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EFFECTS OF AUTOMATIC FLIGHT CONTROL SYSTEM ON CHINOOK UNDERSLUNG LOAD FAILURES

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Abstract. The problem addressed in this paper concerns the behaviour of a helicopter following the premature breakdown of one of its slung load cables. Within The Royal Netherlands Air Force (RNLAF), one of the active operating helicopters, employed for both military and humanitarian actions, is the Chinook tandem helicopter with external slung load. Up to the present, during RNLAF operations with Chinooks, every tandem configuration external load was underslung by means of a three-point suspension system, i.e. a two-strop suspension system backed up by a third point of suspension called "redundant HUSLE" (Helicopter Under Slung Load Equipment) representing a redundant set of slings which come into action if one of the normal strops fails. The redundant HUSLE is known to be quite expensive in terms of time and operating costs. Therefore the question arose whether it would be safely enough to replace the three-point suspension system by a two-point suspension system, eliminating the redundant HUSLE. The goal of the present paper is to determine how the automatic flight control system (AFCS) influences the recovery prospects of a Chinook helicopter with an external slung load when one of its cables brakes. It will be demonstrated that the assistance of the AFCS expands the number of occasions at which the helicopter motions stay within the handling limits during recovery of a cable failure. It appears that, in particular, the AFCS cancels the negative effect of a delayed pilot response, supporting the supposition that the combination of active pilot control and AFCS backup could push the flight envelope boundaries even further.

NOTATIONS

q	Angular velocity around local y-axis [rad/s]
u	Velocity in local x-axis [m/s]
v	Velocity in local y-axis [m/s]
w	Velocity in local z-axis [m/s]
θ	Attitude angle [rad]
τ	Pilot reaction time to the failure [sec]

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ABBREVIATIONS

ADS	Aeronautical Design Standard
AFCS	Automatic Flight Control System
BOL	Begin-Of-Life
CCDA	Cockpit Control Driver Actuator
CPT	Control Position Transducer
DASH	Differential Airspeed Hold actuator
EOL	End-Of-Life
HUSLE	Helicopter Underslung Load Equipment
ILCA	Integrated Lower Control Actuator
ILS	Instrument Landing System
LCT	Longitudinal Cyclic Trim
PID	Proportional, Integrator, Derivative control
RNLAF	Royal Netherlands Air Force
SAS	Stability Augmentation System

1. INTRODUCTION

The CH-47 is a military medium lift tandem rotor helicopter used actively during the military and humanitarian operations of the Royal Netherlands Air Force (RNLAF). Up to the present, during RNLAF operations with Chinooks, every tandem external load was underslung by means of a three-strop suspension system, i.e. a two-strop suspension backed up by a third point of suspension, the so-called ‘redundant HUSLE’. A redundant HUSLE is actually a redundant set of slings which come into action if one of the normal strops fails (see Fig. 1).

Fig. 1: Three-point (redundant) suspension of a tandem slung load

However, such a system is expensive in terms of both money and time. The question arose whether the three-point suspension system could be safely replaced by a two-point suspension. In other words, the question was posed how reliable the two-strop suspension is when compared to the three-point suspension; will the pilot able to recover the helicopter when the front or the rear strop of the suspension system breaks, and, if yes, what are the limitations imposed to the flight envelope? In a previous research, Van der Kamp, Pavel et al. [ref. 1] investigated whether the three-strop suspension system can be safely replaced by a two-strop suspension. They developed a generic 6-degree of freedom (dof) tandem helicopter+load model for piloted simulations and "flew" different failure scenarios. Their conclusion was that although in general flying with the redundant HUSLE results in less violent helicopter reactions after load failure, redundant HUSLE does not necessarily mean safer. More specifically, they demonstrated that loads up to 2 tonnes could be safely suspended only in two-points without the need to use the redundant HUSLE.

However, they based their analysis on simulations giving the pilot behaviour as a proportional-integral-derivative (PID) controller. One of the many features of the CH-47 is its automatic flight control system AFCS (analogue in Chinook D-version and digital in the latest version F), implemented in order to improve the handling qualities characteristics for CH-47 operations. One of the recommendations made by ref. 1 relates to the implementation of a higher level of sophistication in the pilot model using the AFCS characteristics of the Chinook.

The goal of the present paper is to implement an advanced flight control system (AFCS) replicating the existent longitudinal axis AFCS of a Chinook CH-47D and use this system switched on to simulate a load failure scenario. The paper will consider a multitude of failure scenarios of the load suspended on two- and three-points and determine how the AFCS influences the recovery prospects of the Chinook helicopter after a front suspension failure. The paper is structured as follows:

- The first section describes the AFCS characteristics;
- The second section develops the control laws for a longitudinal AFCS with pitch attitude hold and airspeed hold;
- The third section simulates an example of a failure scenario flown and determines the AFCS effects for recovering;
- The forth section defines safety envelopes as boundaries of the maximum helicopter forward velocity achievable when recovery is possible after a load failure as a function of the load mass that can be safely transported;
- Finally, general conclusions and potential further extension of this work are discussed.

2. DESCRIPTION of the CHINOOK AUTOMATIC FLIGHT CONTROL SYSTEM

An Advanced or Automatic Flight Control System (AFCS) employs the aerodynamic control surfaces to manipulate the forces and moments of an aircraft to control its velocity, attitude and position. The AFCS can do this with or without assistance from the pilot. The performance of the AFCS is largely governed by its flight control laws that translate the input of various sensors to control surface output. Just like the complete system, the design of these control laws, especially for military aircraft, is determined by the requirement to provide good handling qualities, over a wide range of operating conditions (including cargo transport), with a low pilot workload, while being easy to expand or modify.

For the Chinook helicopter, pilot control is done by varying the pitch of the blades either cyclically or collectively. This is done with the thrust control lever (collective), a cyclic control stick and the directional pedals, which are all coupled between the pilot and the co-pilot's position. The stick and pedal movements are transferred with a system of bell-cranks, push-pull tubes and actuators to a control mixing closet, located in the small hallway connecting the cabin to the cockpit. In this mixing unit, the pilot control inputs are combined with the signals from the AFCS computers and then mixed to result in the required lateral cyclic and collective pitch of the two rotors.

Earlier models of the CH-47 only had a Stability Augmentation System (SAS) installed to assist the pilot in attitude stabilization. With the D-version, the AFCS was added, which brought a number of modifications and additions to the SAS. Still, the main objective remains attitude stabilization, including rate damping, of the helicopter about all three axes. However, it is extended with a number of features, that for example maintain the desired value of certain flight parameters such as airspeed, pitch attitude and bank angle. The CH-47F is to be the first of the Chinook family equipped with a digital AFCS (DAFCS), granting it Level I handling qualities and meeting the stringent ADS-33 requirements for operation in degraded visual environments. A few of its impressive features include position adjustment with 30 cm increments, automatic hover capture when the cyclic stick is released below 8 kts ground speed and an altitude hold mode that eliminates drift (see [ref. 3]). Since the flight control actuation on the F-version remains unchanged from the D-version, the control system still contains mechanically linked actuators. Hence it does not qualify for the term fly-by-wire: this notion originated from the replacement of mechanical linkages by electric signalling.

The present paper will develop the AFCS as implemented in the Chinook version D. The main features of this system consist of [ref. 2]:

- Pitch attitude and long term airspeed hold, taking the position of the longitudinal cyclic stick as a reference;
- Long term bank angle and heading hold in level flight, bank angle hold in turning flight (performing coupled turns);
- A stable positive longitudinal stick gradient throughout the entire flight envelope;
- Fine adjustment of bank angle and airspeed trim (Vernier beep trim);
- Altitude hold by means of barometer or radar signals (this mode is valid in the CH 47D of the US Army; the Royal Netherlands Air Force replaced this mode by Flight Director);
- Improved manoeuvrability with the use of control position transducers for all cockpit controls;
- Electronic detent switching on lateral stick and pedals based on signals supplied by the AFCS;
- Longitudinal cyclic trim scheduling and automatic LCT positioning to ground mode when the aft wheels touch the ground;
- Use of the HSI bug error (error between actual and desired heading, indicated by a small token on the HSI instrument) for heading select (only in the CH 47D of the US Army; the Royal Netherlands Air Force replaced this mode by Flight Director);

Fig. 2 presents the cockpit interior of a CH-47D. Looking at this figure one can identify: 1) the AFCS control panel; 2) co-pilot pitch-roll control (cyclic stick); 3) pilot thrust control; 4) AFCS computer; 5) co-pilot multifunction display MMFD; 6) instrument panel; 7) centre console; 8) pilot pitch-roll control (cyclic stick); 9) multifunction display (AVMFD).

Fig. 2 Cockpit interior of a CH-47D

Regarding the AFCS of a CH-47D, this consists of the following parts:

- A cockpit control panel
- Two AFCS computers
- Three integrated lower control actuators (ILCA's)
- Two differentials airspeed hold actuators (DASH)
- Two Longitudinal Cyclic Trim actuators (LCT)
- Attached to the cockpit controls are 2 magnetic brakes for yaw and roll, a longitudinal cockpit control driver actuator (CCDA) and a collective CCDA
- Three control position transducers (CPT's)

The AFCS cockpit control panel (number 1 in Fig. 2) contains 7 switches to control the many AFCS functions (see Fig. 3). On top, the flight director coupling switches that when pressed engage the coupling between the AFCS and the Flight Director. Only one flight director may be coupled at a time. The left lower side contains the switches that control the cyclic trim actuators. Normally the longitudinal cyclic trim (LCT) actuators are automatically operated by the AFCS computers, with computer 1 controlling the forward LCT and computer 2 governing the aft LCT actuator according to the LCT trim schedule. When the switch is flipped to manual setting, the pilot is able to independently direct the extension or retraction of both actuators. The AFCS system select switch can be found on the lower right side of the display. Usually both AFCS systems will be selected. When one AFCS system is switched off, the Flight Director coupling and LCT functions continue to operate. The latter even keeps working with neither AFCS in operation.

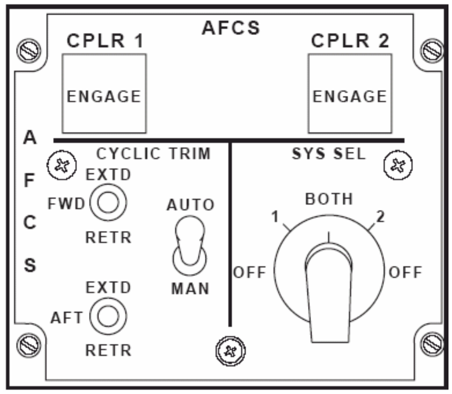
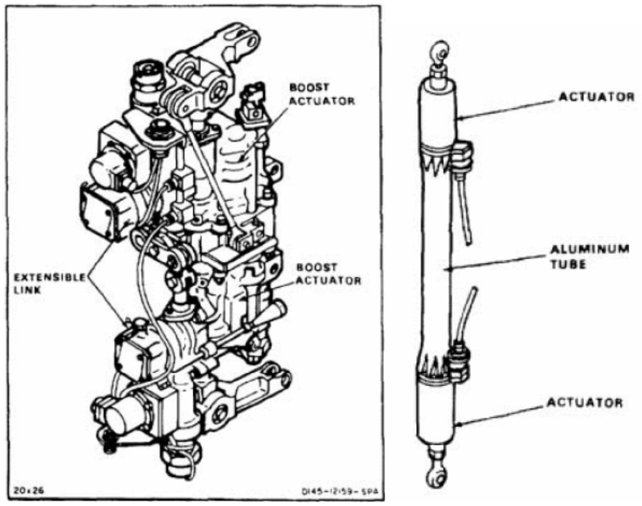


Fig. 3 AFCS control panel scheme

Two AFCS computers are located in the avionics compartment. Since the AFCS is a redundant system, in normal operation, each computer controls half of the input to the flight controls. This is described as "operation at half gain and half authority". Failure of one of the computers results in the other computer taking over at ¾ gain but like regular operation, it has only up to half of the maximum travel of the working system available. In that case the remaining system is said to function at ¾ gain and half authority (see ref. 5). When operational, the computers receive flight data from sensors and convert this into command signals that are fed to the actuators. Each unit directs its signals to the actuators according to a different path. Each actuator provides a position feedback signal to the related AFCS computer.

The Integrated Lower Control Actuators (ILCA) (see Fig. 4(a)) span 3 channels: pitch, roll, yaw. They separate the pilot control forces from the forces required to move the swashplates, which are generated by the upper controls. The ILCA's consist of two parts: a lower boost actuator and a dual extensible link. The hydromechanical lower boost actuators assist the pilot in controlling the helicopter. They are mechanically linked to the cockpit controls and will extend or retract in response to pilot inputs. The hydroelectrical dual extensible links incorporate an upper link, controlled by AFCS computer 1, and a lower link, driven by computer 2. This means that for full travel (full authority) both computers have to supply input. The actuating cylinders move solely based on AFCS commands without any corresponding cockpit controller motion. In the case none of the AFCS computers are working, the extensible links act as rigid links. The thrust input is enhanced with a lower boost actuator without extensible links, thereby assisting the pilot in moving the thrust control without providing a hydroelectrical input for the AFCS.



(a) Integrated Lower Control Actuator (b) Differential Airspeed Hold Actuator

Fig. 4 Chinook actuators connected in series to cockpit controls

The differential airspeed hold (DASH) actuator (see Fig. 4(b)) is installed between the cyclic stick and the pitch ILCA. The actuator is in fact a combination of two electro-mechanical linear actuators mounted end to-end inside a tube. Like an ILCA, the upper half is controlled by AFCS No. 1, the lower half by No. 2, so again both AFCS computers are required for full authority, which is equal to 50% of the longitudinal control range, taking about 5 seconds to complete full travel. The DASH extends and retracts with the purpose of long term stabilization of the pitch axis, arranging a positive stick gradient and maintaining airspeed about a fixed stick position. Its performance depends on the mode of operation, of which there are three:

- A normal mode in which it stabilizes 1) the airspeed when flying faster than 40 kts and 2) the pitch attitude at speeds below 40 kts.
- A Differential Collective Pitch Trim (DCPT) mode. This is turned on in special conditions such as high cyclic stick rate, large pitch attitude or on the ground. This is to prevent an exaggerated response from the actuator that would occur in these instances with the DASH in normal mode.
- The transition mode. This mode is entered when the DCPT conditions do not apply anymore and the AFCS is engaged. The system switches to a low rate driver (20% of the normal rate), forcing the DASH actuator to return to its normal position corresponding to the airspeed. This avoids a step-like control input when the DASH resumes normal operation.

The two longitudinal cyclic trim (LCT) actuators installed under the swashplate have as primary task to minimize fuselage drag by reducing the nose down attitude as airspeed and altitude build up. To manage this, the AFCS transmits signals to the LCT actuators which in turn increase the longitudinal cyclic pitch angle of the fore and aft rotor. This way blade flapping is also reduced, lowering stresses on the rotor shafts. The pilot can also manually select the LCT actuator positions.

3. Developing control laws for the longitudinal AFCS

The present paragraph will develop pitch control laws for operating the Chinook longitudinal AFCS. The pitch control laws have 6 input paths: pitch attitude, pitch rate, yaw rate, bank angle, limited airspeed and the longitudinal control position. These signals arrive from the gyros, CPT and pressure sensor and are manipulated to steer the pitch ILCA extensible links to provide pitch rate damping and the DASH actuator to maintain airspeed and a positive stick gradient. Fig. 5 displays the pitch control laws transferred to a Simulink computer model.

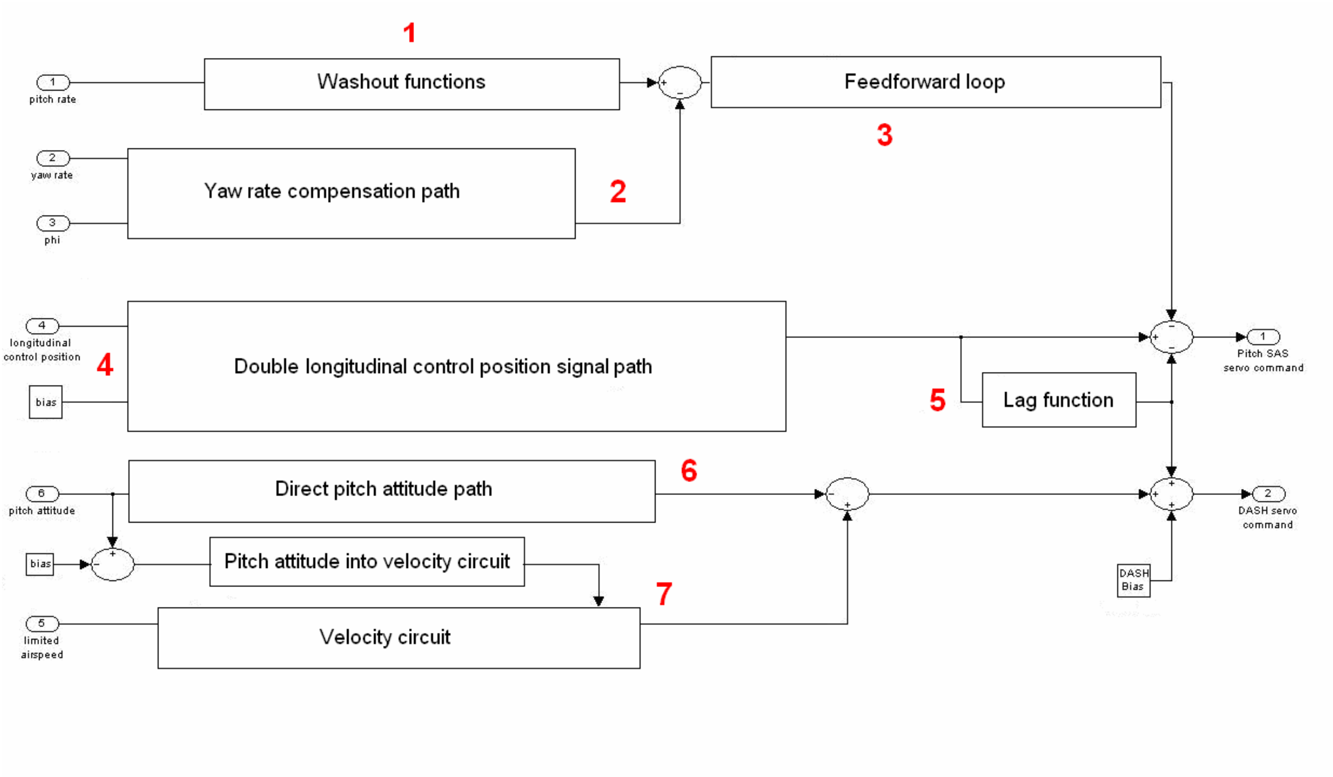


Fig. 5 Pitch control laws for the longitudinal AFCS

Looking at this figure, one can distinguish the various parts of the control laws. Starting with location 1, this is the primary input for the ILCA path: the pitch rate. It passes through washout functions which act like a sink and filter the signal for certain frequencies. These washout transfer functions can be tuned to select a desired filter strength and a frequency that should be eliminated from the signal. Moving to location 2, the filtered pitch rate signal is compensated by the yaw rate and roll attitude, presumable to cater for the effects of the coupling between the longitudinal and lateral flight dynamics. In location 3 the compensated signal passes through a feedforward loop; the combination of a feedback and feedforward loop increase the responsiveness of a system, decreasing the time to return to the desired state after a disturbance. The longitudinal control position (location 4 in the figure) also contributes to the ILCA signal with the purpose of control augmentation. The CPT signals pass via a direct path and high gain path, which incorporates a rate limiter. The rate limiter constricts the appliance of the CPT signal to repress the effects of rapid stick movement, which could otherwise result in overreaction of the system. The direct and rate limited signals are summed and together form the resulting longitudinal CPT signal to be used for the ILCA and DASH actuator. But before the CPT signal reaches the ILCA, it is modified by a special construction involving the regular signal subtracted by the signal that has been filtered by a lag function. Generally, the task of a lag function is to cancel high frequency throughput to prevent saturation. They are defined by the transfer function $\frac{1}{\tau s+1}$ in which τ is the time constant that defines the effectiveness of the filter. The higher the time constant, the better is the capacity of filtering high frequencies. Then at location 5 one can see the washout circuit designed to only produce output during the transient period, cancelling the steady-state throughput. The resulting longitudinal CPT signal not only directs ILCA extension, but also controls the DASH actuator. The signal is supplemented with the pitch attitude that enables pitch attitude hold (location 6). The pitch attitude also works as input for the velocity control circuit in location 7. This velocity control circuit enables the DASH system to provide a positive stick gradient, but also includes feedback and feedforward loops to act on attitude changes caused by gusts.

4. SIMULATING FRONT CABLE FAILURE SCENARIOS

The generic control scheme of Fig. 5 is implemented in the generic tandem helicopter model + load model of ref. 1. Mainly, this model consisting of: 1) an 8 degree-of-freedom (dof) piloted simulation model including the 6-dof rigid body dynamics and quasi-dynamic inflow dof's of both front and rear rotor; 2) a 6-dof pendulum model for external load that could be suspended in two/three points; 3) cables modelled through their spring and damping properties. To fly the helicopter, this model considers PID controllers that generate all control positions. For more detail on this model the reader is referred to [ref. 1].

Next, the initial PID controlled model is replaced with a longitudinal AFCS controlled system, the other inputs remaining still PID controlled. This new model is used to simulate different failure scenarios of the front cable. The following steps are taken to complete a failure scenario with the longitudinal AFCS switched on:

- Calculate the trim state for a desired airspeed;
- Use Bilinear Transformation to map the continuous time transfer functions to the discrete domain;
- Compute the new pilot input value for smooth transition;
- Simulate the first 25 seconds with a full PID control. This is done because when the AFCS is turned on in flight after it has been switched off, or it leaves ground mode, a DASH error signal could exist. This means that DASH actuator operation and the longitudinal stick position are out of sync, requiring a small period of time for the actuator to cancel the error signal after which it is able to resume normal operation. This is done with the Transition Mode of the DASH. Discussions with RNLAF test pilots provided the indication that approximately 25 seconds is a realistic value;
- At 25 seconds, switch to longitudinal AFCS with all other inputs (collective, lateral and pedal) PID controlled;
- At t = 26 seconds, a cable failure will be introduced. The control laws will keep operating, immediately responding to the changing helicopter states.
- From the start of the failure until the specified pilot reaction time of either 0, 1 or 2 seconds, the PID controllers will enter a stick-fixed mode, remaining at the position they were in at $t = t_{failure}$.
- When the reaction time period has expired, the PID controllers will kick in and the simulation will again run in mixed mode until it is finished, covering the same 5 seconds from $t = t_{failure}$ that have been simulated in ref. [1].

A tandem V-shape suspended load is assumed to hang underneath the helicopter so that failure of the front hook means actually failure of the two front cables. It is assumed that if the remaining cables are not strong enough to carry the failed load they will snap and the load will be lost. As sling specifications it is considered that the begin-of-life factor is 7 times the design load and end-of-life strength factor is 4.2. It is assumed that the slings snap when the begin-of-life is reached. As in ref. 1, the following scenarios are considered:

- the load is suspended on two-point or three-point suspension systems. In the three-point suspension the redundant set of slings (between the front and rear hook) come into action when the front cables fail.
- the load can be suspended either in a nose-down position (so-called 'nose-down rigged load') or in a horizontal position (so-called 'level rigged load').
- the helicopter is flying initially in level flight at velocities varying between 10 and 100 kts
- the helicopter can carry three different container of 2 tonnes, 6 tonnes or 10 tonnes.
- the pilot reaction time to failure varies from instantaneously reaction (ideal case) to a delay in response of 1 and 2 seconds.

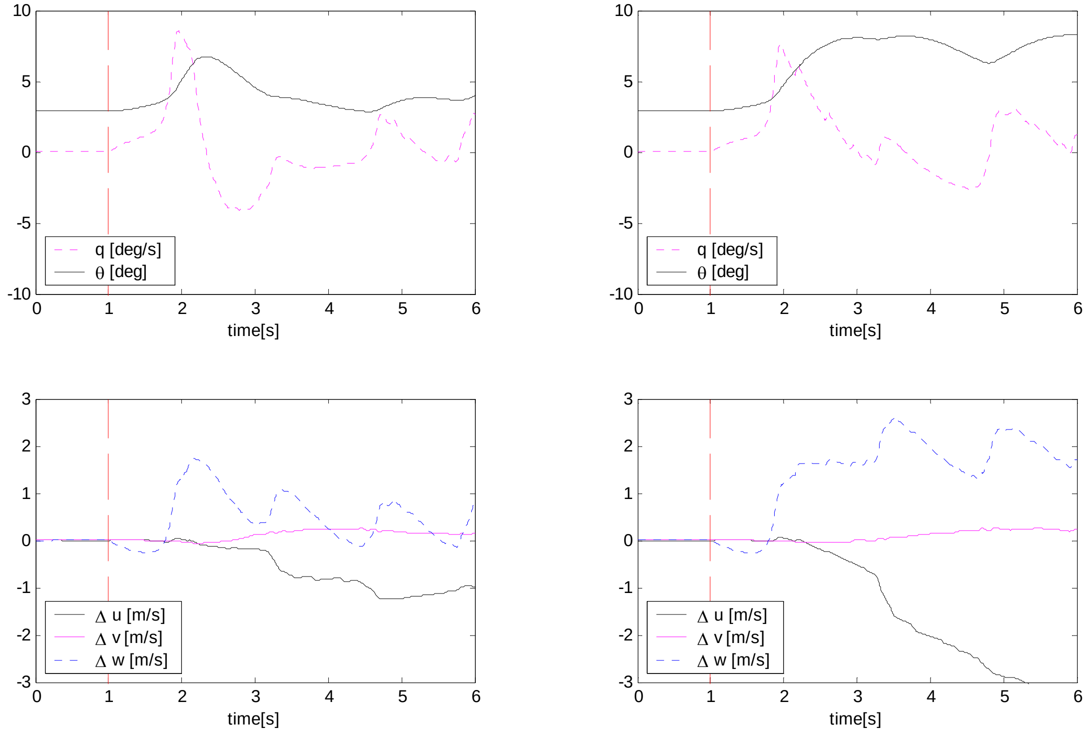
The limits within which the pilot can control the recovery after the load failure are taken from the ADS-33 standard [ref. 4]. Table 1 gives the Level 1 handling limits for large-amplitude attitude changes in hover and low speed flight (<45 kts) for aggressive agility manoeuvres. In forward flight (>45 kts), ADS-33 is qualitative in terms of achievable pitch rate and attitude angle where no limits are given.

Table 1: Level 1 ADS-33 requirements for large-amplitude changes - hover and low speed

Angular rates [deg/s]		Attitude angles [deg]	
p	± 50	ϕ	± 30
q	± 30	θ	± 30
r	± 60		

An example of a typical failure simulation can be seen in Fig. 6 where the helicopter pitch rate, attitude and velocities after a cable failure are given in the case of a PID controlled helicopter (left hand side of the figure) and an AFCS controlled helicopter (right hand side). The case considered is the helicopter flying forward at 50 kts when a front failure occurs with a 2-point suspended load of 2000 kg. It is considered that the pilot PID control will start to react at 1 sec after the front suspension point has failed. The controls remain unchanged from the moment of failure to the moment of pilot reaction (i.e. for 1 second). It is interesting to discuss how the AFCS affects the simulation. While the PID controller is restrained by the pilot reaction time, the AFCS control laws immediately start reacting to the change in helicopter pitch attitude caused by the swinging of the load. This should result in a lower maximum pitch rate, an expectation confirmed by the results. The maximum pitch rate q_{max} of the PID controlled helicopter is equal to 8.6 deg/sec (27th second), whereas the q_{max} resulting from AFCS control comes to 7.6 deg/sec (2nd second), an 11% attitude reduction. Concerning the pitch attitude, one can see that the AFCS controller clearly has trouble to maintain the trimmed pitch attitude, allowing it to increase to 8 degrees. This immediately has its effect on the forward velocity that begins to decline as soon as the pitch angle starts to build up at about 27 seconds. The faltering of the pitch attitude control also has its effect on the vertical velocity, but this is neither vital to the survival of the helicopter nor relevant to the

ADS-33 handling limits. Simulating different scenarios it was observed that the DASH control circuit fails to maintain airspeed when flying faster than 40 kts. Though it appears more and more likely that the implementation of the DASH control circuit does not wholly agree with the real-life situation, the pitch ILCA is still doing its job just as intended, keeping the pitch rate within handling limits and making recovery possible.

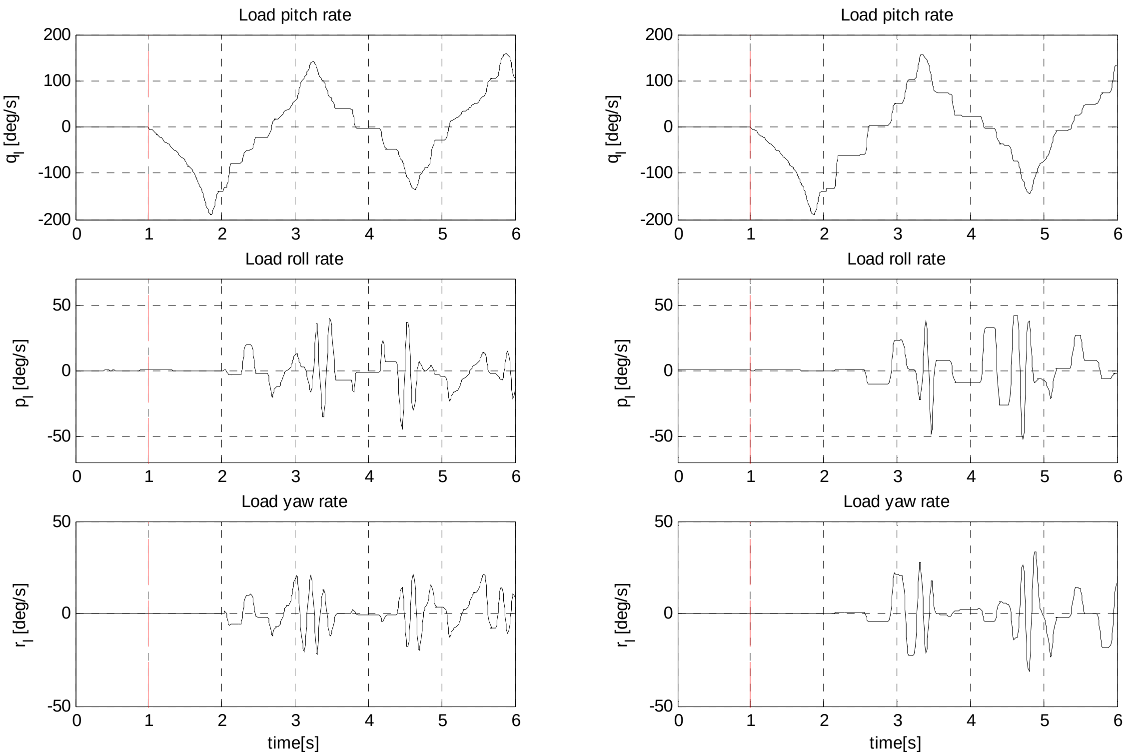


PID controlled AFCS controlled

Fig. 6 Helicopter motion after front suspension load failure, 50kts, two-point suspension, 2 tonne mass load

Fig. 6 clearly shows the advantage of the running AFCS: the pitch ILCA picks up on the increasing pitch rate right after the cable failure, resulting in a lower maximum pitch rate compared to PID control with a one second reaction time delay. The PID controlled pitch rate ranges from -4 to +8 deg/s, the AFCS improves on this with a range of -2.5 to +7.5 deg/s.

The difference in helicopter motions result in a small difference in the way the load swings. But surprisingly, the change is not to be found in the axis in which the controller actually differs. Fig. 7 presents the pitch, roll and yaw motions of the container. Apart from the deviation in shape, the longitudinal AFCS controller causes an increased negative load roll rate and larger overall yaw rate amplitude. The swinging of the load may even result in a destructive collision between the container and helicopter hull before the load can be safely detached. This danger should be investigated in future research.



PID controlled AFCS controlled

Fig. 7 Load motion after front suspension cable failure

5. DEFINING SAFETY ENVELOPES FOR THE LOAD FAILURES

The numerous failure scenarios simulated have been plotted in safety envelopes giving the velocity when recovery was possible as a function of load mass carried. Fig. 8 and Fig. 9 present the envelopes for a two-and respectively three-point suspension level rigged container after the front suspension point failed as a function of pilot reaction time to recover. Two controls are analysed: (a) a PID controller and (b) an AFCS controller. Looking at Fig. 8 one can see that in case of a two-point suspension, the PID control covers a larger envelope area than the partial AFCS control when the pilot reacts instantaneously to the failure (τ = 0 sec). However, in case of a three-point suspension this difference is not present. Fig. 8(b) shows a kind of inverse trend in safety when switching on the AFCS: if the pilot reacts instantaneously to the failure (τ=0 dotted line envelope) he has less chances to recover than if he reacts one second later (τ=1sec point dotted line). This can be explained as follows: the AFCS is actually first attempting to converge to reference (trim) values. If the pilot reacts immediately to the failure, the AFCS has difficulties in combining pilot inputs with own convergence algorithm. But as soon as the circumstances favour the AFCS controller, i.e. the pilot reaction time becomes 1 or 2 seconds, the advantage of its application becomes clear.

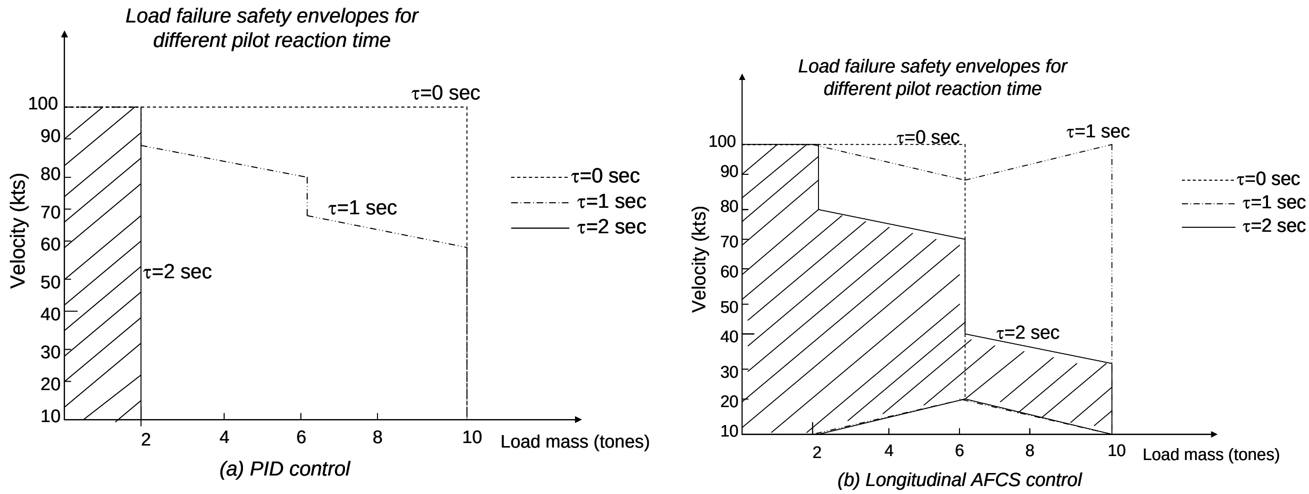


Fig. 8 Safety envelopes for a two-point suspension

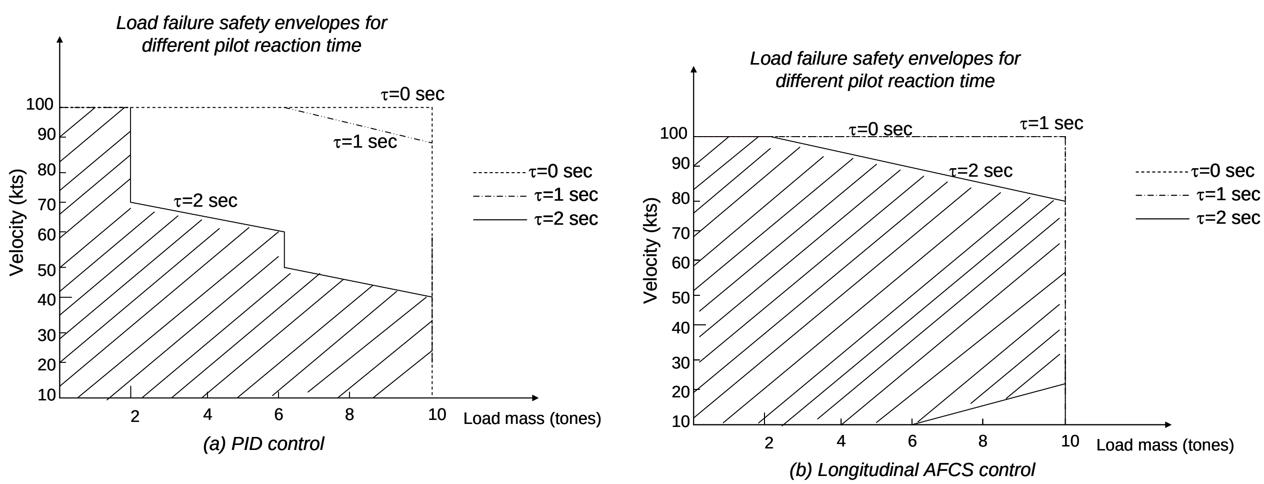


Fig. 9 Safety envelope for a three-point suspension

Especially with a 2 second reaction time the contribution of the AFCS to the helicopter recovery emerges as invaluable. This can be seen when comparing Fig. 8(a) with Fig. 8(b), showing even more than doubling the envelope area when τ=2 sec and when instead of using PID controller the AFCS is switched on. This means that, when compared to a basic PID controlled helicopter, the AFCS is offering a much broader flight regime in which under slung loads can be transported. While the PID only stabilizes the helicopter motions by limiting the rate at which the attitude changes, the AFCS is attempting to converge to trim values.

Comparing the two-point and three-point suspension for an AFCS controlled helicopter (i.e. Fig. 8(b) with Fig. 9(b)) it appears that a three-point suspension is safer. However, this does not mean that the two-point suspension is not safe for a certain condition. For example, if a 6 tone load needs to be transported, one can choose for a two-point suspension with the condition of not exceeding 70 kts in level flight. Above this velocity the chance to recover in case of a load failure is questionable. In case of a 10 tones load, the AFCS for a two-point suspension cannot contribute to the pilot efforts to recover the load if the failure occurs above 30 kts. In this case it is safer to choose a three-point suspension for load transportation.

6. CONCLUSIONS AND FUTURE WORK

The exercise of this paper was to determine how the AFCS influenced the recovery prospects of a Chinook helicopter with an external sling load when one of its cables brakes. This can be of vital importance for deciding whether to replace the safer three-point redundant suspension to a two-point suspension during Royal Netherlands Air Force operations. The paper used the TU Delft generic six degree-of-freedom non-linear model [ref. 1] for the helicopter combined with a 6-dof load model and developed control laws for a longitudinal automatic flight control system (AFCS). The general conclusion that could be drawn was that the assistance of the AFCS expanded the number of occasions at which the helicopter motions stayed within the handling limits during recovery of a cable failure. In many cases, the AFCS cancelled the negative effect of a delayed pilot response, supporting the supposition that the combination of active pilot control and AFCS backup could push the flight envelope boundaries even further. The paper developed safety envelopes covering the areas that define the conditions at which a cable failure at a suspension point could happen without presumable fatal consequences. It was demonstrated that since the longitudinal part of the AFCS was operating continuously, it was not bound by the obstruction of the imposed pilot reaction time. For this reason, partial AFCS control gained an advantage when the pilot reaction was delayed. Flying with a two-point suspension is just as safe as a three-point suspension stipulating that the safety envelope boundaries are obeyed.

The longitudinal AFCS model developed in this paper was implemented with full authority. Therefore, in the future it is planned to consider in the model the limited authority of the actuators. This limited authority may limit the safety envelopes because it introduces additional problems such as actuator saturation possibly leading to premature pilot loss of control and pilot induced oscillations. Also, in the future, the AFCS control laws will be extended to control all helicopter axes.

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