ANALYSIS OF CHINOOK AFCS INDUCED DIVERGENT PITCH OSCILLATIONS WITH REFERENCE TO AN AUSTRALIAN ARMY ACCIDENT

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Abstract

In 2011 an Australian Army CH-47D Chinook was involved in an accident in which a series of uncommanded pitch oscillations were experienced, resulting in one fatality and the loss of the aircraft. The accident was followed by three similar incidents. The Flight Data Recorder was not recovered for the accident but was recovered for the incidents, and this data was used to investigate a possible cause of the oscillations which occurred in the lead up to the accident. Simulations were undertaken to demonstrate that the likely cause of the oscillations was limit saturation of the Advanced Flight Control System. Recovery procedures were developed to help prevent future occurrences, and handling qualities for recovery were assessed. This accident highlighted the importance of testing aircraft systems to their limits and the importance to operators of understanding the implications of these limits.

1. INTRODUCTION

On May 30 2011 an Australian CH-47D Chinook was involved in an accident, which occurred in Afghanistan while assisting with the recovery of a downed US Army Blackhawk. Immediately prior to the accident the aircraft crossed a sharp ridgeline at around 1500ft above ground level (AGL). A sharp nose up pitch excursion was experienced followed by a series of pitch oscillations. Pitch attitudes are reported to have reached 60-80° nose up and 120° nose down (inverted) in the fourth oscillation. During the fourth oscillation the pilot applied large longitudinal cyclic inputs and the aircraft was returned to a level attitude at around 10ft AGL but with insufficient rotor energy to maintain a hover. Subsequently, the aircraft contacted the ground, rolled over and caught fire. The aircraft was later destroyed for tactical reasons before the Flight Data Recorder (FDR) could be recovered.

Following the accident, three further incidents of pitch oscillations were encountered by Australian CH-47D aircraft during operations in Afghanistan over a three month period, and flight data was recovered for each of these. Comparison between witness statements taken from the accident and the incidents indicated that the conditions of the accident were likely to have been very similar to those of the incidents. Consequently, analysis of the data from the incidents was used as a basis for looking at the circumstances of the accident.

The FDR did not provide information on the behaviour of the Advanced Flight Control System (AFCS), and knowledge of the AFCS performance was important in order to examine a possible driving force for the oscillations. Consequently, simulations were undertaken at DSTO using the FDR data in order to estimate the performance of the AFCS during the incidents. This indicated that saturation of the longitudinal AFCS was likely to have been the primary cause for the oscillations experienced during the incidents.

Subsequently, verification work was undertaken at the Boeing Helicopters Simulator (BHSIM) in Philadelphia, which added confidence to the DSTO simulation results and allowed for parametric studies and recovery procedures to be developed to prevent future occurrences.

The following sections outline the details of AFCS simulations undertaken and the follow up work conducted in the BHSIM. The aircraft behaviour with the AFCS in a saturated state is discussed, along with the initiation of oscillations and pilot recovery procedures.

2. AFCS SIMULATIONS

The FDR units did not provide information on the behaviour of the AFCS, but recorded information on the aircraft attitudes, airspeed, altitude and pilot controls. In effect, the data recorded on the FDR was the input data used by the AFCS computers to determine the required flight control actuator positions. Consequently, a simulation model was developed which modelled the behaviour of the sensors, computers and flight control actuators based on inputs from the FDR. Essentially, this is the processing which would be normally performed on the aircraft in real time. The output of these simulations was an estimate of the AFCS actuator positions.

These actuator position estimates were effectively semi-closed loop, as the input data was generated in a closed loop situation (in flight with the AFCS on) while the simulation was open loop (estimated actuator positions did not affect the input data). Hence, in order for the estimated actuator positions to be representative of the actual in-flight positions, a number of conditions must be true:

1. The model replicating AFCS processing and actuator dynamics must be correct
2. The flight control system on the aircraft during the incidents must have been intact and operating 'normally'
3. The FDR data must be representative of the actual aircraft state

The AFCS simulation model was developed using detailed specifications of the CH-47D AFCS architecture. Comparison between the model performance and Boeing Simulator data along with flight test data during normal flight indicated that the model was able to reproduce the actuator behaviour quite well.

For the three incidents the aircraft returned to normal flight following the oscillations, and for each case the aircraft was declared serviceable before and after flight. This indicated that during the incidents the flight control system was most likely to have been intact and operating normally.

Finally, validation of the FDR units was undertaken through comparison between flight parameters and the recorded values. This indicated that although some errors were present, the data was generally indicative of actual flight conditions. Consequently it was concluded that the modelling approach was likely to produce results which were representative of the conditions of the AFCS during the incidents.

2.1. Description of CH-47D AFCS

A brief description of the CH-47D AFCS is provided below for reference. The flight control system incorporates a hydro-mechanical primary Flight Control System (FCS) and an electro-hydraulic AFCS. The primary FCS amplifies the pilot controls, passing them through a mechanical mixing unit to the forward and aft rotor heads. All control forces are removed by the lower boost actuators, and artificial control force is provided by the force feel pallet using springs and dampers. The AFCS utilises two separate series actuators, which are both located after the force feel unit, which means there is no direct indication to the pilot of the behaviour of either actuator. A schematic diagram of the primary and advanced FCS is presented in Figure 1.

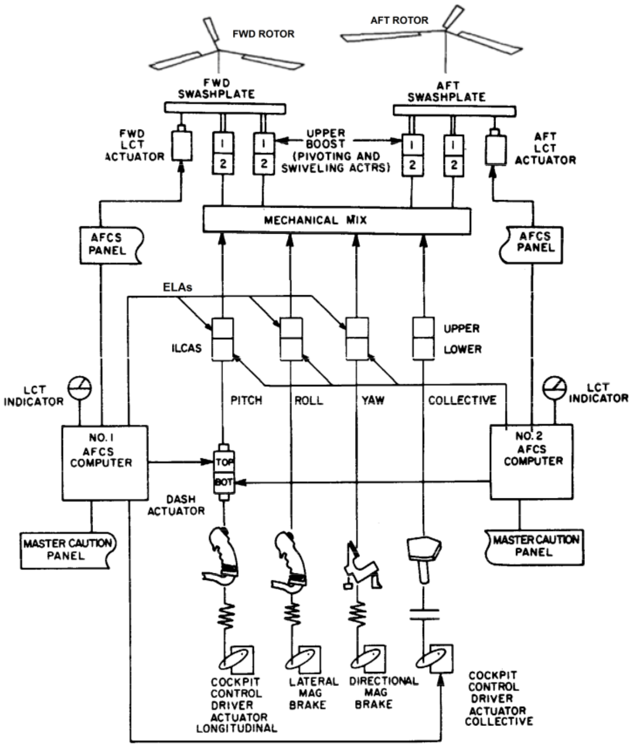

Figure 1: CH-47D Flight Control System Schematic [1]

During the incidents and accident, oscillations were experienced in the pitch axis only and hence the following discussion will be limited to the pitch axis. Longitudinal AFCS commands are incorporated into the primary FCS using two separate actuators; the Differential Airspeed Hold (DASH), and the Extensible Link Actuators (ELAs). The DASH is an electromechanical actuator commanded by pitch attitude, airspeed and lagged stick position. Below 40kts the airspeed component is removed. The pitch ELAs are incorporated as part of the Integrated Lower Control Actuators (ILCAs, which also provide the lower boost in the primary FCS), and are commanded by pitch rate. Effectively, the ELAs provide pitch damping while the DASH produces artificial attitude/airspeed stability and a stable longitudinal control gradient. The resultant control response in forward flight is attitude command-velocity hold, although in many ways it operates like a rate command [2]. With the AFCS on under normal conditions the response is stable and heavily damped in the pitch axis. Control power is very high as a result of the use of differential collective for pitch axis control.

To mitigate for the effects of actuator failures the ELAs are high bandwidth low authority (22%) actuators and the DASH is a low bandwidth high authority (44%) actuator. The DASH is rate limited to 1.4 equivalent inches of pilot control (eq-in) per second [3].

2.2. AFCS Simulation Model

The AFCS simulation model was run in the FLIGHTLAB [4] environment, which is a multi-body dynamics code tailored towards rotorcraft flight dynamic modelling. FLIGHTLAB includes components for control system simulation. The DSTO model was a stand-alone flight control system, with inputs of attitudes, angular rates, airspeed, altitude and control positions as for the CH-47D AFCS. Inputs were obtained from the FDR, and filtering and linear interpolation was applied to produce signals suitable as inputs to the model. Savitzky-Golay [5] filters were used for the airspeed and altitude signals as the input data was particularly noisy. Where required by the model additional parameters were derived from existing FDR parameters using second order central schemes.

2.3. Verification of Simulation Model

Verification of the simulation model was undertaken using data from the BHSIM as well as flight test data. Shown in Figure 2 is the comparison between the simulation model and the BHSIM for the two actuator positions for a 2¼in longitudinal step input.

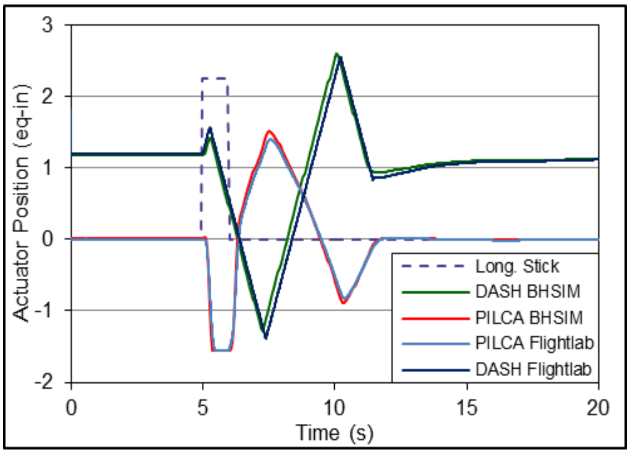

Figure 2: Verification of model using BHSIM data

The agreement between the two was good, and this serial captures the major elements being modelled including system gains, rate limits, authority saturation and phase lag. Agreement with flight data was also quite good.

2.4. Model Sensitivity to Input Data Uncertainty

The sensitivity to errors in the input data was investigated in order to examine the likely effect on the model accuracy. The largest measurement uncertainty in the input data was in the airspeed and altitude signals, while the model was particularly sensitive to control position due to the high control feed-forward gain.

It was determined that uncertainty of the absolute magnitude of the airspeed signal was quite high, however, relative changes of ±10kt in airspeed were recorded with reasonable accuracy. The airspeed input into the model is only via the DASH actuator, and variations in the absolute magnitude of airspeed correspond to movements in the actuator of approximately 0.1 eq-in/kt. In effect, the absolute magnitude of the airspeed corresponds to the position of the actuator, while relative variations in airspeed correspond to relative motions of the actuator. In steady cruise at the airspeed of the incidents the DASH actuator is approximately mid travel, and consequently it was only the relative motion of the actuator that was important for qualitative analysis, and hence the effect of airspeed errors on model accuracy was limited.

Similarly, the high control feed-forward gain on the DASH actuator made the output very sensitive to variations in the input data, but the result was predominately just a linear shift in the steady state actuator trim value as long as relative motions were captured adequately. Validation of the FDR units indicated that the control position measurements generally provided adequate resolution to provide reasonable qualitative results, and a small adjustment was made in order to adjust the DASH actuator to the correct length for the flight condition being analysed.

2.5. AFCS Behaviour during Pitch Oscillations

Oscillations in the incidents occurred with peak pitch rates of around ±20°/s and peak pitch attitudes of around ±30°. Analysis of the behaviour of the longitudinal AFCS actuators indicated that saturation of rate and authority limits was likely to have occurred during the oscillations. In addition, there was a high degree of correlation between the FDR pitch rate and the simulated DASH actuator position, with the DASH actuator leading the pitch rate. This indicated that the AFCS was likely to have been the driving force behind the oscillations.

Simulations were undertaken in the BHSIM to further investigate this, which indicated that once saturated, the AFCS response became divergent and oscillatory even without additional pilot inputs. The source of this divergence is the command architecture of the DASH actuator. The attitude/airspeed component of its input gives it a phase lag of greater than 180° producing a dynamic instability. Under normal conditions the damping component of the ELAs counteracts the instability of the DASH, producing an overall response which is stable and heavily damped.

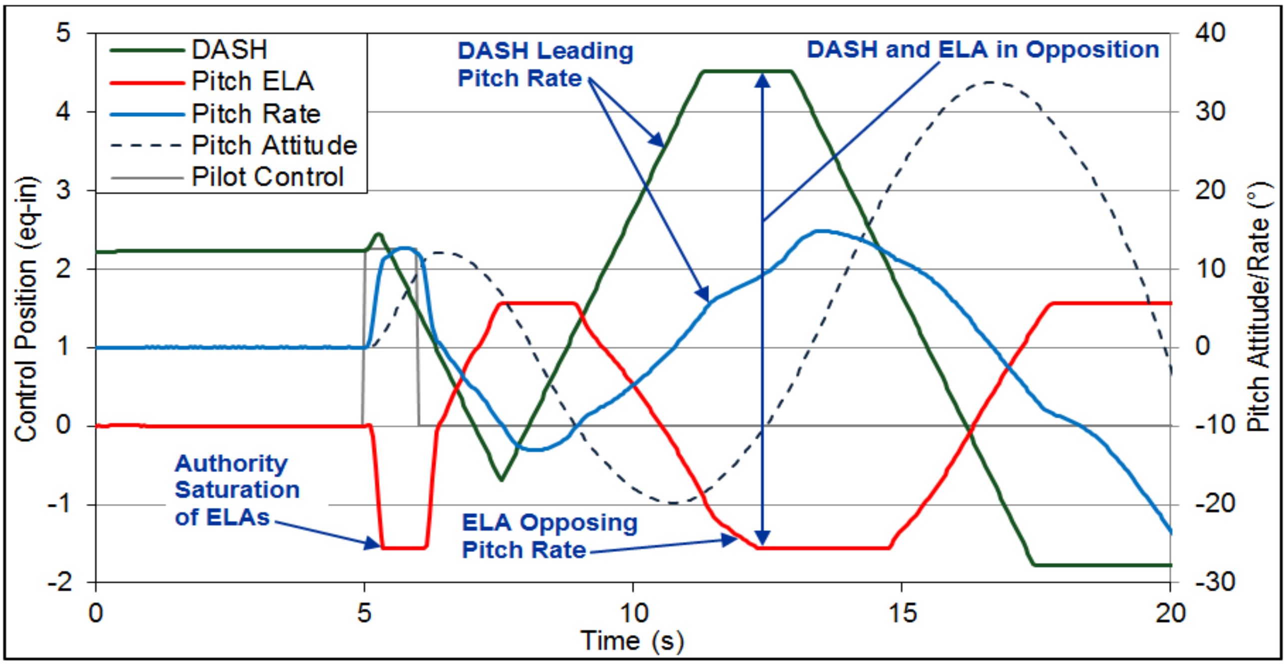

Figure 3: AFCS Saturation leading to a divergent pitch oscillation - BHSIM

As the pitch rate of the oscillation increases the rate of DASH movement also increases, along with the magnitude of the ELA inputs. Consequently there is a threshold pitch rate above which the DASH reaches its rate limit and where the ELAs reach authority limits. BHSIM simulations indicate that both saturation limits are reached within a range in the order of 5-10°/s. Once the DASH rate limit is saturated it is commanded to move faster than its capabilities, causing the actuator to lag behind the command signal. Authority saturation of the ELAs limits the total amount of pitch damping which can be provided, progressively reducing the pitch rate gain above the saturation point.

The end result is that once both saturation limits are reached, the phase lag in the DASH input increases and the amount of total damping provided by the ELAs reduces. This allows the total AFCS output (the sum of both actuators) to become dynamically unstable, driving a divergent pitch oscillation. This process is illustrated in Figure 3, which shows the BHSIM response to a one second 2¼in step input, applied at time 5s. Following this input no further control inputs were made. The pitch attitude can be seen to diverge to greater than 30° following the first oscillation, which is representative of the divergence rates experienced in the incidents and the accident.

Throughout the oscillations, the DASH actuator can be seen to be in phase and leading the pitch rate, effectively driving the pitching motion. The linearity of the DASH response indicates that it is operating in a rate limited condition. The ELA inputs continue to provide damping which opposes the DASH motion, but authority limits restrict this magnitude to half the magnitude of DASH inputs. Consequently, the total AFCS output is dominated by the DASH, with a resultant magnitude equivalent to 22% of total control authority.

Similar characteristics are observed in the simulated AFCS behaviour for the three pitch oscillation incidents, as shown for one incident in Figure 4. For this particular case the peak pitch attitudes were around 25°. The pilot controls were held almost constant for the majority of the first oscillation, and were applied approximately in opposition to attitude for the remaining oscillations, with magnitudes of up to around ±2in. The phase lead between the DASH actuator and the pitch rate is greatest in the first two oscillations, where pilot inputs were lowest. For this incident normal flight was resumed after five oscillations.

2.6. Initiation of Oscillations

Saturation of the DASH and ELAs occurs above a threshold pitch rate of around 5-10°/s, which means that whenever the pitch rates exceed this value and are sustained for a short period of time the aircraft can enter an AFCS induced divergent pitch oscillation. Once initiated, the oscillation is self-sustaining as long as the pitch rates remain above the threshold. The two primary sources of pitch disturbances are control inputs and aerodynamic gusts. Simulation of the gust response in the BHSIM indicated that gusts of as low as 7.5m/s were capable of producing the pitch rates required to initiate an oscillation under the right conditions.

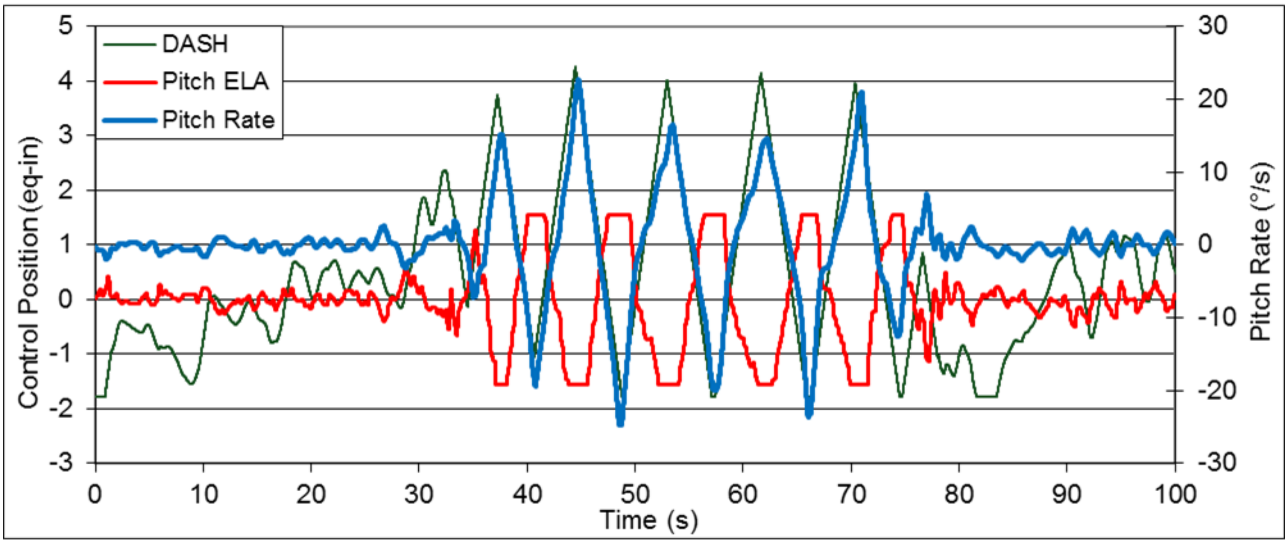

Figure 4: Simulated longitudinal AFCS positions and FDR pitch rate for one incident

Similarly, aggressive longitudinal control inputs can produce a pitch oscillation, with BHSIM results indicating that a 2¼in step input provides the right conditions. Oscillatory inputs are much more effective when made at the right frequency and under such conditions the required magnitude for an oscillatory input is lower.

When progressively increasing the magnitude of a disturbance, the transition from a stable and heavily damped response to a divergent oscillation was quite abrupt. Saturation of the AFCS occurs within a relatively narrow range of pitch rates, and the aircraft response becomes divergent as soon as the DASH gets out of phase. In the BHSIM, the response to a (one second) 2in control input was stable and damped, while a 2¼in input produced a divergent oscillation, as demonstrated in Figure 5. The increase in pitch rate for the initial disturbance from the stable damped response to divergent oscillatory response was in the order of 2½°/s.

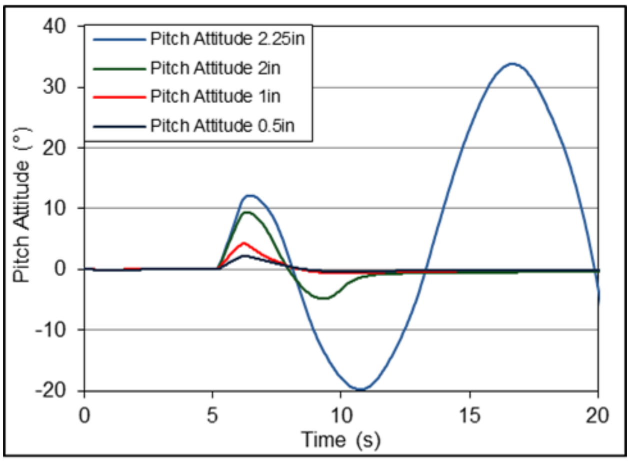

Figure 5: Transition to divergent oscillation

Indications are that the initiation of two of the recorded pitch oscillation incidents was due to atmospheric turbulence, given that no significant pilot inputs were made prior to fully developed oscillations. While it is impossible to quantify the magnitude of these disturbances, the apparent frequency of occurrence of the events indicates that the magnitude of disturbance was not particularly unusual. For each case, indications are that the initiating gust(s) had an oscillatory component which was in a similar frequency range to the aircraft motion, which allowed progressive disturbances to excite the system until the required pitch rate saturation threshold was reached.

3. PILOT INPUT DURING OSCILLATIONS

The DASH actuator is limited to 44% of total control authority, and the total magnitude of divergent AFCS inputs during an oscillation is no larger than 22%. Consequently the pilot still has considerable control authority available in order to affect recovery. In general, when an AFCS enters a saturated state the aircraft stability reverts to that of the unaugmented airframe [6]. This particular case is slightly different in that the basic airframe is statically unstable while the degraded AFCS produces a statically stable but dynamically unstable response. Essentially, the saturated AFCS increases the attitude stiffness component without increasing the total system damping. The resulting divergence rates are slightly higher than the unaugmented airframe, while the basic aircraft response is unchanged. Consequently, ‘rate-based’ restorative control inputs are effective in recovering from these oscillations. Rate-based refers to inputs which target a pitch rate in order to achieve a desired attitude, where the inputs are primarily in opposition to the aircraft pitch rate. These techniques are very similar to those used when flying with the AFCS off.

During two of the recorded pitch oscillation incidents pilot inputs were applied primarily in opposition to pitch attitude, which sustained the oscillations, allowing the sequence to continue for up to 10 oscillations in one case. For each case the final input was rate-based which ultimately led to the recovery. During attitude-based pilot inputs, the aircraft response is dominated by the pilot input while the AFCS continues to oscillate in a saturated state. As soon as the pilot inputs cease the AFCS becomes dominant and continues to drive the divergent oscillation. Under these conditions, predominately attitude-based pilot inputs can sustain the oscillations without divergence until either a rate-based input is made (leading to recovery) or pilot inputs cease, at which point the oscillations begin to diverge. Rate-based recovery techniques are effective because the pilot inputs act faster than the AFCS, taking it out of the loop. In addition, rate-based inputs contribute damping to the system, which reduces the pitch rates allowing the AFCS to un-saturate.

Handling qualities assessments in the BHSIM indicated that recovery from a fully developed oscillation of ±30° corresponded to HQR 8, with recovery requiring pilot inputs of up to ±2in with 4 control reversals. This workload reduced significantly if recovery actions were initiated earlier. When recovery actions were initiated at 10° the corresponding workload was assessed as HQR 5 [7].

Following the work in the BHSIM, Boeing released a Service Note [8] outlining the issue of Uncommanded Pitch Oscillations due to atmospheric turbulence and other disturbances, and highlighted the importance of pilots actively arresting any pitch rates greater than 10°/s.

4. EFFECT OF DENSITY ALTITUDE

The divergence rate of the oscillations is predominately a function of the degree of attitude and speed instability of the unaugmented airframe, which arises due to the combined effect of rotor interference on the aft rotor and the fuselage aerodynamics [9]. The level of pitch damping also plays a significant role. Consequently, increasing the Density Altitude (DA) has a noticeable effect on the oscillation initiation threshold and divergence rates of ensuing oscillations. The CH-47D is therefore particularly susceptible to AFCS induced pitch oscillations during operations at high DA, and care must be taken to actively arrest pitch rates before an oscillation is allowed to develop. The three recorded incidents and the accident all occurred when operating in a high DA environment.

5. GENERAL DISCUSSION OF CH-47D AFCS

The CH-47D was developed throughout the late 1970s, and featured a new AFCS with significant improvements in handling qualities over the CH-47C [10]. Preliminary and final airworthiness evaluations were conducted in 1979 and 1983 respectively [11, 12]. These evaluations included handling qualities assessments, however, the ADS-33 handling qualities requirements had not been introduced for cargo helicopters and this testing was not conducted. As such, the CH-47D AFCS was not designed to meet ADS-33 requirements. Additionally, dynamic stability testing in forward flight in both the preliminary and final airworthiness evaluations was limited to below 7000ft DA, and the maximum control input magnitudes were no larger than 1in. These conditions would not have been expected to test the AFCS to its limits, and consequently the resultant pitch responses were always deadbeat and heavily damped.

The CH-47D was subsequently used as a test bed for the development and evaluation of a set of ADS-33 requirements for cargo helicopters throughout 1994-95 [13, 14]. AFCS saturation was encountered in low speed flight during the Precision Hover and Normal Depart/Abort to Hover MTE’s, which featured aggressive longitudinal manoeuvring. For these cases analytical assessments of Level 1 handling qualities were not able to be replicated in flight due to control system non-linearities. The DASH actuator was identified as the source of this discrepancy, but investigations appear to have been limited to the effect of aggressive pilot handling in low speed regimes.

The aircraft was originally assessed as acceptable for certification based on guidelines which were available at the time of production, however, these guidelines did not adequately evaluate the effect of system limitations on handling qualities. The recently fielded CH-47F incorporates a new Digital AFCS, with updates to the DASH command logic [2] to address issues of rate limit saturation. A 2 HQR improvement from the CH-47D to F was achieved for the Depart-Abort MTE, which indicates that a significant improvement in DASH rate limiting characteristics has been obtained with the new system. It is however important that the implications of the new AFCS from a stability and control perspective are well understood, particularly in high DA environments.

While AFCS induced divergent pitch oscillations have been demonstrated to have potentially disastrous consequences, if managed correctly they represent nothing more than an undesirable handling characteristic. At the time of the Australian accident, modern aircraft in the Australian helicopter inventory included those with complex flight control systems which were specifically designed to meet ADS-33 standards. In a sense, expectations of the performance of these modern systems were applied to legacy aircraft and a discrepancy between the expectations and capabilities of legacy systems was allowed to develop. Hence the Australian accident of 2011 highlighted the critical importance of a detailed understanding of system performance and limitations for operators.

Following on from the accident, the Australian Army has invested considerable effort in developing a detailed understanding of CH-47D handling qualities. This included a collaborative DSTO/Army project to develop a pilot-level training document [15], addressing the more complex issues associated with CH-47D operation. This document details tandem rotorcraft aerodynamics, stability and control and potentially hazardous flight characteristics, based largely on the CH-47D. It also includes a detailed description of the performance and limitations of the CH-47D AFCS.

6. CONCLUDING REMARKS

Simulations based on data from Flight Data Recorders for three Australian Army CH-47D incidents have indicated that AFCS saturation played a key role in the pitch oscillations which were experienced. Correlation between the conditions of the incidents and witness accounts of the 2011 accident suggests that this is also likely to have been the case for the accident. Detailed analysis of the performance of the AFCS in a saturated state allowed for its behaviour during pitch oscillations to be characterised, and handling qualities assessments to be undertaken for pilot recovery. This accident highlights the importance of testing aircraft systems to their limits, and the importance to operators of understanding in detail the performance and limitations these systems.

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