Approximately forty flight hours of testing had been previously accomplished at the Boeing Wilmington Test Facility. Plans to ferry the aircraft to the NAS Patuxent River Air Station (Pax) were accelerated to permit a planned shutdown of the Wilmington Facility. Shortly before aircraft transfer, the team held a data review with NAVAIR, Boeing engineers and flight test representatives. This review included a Boeing pilot debrief and summary review of Boeing flown test matrix. The aircraft departed Wilmington and arrived at NAS Patuxent River in March of 1996. While the government was performing routine maintenance acceptance inspections at NAS Patuxent, Boeing discovered some vendor quality issues with the aft and forward swashplates which halted testing for about 4 months. During this time Boeing conducted a thorough review of all DCU parts and requested Pax halt planned evaluation flights in the interim. To keep the test program on track, the program office substituted a pre DCU stationary forward swashplate in the forward swashplate assembly. The forward swashplate assembly (1/2 DCU and 1/2 pre-DCU) was delivered from Naval Depot Cherry Point NC in June. The test team received NAVAIR flight clearance for the assembly in July of 96. Post maintenance functional check flights and instrumentation re-installation and calibration were accomplished during August and September. The first flight at Patuxent was flown in 11 October 1996.

Critical Parameters/The Cruise Guide Indicator (CGI)

The flight included monitoring of defined "critical parameter" data by real time telemetry processing. The critical parameters were composed primarily of the mechanical links, blade and fuselage aerostructure, and dynamic components where aerodynamic flight loads were transmitted to mechanical structural loads. One critical parameter, that also defines stall in the H-46 is the Cruise Guide Indicator (CGI). This instrument was included into the aircraft during it's initial design phase after positive pilot comments. The purpose for including it into the pilots instrument panel was that it gives real time indication of incipient blade stall. Retreating blade stall can be encountered when operating the helicopter at high airspeeds, high gross weight, high altitudes, and in turbulence, or when maneuvering in a combination of the above conditions. Lift is proportional to blade angle of attack and relative wind velocity over the blade. On the retreating blade, the resultant velocity is equal to the rotational velocity, minus the forward speed of the helicopter. Therefore, as airspeed is increased, a corresponding increase in retreating blade angle is required to maintain lift. When the retreating blade angle reaches critical angle of attack, blade stall occurs. During a stall sequence extremely large structural loads are transmitted to various rotating and stationary components. Constant application of loads of this magnitude will result in material failure and loss of aircraft control. Blade stall is the primary limiting factor for forward speeds for all conventionally designed helicopters. Most helicopters have an elaborate system of charts that define the correct maximum operating speeds. The reason these charts are so elaborate is due to the fact that forward airspeed limits are so dependent on aircraft weight, operating altitude, and angle of bank/maneuvering. The H-46 CGI employs two strain gauges on the forward and aft rotor systems each that measure structural loads directly. The airspeed limit in the operators manual is 145 KIAS or CGI limit, whichever is lower. The only time that charts are used is if the CGI is inoperative. There is one cockpit gauge only, located on the pilots (right) side of the instrument panel. The gauge is presented in figure 1. Steady state operation in the green (cross-hatched area) is allowed with occasional spikes in the yellow/avoid (white) area. Steady operation in the avoid area is not allowed and requires decreasing forward airspeed to resume operation in the green. Operation in the red (dark) area is prohibited, and an indication of fully developed stall requiring immediate increase of rotor rpm, reduction of collective pitch, reduction of airspeed, or, if maneuvering, a decrease in the severity of the maneuver.



Cruise Guide Indicator (CGI)
Figure 1

The Flight

The first flight at Patuxent was flown on 11 October 1996. This consisted of 1.3 flight hours in the Pax local flying area under day VMC conditions. The tests were comprised of; engineering flying qualities including qualitative evaluations. The briefed sequence of events included; vertical take off to hover, maximum continuous power climbs at 70 knots indicated airspeed (KIAS) to the working altitude of 2000 ft density altitude (Hd), acceleration and steady state flight at 98 KIAS and 2000 ft Hd, longitudinal doublets to 2 inches cyclic displacement at 98 KIAS, followed by constant altitude/airspeed turns from 15° to

60° angle of bank building up in 15° increments. During a sixty degree angle of bank right level turn at 22,800 pounds and forward center of gravity CH-46E bureau number 153355 experienced incipient blade stall indicated by increased airframe vibration and a departure of the cruise guide indicator (CGI) from the edge of the green band area to the red prohibited region.. During the recovery sequence, the aircraft experienced a pitch oscillation episode that resulted in exceeding peak static and oscillatory limits on various components in addition to aircraft damage.

Excerpt from Flight Daily

The sequence of events was subsequently described in the flight daily;

"Constant altitude/airspeed turns were uneventful until a 60° right turn was executed. After stabilizing in the turn with 100% torque set, the pilot at the controls (PAC) noticed the CGI progress from the green zone into the red prohibited zone where the needle pegged. The PAC initiated immediate left lateral cyclic to return the aircraft to a level attitude and reduce the severity of the maneuver. Upon reaching a wings level attitude, the aircraft suddenly, and without any conscious pilot input started to nose down causing the crew to experience a less than one "g" condition. At the same time as the aircraft's nose dipped, a shudder in the airframe was felt by the entire crew. The aircrew was concerned with aircraft integrity at this point (especially after the project engineer radioed from the TM room "what was that!"). The PAC commenced an approach to a nearby field, the project engineer radioed that the aircraft appeared normal, but a few parameters were not working and that it would be prudent to return to base (RTB). After RTB and landing at Pax, a post flight revealed the fairing on the aft pylon was gouged."[1]

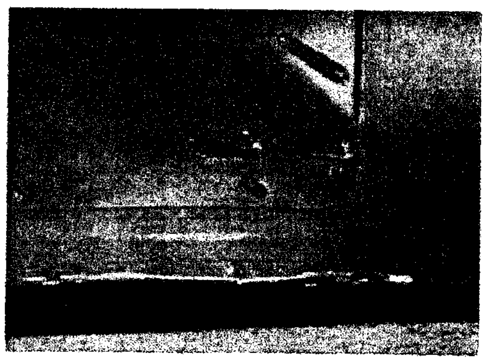
Results

The test plan specified that any excursion of oscillatory, warning, static, or peak limits would require a cessation of testing and all data sent to Boeing for engineering investigation and recommendation prior to resuming flight test. A quick review of data by the Pax test team while the aircraft was in flight revealed that empirical retreating blade tip speeds (ERITS) data, CGI, and forward/aft collective pitch link loads indicated blade stall. In addition, the following excursions were noted and confirmed by further Boeing analysis; forward blade lead/lag, forward/aft rotor shaft torque's, forward/aft longitudinal rigid links, aft collective pitch link, and aft drive scissors exceeded upper oscillatory limits. analysis also showed that the aft longitudinal link load exceeded peak static limits. A detailed aircraft inspection revealed that in addition to the aft fairing scoring

[1] Maj. Treworgy, Eric. DCU PROJECT. Flight Report for Flight X-57. Attack Assault Branch, RWATS, NAS Patuxent River MD. 1996.

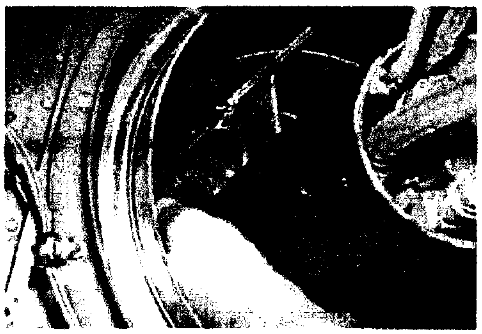
mentioned in the flight daily (figures 2 and 3)., there was evidence of scoring on the aft (rotating scissors) drive arm (figure 4) and a crack on the front frame of the number one engine (figure 5, previously repaired with weld).

Aft Fairing Right Side
Figure 2



Aft Fairing Left Side
Figure 3

Aft Drive Arm
Figure 4



Front Frame Number 1 Engine Intake
Figure 5

Team Response

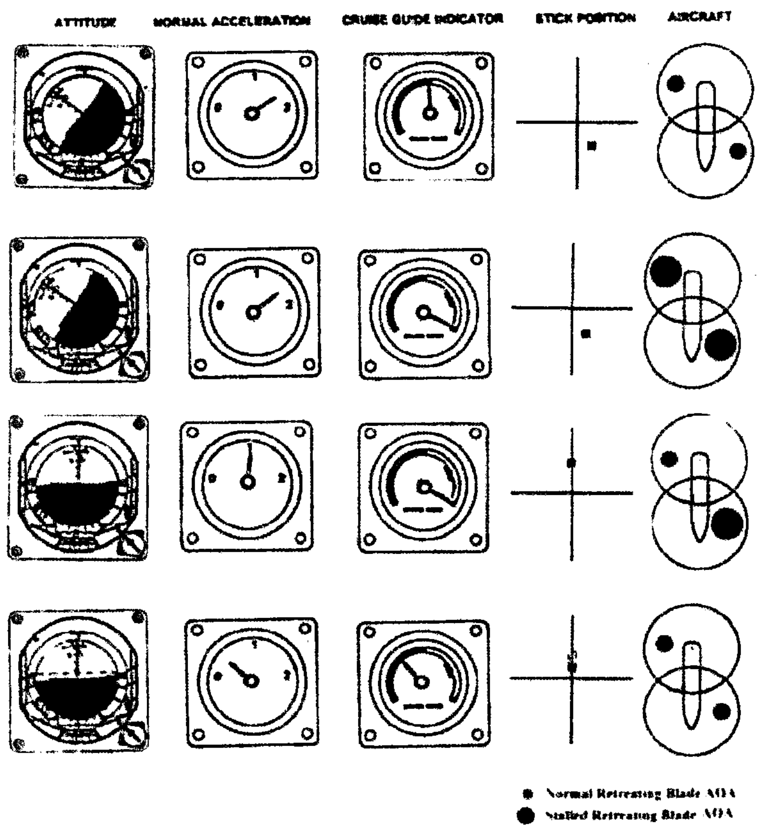
In addition to sending the airborne data tapes to Boeing, the team performed a detailed non-destructive inspection of all components involved in peak and oscillatory limit excursions to include all supporting aircraft structure. The aft longitudinal link, aft drive arm, and number one engine were removed and replaced. The team amended the test plan to remove 60° angle of bank points (current NATOPS limit is 45°) and added blade stall precautionary/recovery procedures to the hazard condition table.

Lessons Learned

Aircraft Dynamics and Stall Response

The aircrew had previously experienced aircraft blade stall only during straight and level flight. Aircraft blade stall characteristics in straight and level flight are relatively benign. The onset of incipient blade stall is indicated by an increase in one per revolution vibrations and progression of the needle on the CGI gauge from the green through the yellow avoid region to the red prohibited region. During the right turn, the aircraft exhibited the expected response, The pilots recovered from the stalled condition by rolling wings level. Another factor, which will be more fully explored in the next paragraph, is that during recovery, the pilots never reduced the collective pitch setting. In a constant altitude constant angle of bank steady state turn, the turn rate is directly related to pitch rate, the cyclic control position is slightly aft of trimmed position in constant altitude wings level flight at the same airspeed. As the aircraft rolled to wings level, the cyclic was translated forward by the pilot to maintain a level fuselage attitude. Due to the more fully stalled condition of the aft rotor system as compared to the forward rotor system longitudinal effectiveness was reduced, causing additional forward cyclic to unconsciously be applied. In addition, in a tandem design, forward cyclic increases the aft rotor system collective pitch, increasing stall.

When the aircraft returned to wings level flight, and the aft rotor system was no longer in the disturbed air flow of the forward rotor system, the stall condition abruptly ended, the longitudinal control effectiveness abruptly returned. This caused a violent nose down pitch, the aircraft went from a positive 1.8 "g" flight, to positive .3 "g". The ensuing damage occurred during the recovery which also included a pitch oscillation episode. This is a documented deficiency that has been known to occur during rapid longitudinal cyclic inputs and is due to a differential air speed hold (DASH) actuator phase shift phenomena. A graphical representation of this sequence of events is presented in figure 6.



Aircraft Blade Stall Event Sequence
Figure 6

The above graphical representation of events was deduced from the data collected with real time telemetry, in addition to air crew interviews of the event. By examining the data, which, in addition to vehicle state parameters/rates included control positions/structural loads, the cause of aircraft damage became readily apparent.

Aircraft C.G. Differences Can Significantly Alter Aircraft Response

These points had been previously flown by Boeing at the Wilmington test facility at the same weight and density altitude, but at an aft center of gravity. Boeing reached aircraft stall at 60° angle of bank and an airspeed of 140 KIAS. The Pax test team achieved stall at 98 KIAS, significantly below the Boeing achieved airspeeds. The most significant difference between test points was aircraft center of gravity which was varied to the two extreme end points of the manufacturer approved band at the planned weight.

Differences in Operators Manuals

During a post flight debrief of the aircraft blade stall response, the aircrew were discussing the pitch characteristics with the test team. It was during this discussion that it was discovered that the Navy and Marine Corps operators manuals had significant differences when discussing aircraft stall characteristics. Although the aircraft are different models; the Navy designation being H-46D and the Marine designation H-46E, the model differences relate mainly to engines and mission equipment and have nothing to do with aircraft flying qualities. The phenomena the pilots had experienced was more fully described, along with suggested recovery techniques in the Navy operators manual. The Marine operators manual discusses blade stall with the following paragraph;

> "Retreating blade stall can be encountered when operating the helicopter at high airspeeds, at high gross weight, at high altitudes, in turbulence, or when maneuvering in a combination of the above conditions. Lift is proportional to blade angle of attack and relative wind velocity over the blade. On the retreating blade, the resultant velocity is equal to the rotational velocity, minus the forward speed of the helicopter. Therefore, as airspeed is increased, a corresponding increase in retreating blade angle is required to maintain lift. When the retreating blade angle of attack reaches the stall point, blade stall occurs.
>
> Blade stall is indicated by a progressive increase of 1-per-revolution and 3-per-revolution vibrations resulting in a CGI (cruise guide indication) in the red band. The severity of the vibrations will increase as the helicopter is flown further into blade stall; however, no loss of control

will result within the airspeed envelope presented in chapter 4. Prolonged operation in blade stall should be avoided because of high stress loads imposed on the dynamic components.

> Recovery from blade stall is accomplished by executing one or more of the following: increase rotor rpm, reduce collective pitch, reduce airspeed, or, if maneuvering, decrease the severity of the maneuver."[2]

Comparing this description with the description from the Navy operators manual, which for the purposes of this discussion is essentially the same aircraft;

> "Blade stall is a loss of lift that normally occurs on the aft rotor in tandem designs. The aft head stalls first because of the disturbed rotor wash from the forward head and the fact that the aft head supports more than half the weight of the aircraft. Blade stall is more likely to occur at high airspeeds, gross weights or altitudes, in turbulence, or when maneuvering under a combination of the above conditions. CGI indications directly reflect the severity of blade stall and the resulting flight control strain loads. The stall generates a vibration that is felt by the pilot through the airframe and controls as a progressive one-per-revolution and three-per-revolution.
>
> Since the aft rotor system stalls first and drops, the pilot may perceive this as a pitchup maneuver. Attempting to push the nose over with cyclic will be less effective than normal and may increase the pitchup since increased blade pitch on the aft rotor will aggravate the stall. A temporary reduction of 1 to 2 inches of collective will quickly alleviate the stall and provide improved longitudinal response. No loss of control will occur within the airspeed limitation and load factor (g limit and angle of bank) envelope of chapter 4.
>
> Figure 4-11 is only valid for straight and level flight. For flight conditions other than straight

[2] NATOPS FLIGHT MANUAL, Navy Model CH-46E Helicopter, Nov 1994

and level, reduce the maximum airspeed accordingly. Prolonged operation in blade stall must be avoided because of the high loads imposed on the dynamic components. If blade stall occurs, eliminate it by doing one or more of the following:

1. Decrease severity of maneuver.

2. Lower collective.

3. Reduce airspeed.

4. Increase rotor speed.

5. If possible, descend to a lower altitude at approximately 500 fpm."[3]

The aircrew had briefed blade stall, and blade stall recovery techniques using the recovery procedures of the Marine operators manual, which was the model aircraft undergoing test. The purpose of the initial roll out of the turn to straight and level flight was to decrease maneuver severity. In the Marine blade stall description paragraph it could be argued that this activity should rectify the condition independently of other actions. Even though the Navy operators manual stresses the importance of lowering collective, it lists decreasing maneuver severity first in the list of recommendations, giving it a primacy over the other actions. The problem encountered in flight, was that by performing these actions in a linear vice simultaneous fashion, the pilot became so involved in reacting to the pitch oscillation, the collective was only lowered after the oscillations had subsided and the damage had occurred. In the post flight analysis it was apparent that the collective pitch setting greatly contributed to the conditions experienced. As the aircraft blade stall response was unknown to the individuals who authored the test plan, it was not covered in the hazard analysis table. This was subsequently added to the precautionary/recovery procedures portion of the hazard condition table. Although this change allowed for the continuation of testing, the conditions for this type of damage, both immediate, and long term, where not necessarily eliminated. More importantly, even if visible damage does not occur, team data indicated that it is possible to put loads on dynamic components that can lead to reaching calculated fatigue lives in a single cycle.

[3] NATOPS FLIGHT MANUAL, Navy Model CH-46D Helicopter, Navy Technical Manual A1-H46AD-NFM-000. 15 March 1996.

Operator Inattention to Stall Indications

Discussing the flight during a brief with the Boeing test pilot brought to light the trend of an operator unfamiliarity with the conditions and precautions that cause and/or prevent high CGI indications. With a background primarily in H-47's (which also utilizes a CGI gauge), it was his observation during H-46 transition training that this gauge was frequently ignored. This is probably due to the limited requirement of the H-46 to fly at maximum gross weight condition because of restrictions placed on the aircraft which, in turn, has limited pilot experience in the last five years. In addition, during the first design and fielding of the gauge, it was inaccurate and not considered representative of true flight conditions. If one of the strain gauges was inoperative, a fairly frequent instance due to the poor reliability of this item, it was tied off and an annotation was placed in the aircraft discrepancy book. A problem with this procedure was that the cockpit gauge would indicate erratically. Eventually pilots became desensitized to the gauge altogether. Later design changes and current test results point to the exceptional accuracy of the current gauge, unfortunately, it is not uncommon to find it ignored.

Flying a Different Aircraft

During the last ten years, the H-46 has gone through some significant changes. These changes have included; fiberglass composite rotor blade upgrades, a survivability/reparability/maintainability upgrade (including a new AFCS), and an increased stubwing fuel capacity upgrade. These upgrades greatly contributed to improving mission capability of the aircraft over the years, but incrementally, these changes have created an aircraft that may be substantially different than its distant forbear. A re-designed AFCS allows increased aircraft reliability and maintainability, but it also inserts a phase delay that required the flying pilots full attention during stall recovery and delayed the initiation of the proper recovery techniques while the flying pilot was occupied with recovering from a pitch oscillation episode. The addition of increased capacity fuel cells allows heavier aft weight distribution, even during c. g. 's that are well forward.

Simulator Employment to Practice High Risk Technique or Aid in Skill Sustainment

For the test team, one limiting factor was that of simulator location and availability. The only CH-46E trainers available were both down for extensive upgrade modifications. An H-46D trainer was available, but risk and hazards analyzed during the test planning sequence did not appear high enough to justify the added program costs. Another issue at question was how well does the simulator model the aircraft? When a simulation was flown, the CGI did not always model the actual stall response very well.

An important aspect of the simulator, in addition to practicing flying difficult data points is skill sustainment. The test team had another H-46 test aircraft so that sustainment was not as important of an issue.

Telemetry Room Training

The test team enjoyed the advantage of having a skilled and highly experienced engineering test team manning the real time telemetry processing room. In addition to personnel training and assignments the lead engineer accomplished prior to the first flight, a detailed plan of required flight parameters, with pre-determined limit levels and spelled out actions to be taken on achieving a pre-determined level were established in the test plan. In addition, the TM room equipment had an automated limit checker warning system to assist in tracking critical parameters. Without the benefit of a dedicated telemetry team, after the initial excitement of the aircraft response, it was considered a likely scenario that the aircraft team may well have continued testing. After the incident, there was no noticeable degradation in aircraft control, characteristics, or warning indications. Momentary excursions into the prohibited region by the CGI currently require no special inspections or maintenance provisions.

The test was designed to put low risk points up front to allow the test team to reach maximum cohesiveness prior to the highest risk test points. The reality was that sometimes high risk points are not discovered until they are reached as was in the case of the test team.

Team Actions

Train the Trainers

Team members visited both sites where H-46 transition and fleet replacement training take place in the Navy and Marine Corps. During these visits flight instructors were briefed on the unseen results of severe blade stall and proper recovery techniques should severe stall occur. This is a continuing process that has included fleet pilots at NAS Whiting Field in addition to NAS North Island and MCAS New River.

Operators Manuals

The deficiency of the Marine current operators manual has been discussed. The team has sent change recommendations to the appropriate model managers. Although the Navy manual more clearly describes the phenomena the test team experienced, it does not address the overriding importance of lowering collective pitch when experiencing incipient blade stall and both manuals will be changed to reflect the primacy of this procedure. The team recommended procedure reads;

"Blade stall is a loss of lift that normally occurs on the aft rotor in tandem designs. The aft head stalls first because of the rotor wash from the forward head and the fact that the aft head supports more than half the weight of the aircraft. Blade stall is more likely to occur at high airspeeds, gross weights or altitudes, in turbulence, or when maneuvering under a combination of the above conditions. CGI indications directly reflect the severity of blade stall and the resulting flight control loads. The stall generates a vibration that is felt by the pilot through the airframe and controls as a progressive one-per-revolution and three-per-revolution.

Since the aft rotor system stalls first and drops, the pilot may perceive this as a pitchup maneuver, or a change in longitudinal control response. Attempting to push the nose over with cyclic will be less effective than normal and may increase the pitchup since increased blade pitch on the aft rotor will aggravate the stall. A temporary reduction of 1 to 2 inches of collective will quickly alleviate the stall and provide improved longitudinal response. No loss of control will occur within the airspeed limitation and load factor (g limit and angle of bank) envelope of chapter 4.

Figure 4-11 is only valid for straight and level flight. For flight conditions other than straight and level, reduce the maximum airspeed accordingly. Prolonged operation in blade stall must be avoided because of the high loads imposed on the dynamic components. As blade stall is directly related to retreating blade angle of attack, the most effective way to decrease retreating blade angle of attack is lowering collective. If blade stall occurs, eliminate it by doing the following:

1. Collective, decrease as altitude and flight conditions allow

2. Maneuver severity, reduce.

3. Airspeed, reduce.

4. Rotor speed, increase.

5. Descend, as conditions allow at 500 fpm.

Physical Stall Indication Maintenance Action

Upon post flight inspection following the stall event, the crew chief noted cuts in the aft cowling from the rain shield (figures 2 and 3). Although there is no definitive data that this damage shows a one to one relationship with exceeding component load limits, the test team is meeting with Boeing in October of 97 to discuss manufacturer recommendations should damage of this kind be experienced in the field.

Recommendations

Cruise Guide Indicator Issues

The CGI gauge is not always monitored due to its location and poor ergonomic qualities. The team found that it is a very accurate indicator of events that are causing fairly serious strain damage. Some problems with the gauge include;

Needle Sensitivity- The indicating needle sometimes varies significantly throughout its range, this is very similar to the needle indication when the strain gauge is disconnected and tends to de-sensitize the operator.

Prohibited Area- The red (prohibited area) of the gauge is hard to distinguish as being red. It is a small red line where the needle pegs. The data indicated loads in excess of those that the operator was able to read off the CGI. During numerous flights, the gauge was monitored and there was a noted time delay that held the needle into the red (pegged/prohibited) area for approximately 4 seconds. Even when the proper recovery procedures are applied, the gauge will remain pegged for up to 4 seconds. Due to this delay, the operator is unsure of the immediate effectiveness of the recovery procedures. In addition, the operator may miss this instrument while flying a particularly demanding flight phase that requires full outside attention.

Stall Indication Warning- One of the primary considerations the team considered was the incorporation of an aural alarm. This would cue the operator when a blade stall incident was imminent, and provide the cues necessary to implement the correct recovery procedures.

Damage Indication- The ability to record the excursions for each flight would assist in determining an appropriate service life adjustment if required. Currently, the incorporation of the military standard 1553 data bus and Communication, Navigation, Control System in the helicopter provide a cost effective means for realizing this system. This would become a relatively simple but effective health usage monitoring system.

Differential Airspeed Hold Phase Change

The Differential Airspeed Hold (DASH) phase change occurs when longitudinal, or pitch inputs are either made at rates greater than 1 Hz, or the amplitudes are larger than two inches. This effectively changes the response rates of the aircraft pitch control and induces pilot control oscillations. The resultant pilot induced oscillations most probably contributed to some of the damage incurred during the flight. The pilot was delayed lowering collective during the stall incident primarily due to reacting to a stall induced pitch oscillation episode The pitch oscillation is due to a phase delay of the DASH actuator imparts to the automatic flight control system (AFCS). The team is recommending further testing of the AFCS and correction of this outstanding discrepancy.

Conclusion

The H-46 DCU load survey program is vital to maintaining Marine medium lift and Navy VERTREP capabilities. Although the damage experienced in the flight test incurred significant program delays and costs it highlights the effectiveness of current NAWC-AD and RWATS flight test safety methodologies. These methodologies were based on flight test experience, at times very dearly purchased, that have assisted the team in minimizing its exposure to risk. The data gathered will be invaluable to assisting fleet users in preventing aircraft mishaps, and enhancing aircraft life cycles.