HANDLING QUALITIES EVALUATION OF AN AUTOMATIC SLUNG LOAD STABILISATION SYSTEM FOR THE ACT/FHS

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Abstract

The Handling Qualities (HQs) of a helicopter can be adversely affected through the presence of an externally slung load. Helicopter stability margins may be reduced, due to the additional dynamics of the load system, which can subsequently increase pilot workload, and reduce the operational envelope. An automatic slung load stabilisation system has been designed and has been successfully tested in flight. This system, alongside slung load scenarios, has been implemented within DLRs Air Vehicle Simulator (AVES). In this paper, the results from a simulated test campaign to observe the influence of the stabilisation system on the vehicle HQs are presented. The system is assessed using three Mission Task Elements (MTEs), designed for externally slung load operations. Results show that the conflict between pilot and stabilisation can cause degradation in HQs. However, it is shown that when the stabilisation system is used only “when required”, both the HQs of the helicopter are conserved, and load oscillations are reduced. The results in this paper are intended to motivate future flights tests using DLR’s Active Control Technology / Flying Helicopter Simulator (ACT/FHS).

ABBREVIATIONS

AC	Attitude Command
ACT/FHS	Active Control Technology/Flying Helicopter Simulator
ADS-33	Aeronautical Design Standard 33
ALDS	Automatic Load Damping System
AVES	Air Vehicle Simulator
BMWi	German Federal Ministry of Economics and Energy
BWR	Bedford Workload Rating
CONDUIT	Control Designer's Unified Interface
DLR	The German Aerospace Center
GVE	Good Visual Environment
HALAS	Hubschrauber-Außenlast-Assistenzsystem
HH	Height Hold
HQ	Handling Qualities
HQR	Handling Qualities Rating
LMR	Load Mass Ratio
MTE	Mission Task Element
OFE	Operational Flight Envelope
RASCAL	Rotorcraft Aircrew Systems Concepts Airborne Laboratory
RC	Rate Command
SCAS	Stability and Control Augmentation System
SISAL	Sicherheitsrelevante Systeme und Ansätze in der Luftfahrt
TPD	Task Performance Display

SYMBOLS

$G(s)$	Transfer function
GM	Gain Margin [dB]
J	Non-dimensional characteristic value [-]
K	Proportional gain
L	Cable length [m]
PM	Phase Margin [deg]
T_1, T_2, T_3, T_4	Time constants [s]
s	Laplace parameter
$\dot{\varphi}$	Lat. cable angular rate [rad/s]
$\dot{\vartheta}$	Lon. cable angular rate [rad/s]
ΔMAG	Magnitude notch depth [dB]
δ	Control command [%]

INDICES

C	Cable
lat	Lateral
lon	Longitudinal
max	Maximum
min	Minimum
w	Worst case

1. INTRODUCTION

The transportation of external loads is an important task for rotorcraft. The ability to support external load operations makes rotorcraft beneficial for missions which require the transport of heavy or bulky cargo between remote locations. The use of an external load often means there is no requirement to land during unloading. Whilst this can increase efficiency of operations, it is also beneficial when no suitable landing site can be found.

For these types of missions, the use of a rescue hoist system can be invaluable. However, its use during operations is accompanied by some challenges. The operational advantage of the rescue hoist is that an object from the ground can be collected, and subsequently lifted into the vehicle. This would usually be a requirement during medical evacuation.

Whilst a major advantage of the system is that there is no need to land the aircraft, the disadvantage is that the system requires a lateral offset, to allow the rescued person/collected resource to be lifted into the fuselage. This results in a coupling between the vehicle motion in the yaw axis and the load motion [1]. Furthermore, the load motion is more restricted than the equivalent centrally loaded system. If the load starts to swing, contact to the landing skids must be avoided, to prevent damage to the hoist cable. Therefore, during operations, the hoist operator is required to guide the cable with his/her hands and/or feet, whilst standing on the landing skids (see Figure 1). Additionally s/he is required to give commands, as the pilot has no direct view on the load. This is particularly true during load set-down operations, so that the load can be safely placed within the intended target area. Furthermore, the hoist operator is responsible to swivel in and out the hoist and to control the cable reel in and out. All these tasks together in combination with the exposed position, standing at the open door or on the landing skids, can result in high workload for the hoist operator.

The vehicle and slung load become a coupled multi-body system. The motion of the vehicle is affected by the motion of the slung load system, and vice-versa. For this reason, it is important that the pilot maintains control over the slung load system. Lightly damped or unstable pendulum motion can occur, dependent upon numerous factors including cable length, load and aircraft mass, and flight speed. Therefore, in some instances, it can be difficult to ascertain if, and when, this instability will occur.

Figure 1: ACT/FHS in flight test with externally slung load and rescue hoist

In order to improve load stability several stabilisation methods have been proposed. The aim of these systems is to reduce the required workload of the pilot during external load operations, through the use of manipulation of the load motion. The methods artificially improve the dynamic stability of the helicopter slung load coupled system. Ivler et al. [2] classified these methods into two main categories: the direct (or on load-control mechanism) and the indirect control mechanism. The direct control mechanism generates control forces or moments directly at the slung load to improve load damping. This is independent from the motion of the helicopter fuselage. The indirect approach controls the load through displacements and rotations of the helicopter. In order to achieve this, characteristics of the load motion are usually fed to the helicopters control system. In Reference [3], the direct and indirect stabilisation methods were compared, where it was found that indirect slung load stabilisation methods are more robust in their effectiveness in controlling different types of load configurations.

This paper focuses on the load stabilisation system using the indirect control method, for the case of an externally mounted rescue hoist system. The concept of indirect slung load control was first considered in the early 1970s. In References [4] and [5], the damping of the slung load pendulum motion was improved through variations in the attitude of the helicopter. In Reference [6], load stabilisation was extended through the addition of independently controlled winches and a pivoting cargo hook. Early experimental in-flight demonstrations of indirect load stabilisation systems are documented in References [7-8] for the Boeing Vertol 347 helicopter and in Reference [9] for the K-MAX Unmanned Aerial Vehicle Helicopter. The goal of these previous systems was to improve load stability.

In recent years, the influence of the slung load on Handling Qualities (HQs) has been assessed. Ivler et al. [2] investigated using cable angle and rate feedback for automatic slung load stabilisation of the RASCAL JUH-60 helicopter. The control law design was conducted using CONDUIT [10] and the quantitative external load HQ criteria proposed by Lusardi et al. [11]. During this study, it was concluded that a conflict exists between load stabilisation and vehicle HQs. Cable angle feedback was found to provide better HQs than the cable rate feedback, with the latter providing superior load damping. Patterson et al. [12] extended this research through the design of two different control laws; one for good load damping and one for good HQs. They also designed and tested a first hybrid load stabilisation system where the indirect and direct load stabilisation were combined with the objective to achieve both good load damping and good HQs [13]. Rigsby et al. [14-15] designed a feedback control law for load stabilisation using H_2/H_∞ control methodology. For all the above mentioned systems, Handling Qualities Ratings (HQR) were collected during investigations using Mission Task Elements (MTE).

All methods and related work so far have been conducted for centrally mounted slung load systems. The case of an externally mounted rescue hoist system has, to date, not been scientifically investigated.

The German Aerospace Center (DLR) has previously conducted research regarding slung loads in the FLIGHT DIRECTOR project (2002-2008) and in the HALAS project (2010-2013). In FLIGHT DIRECTOR, a display system for the pilot using slung load measurement was developed and tested in flight [16]. In the HALAS project, an optical-inertial slung load sensor system for rescue hoist operations, alongside a control law for automatic load stabilisation, was developed and tested [1, 17]. Currently, DLR is undertaking the SISAL project (2014-2017), in collaboration with Airbus Helicopters Deutschland GmbH and iMAR Navigation GmbH. One goal of the SISAL project is to design an automatic slung load stabilisation system that considers aspects regarding HQs. The final system is to be demonstrated in flight tests using DLR's ACT/FHS helicopter, equipped with a rescue hoist.

During the HALAS project, the ACT/FHS was equipped with an externally mounted rescue hoist. This integration was supported by Airbus Helicopters. A first control law for automatic load stabilisation of a 100kg load mass and a fixed cable length of 20m has been demonstrated in flight in 2013 [17]. The sensor system, developed in the HALAS project, to measure the load motion is provided by iMAR Navigation GmbH. The sensor delivers lateral and longitudinal cable angles and angular rates in body-fixed and earth-fixed coordinates. Details of the sensor system and its functionalities are discussed in References [1, 17].

In this paper a first methodology for the design of a control law for variable cable length is presented. The extension of the nonlinear real-time simulation in DLR's Air Vehicle Simulator (AVES) to conduct rescue hoist operations is described. The experimental setup and execution of a qualitative HQ study are discussed. Modified MTEs for the case of slung load transportation with an externally mounted rescue hoist are presented. Furthermore, the results of the study are presented and discussed, with demonstrative examples of the utility of the slung load stabilisation system. The paper concludes with an outlook how the system and the build-up infrastructure can be improved for future research.

2. CONTROL LAW DESIGN

During the HALAS project, the control system for damping the load pendulum motion was designed, through the extension of the helicopter's Stability and Control Augmentation System (SCAS) [17]. The extension was realised by a feedback loop of the load motion, using the proposed control law described in Reference [18], which uses lead and lag filter elements in the feedback paths. The parameters of the filter elements were optimised by an automated loop-shaping algorithm, with the main objective to achieve load stability to provide good load damping characteristics. In the current work, this approach has been extended for the application of a variable cable length, and its impact on vehicle HQs has been assessed.

2.1. Model for Control Law Design

A linear six degree of freedom helicopter model, identified using flight test data of the unloaded ACT/FHS, was used for the control law design for hover and low speed [17]. This model is extended by nonlinear terms of the differential equations. Additionally, it is coupled with a nonlinear slung load model. The cable is modelled as a simple massless spring-damper system and the load as a point mass with drag-only force in direction of the airflow [1]. Structural notch filters, limiters of actuator position commands as well as the actuator dynamics are included in the model used for control law design and optimisation. During the first tests of the optical-inertia sensor in 2013, flights data of the slung load dynamics (cable angles and angular rates) were measured using the system. Data has been used for parameter tuning of the slung load model, in the time domain, using several flight test runs.

2.2. Controller Structure

The Automatic Load Damping System (ALDS) is designed to extend the functionalities of the helicopter's SCAS (see Figure 2).

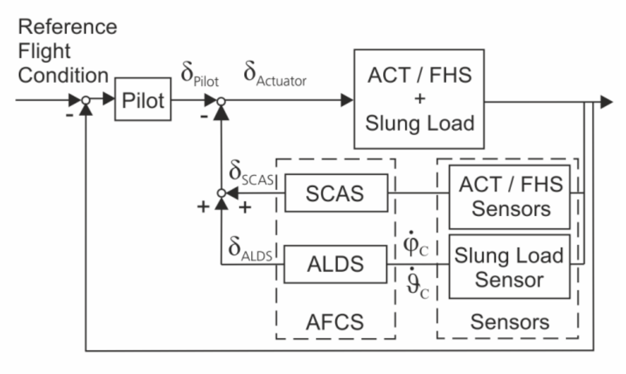


Figure 2: Structure of the control architecture

The SCAS receives signals from the ACT/FHS sensors (e.g. the air data system and the inertial navigation system). To improve the dynamic stability, the angular rates of the helicopter are fed back into the SCAS using proportional and integral control structures in each axis. The proportional and integral gains are adjusted to shape an Attitude Command (AC) in the pitch and roll axes, and a Rate Command (RC) in the yaw and vertical axes. In the vertical axis, a Height Hold (HH) function is also available. The SCAS also includes a filter to suppress the air resonance mode [19]. The optical-inertial slung load sensor delivers the longitudinal and lateral angular cable rates and optionally the cable angles to the slung load damping controller. In the results presented, only angular cable rates in earth-fixed coordinates have been fed back in an additional path parallel to the SCAS. When the ALDS is activated, the controller generates additional actuator commands, which are combined with the commands from the SCAS and the pilot's manual control (see Figure 2).

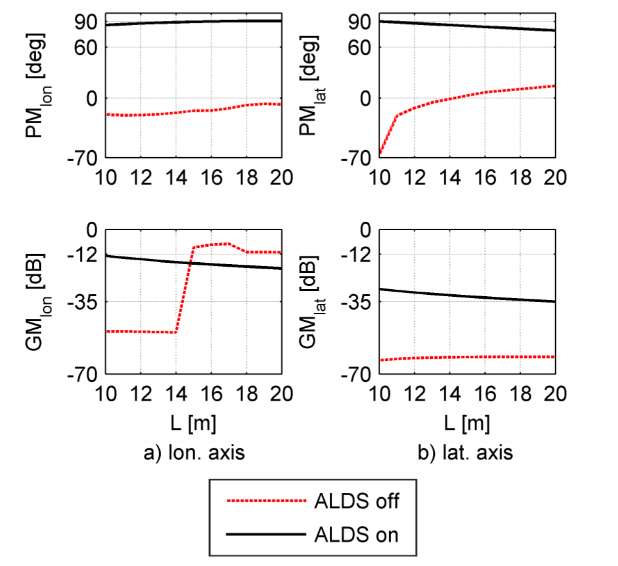
2.3. Design for Variable Cable Length

As mentioned previously, for rescue hoist operations, it is necessary to operate the slung-load system using variable cable length. This is to complete mission tasks required by helicopters using the hoist system. Results from the control law optimisation method used are dependent upon the length of the cable, which in all research to date has been set at a constant value. For this work, a first method of tuning the control law for a variable cable length was completed.

For this first control law design, values were optimised between 10m and 20m cable length. This was due to requirements of MTEs to be investigated. In future optimisation, the full cable range (up to 50m) will be completed.

In the first step of the design, a "worst case" cable length of each axis was identified. The "worst case" cable length refers to the length at which both stability margins, the phase margin (PM) and the gain margin (GM), are the smallest. For this purpose the phase and gain margins of the open-loop frequency responses of cyclic stick input to angular cable rate are calculated for the considered cable length range. A step size of 1m was used.

Figure 3 shows the phase and gain margins plotted over the considered cable length for both axes when the ALDS is "off" and "on". In the longitudinal axis (see Figure 3a), all cable lengths are unstable due to a negative PM. In lateral axis (see Figure 3b), the system becomes unstable for cable lengths which are shorter than 14m (shown through the negative phase margin (PM_{lat}) at this cable length). The jump in the longitudinal gain margin is due to the shape of the phase frequency response (not shown herein). If the cable length changes also the frequency response changes its shape. For longer cables there is a lower frequency -180deg phase crossing resulting in the small gain margins between 15m and 20m. For shorter cable (between 10m and 15m) this lower frequency phase crossing disappears and the phase crossing jumps to higher frequencies what is resulting in higher margins in this cases.



a) lon. axis

b) lat. axis

Figure 3: Phase and gain margins for ALDS "off" and ALDS "on"

In terms of stability, both PM and GM have equal importance. Thus a non-dimensional characteristic value J_w is calculated, weighting both values in the same way. J_w is calculated to find the "worst-case" cable length and is not used as performance index for the later optimisation. The margin values in each axis are normalised using the largest value obtained for the cable range considered. For the sign convention used, a positive phase margin and a negative gain margin represent a stable system. In this respect, PM_{max} and GM_{min} are the optimum phase margin and gain margins respectively. The result of the normalisation is that the largest margin always has a non-dimensional value of unity.

The normalised phase margin (PM_w, see Equation 1), and normalised gain margin (GM_w, see Equation 2), can be added for each axis to calculate the non-dimensional characteristic value, J_w (see Equation 3). The minimum of J_w in the considered cable range indicates the worst case for each axis. For this cable length, the combination of PM and GM is most critical at this point.

(1) $$PM_w = \frac{PM}{PM_{max}}$$

(2) $$GM_w = \frac{GM}{GM_{min}}$$

(3) $$J_w = PM_w + GM_w$$

Figure 4 displays the non-dimensional characteristics values with respect to cable length, and the worst cases (minimum points) found. These are indicated by a marker for both axes. In the longitudinal axis, the worst case is a cable length of 15m, and in the lateral axis the worst case is a cable length of 10m.

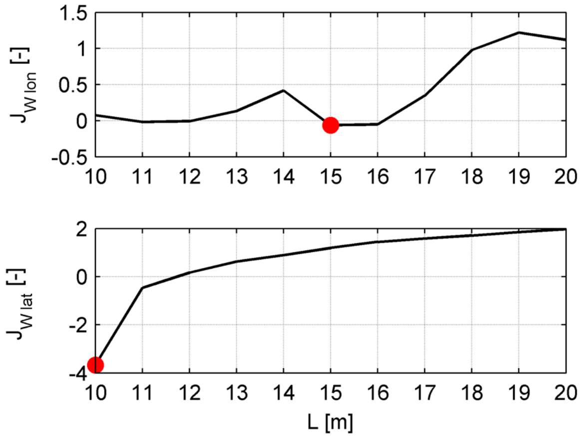


Figure 4: Non-dimensional value for "worst case" selection

2.4. Optimisation Algorithm

The information regarding the most critical cable length is used for the optimisation process. One optimisation is made with a cable length of 10m and one for a 15m case. The resulting parameters of the 10m case are used for the lateral axis and the results of the 15m case for the longitudinal axis. These worst case parameters are later used for the whole cable range considered. This is after it is confirmed that initial specifications (a target phase margin and gain margin) are met for the entire usable cable range (10m-20m).

The main objective of the optimisation process is to satisfy the following requirements:

Phase margin PM: A phase margin between 60deg and 90deg should be reached in order to achieve a stable system and high pendulum damping values [18].

Gain margin GM: A minimum target value of -12dB should be reached, to achieve a robust system with adequate disturbance rejection [18].

The optimisation results are shown in Figure 3 as the ALDS "on" case. As shown, the system meets the requirements in both axes.

The optimisation process is described in detail in Reference [18], and has been used previously during the HALAS project [17]. Brenner used the idea of loop-shaping to design a slung load stabilisation controller. Loop-shaping is used to modify the open-loop frequency responses by using controllers to achieve sufficiently high phase and gain margins. In this case, the frequency responses of interest are longitudinal and lateral stick input to measured pitch and roll cable angular rates respectively. Each axis is optimised and controlled separately, without feedback from cross-coupling dynamics. The controller transfer function $G_{ALDS}(s)$ (see Equation 4) has the same structure in both axes. This transfer function is located in the ALDS block in the feedback path of Figure 2.

(4) $$G_{ALDS}(s) = K\frac{1+T_1 s}{1+T_2 s}\frac{1+T_3 s}{1+T_4 s}$$

Figure 5 and Figure 6 display the performance of the control law in terms of load damping in longitudinal axis for a cable length of 10m and 20m for a 100kg load mass (Load Mass Ratio (LMR) = 0.04) in hover for the simulation model. The load was excited to swing using an impulse stick input. Results show that, for both cable lengths, the load oscillation is efficiently damped by the ALDS.

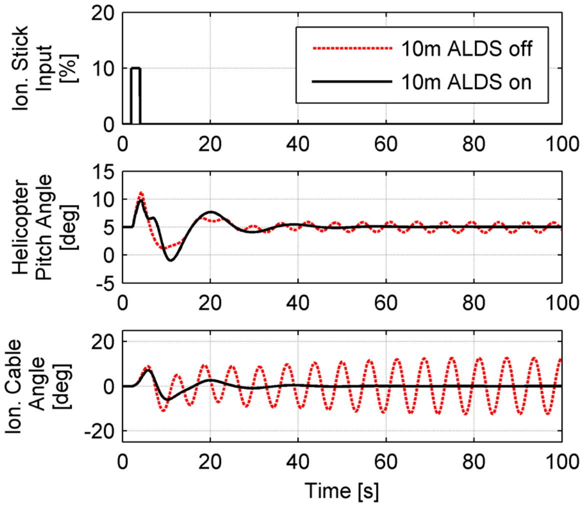


Figure 5: Response to longitudinal stick input 10m cable, Hover

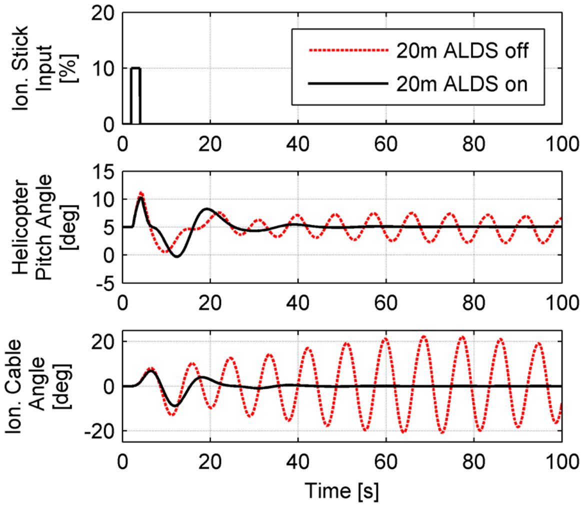


Figure 6: Response to longitudinal stick input 20m cable, Hover

2.5. Predicted Handling Qualities

As the presence of the external load manipulates the frequency response of the vehicle, the ADS-33 bandwidth criteria [20] was not found to be reliable in predicting HQs [11, 21]. During the past decade, novel design criteria have been specifically developed for observation of slung load HQs, some examples include References [11, 21-23]. The most established criterion is the load bandwidth criterion, developed by Lusardi et al. [11]. They discovered that poor HQs correlate with the depth of a notch, which is present in the magnitude response of helicopter attitude due to pilot input. Deeper notches were found to lead to poorer HQs. The depth of the notch (ΔMAG) is measured in comparison to the frequency response of an internally loaded helicopter (see Figure 7). The frequency response data presented here is based on the simulation model used for control law design (see Section 2.1). Load bandwidth is the frequency at which the phase crosses -135deg (due to the presence of the slung load). If the phase does not reach this limit in the frequency region of the slung load, the lowest phase is used to obtain the load bandwidth.

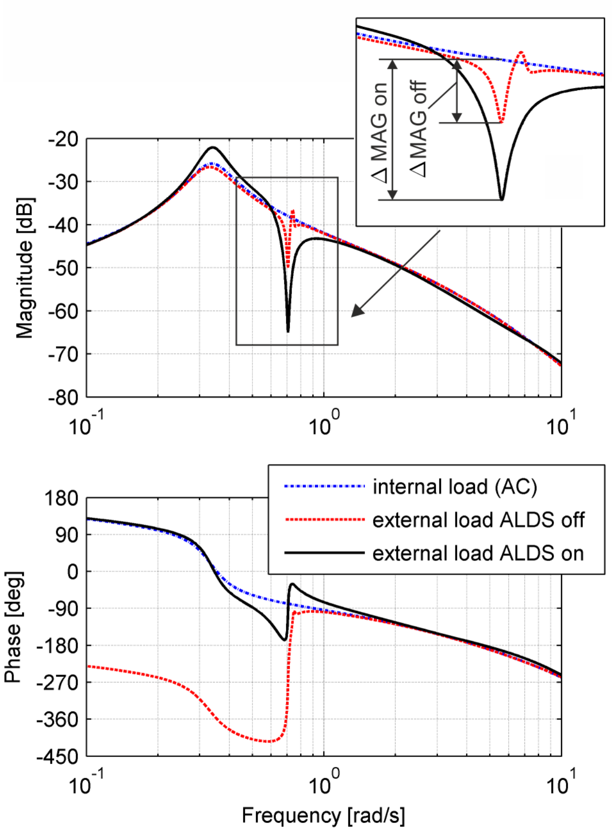


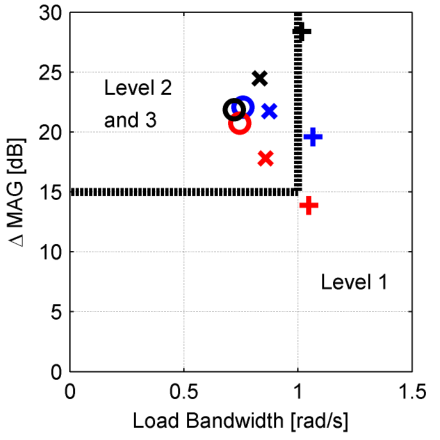
Figure 7: Frequency response longitudinal stick input to pitch attitude, 20m cable, Hover

The criterion was applied to three configurations, used in the simulation study described in the following section. These were the following:

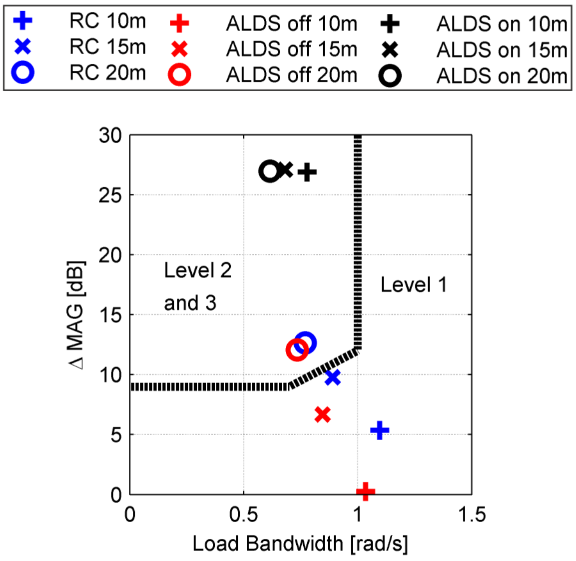
- RC: Rate Command configuration using proportional feedback in pitch, roll and yaw axes. This configuration serves as baseline case for currently operational helicopters, which do not feature highly sophisticated control systems.
- ALDS “off”: Attitude Command (AC) system (described in Section 2.2), with the slung load control ALDS not active.
- ADLS “on”: Attitude Command (AC) system with the ALDS active, to increase the load damping.

The method was applied using three cable lengths (10m, 15m, 20m), to observe how the HQs were predicted to change with different initial cable lengths, and during completion of any manoeuvre where the hoist was used to vary cable length.

Figure 8 shows the results from the application of the criteria, against boundaries presented in Reference [11]. The use of these boundaries should be treated with caution, as they were developed from tests using RC type control systems, and to the author's knowledge have subsequently not been validated for the combinations used in this study. Therefore, here, the results are used for guidance only. Furthermore, the ACT/FHS is a highly modified version of the EC135. For this reason, the data presented here, including the vehicle responses and the predicted and assigned HQRs are not comparable to any helicopter from serial production.



a) Lateral Axis



b) Longitudinal Axis

Figure 8: Slung load handling qualities criterion

The following tendencies were found through the application of the criterion. For all configurations, longer cable length resulted in lower load bandwidth, degrading the predicted HQs. During hoist operations with variable cable length, it is possible that the proposed level boundaries are crossed, suggesting degradation in the HQs. The 20m cable results in the poorest predicted HQs, and therefore is the most critical cable length in this study. The simulator campaign was performed with 20m cable length.

The worst case cable lengths determined from control law design (see Section 2.3) were 10m in lateral direction and 15m in longitudinal direction. The worst case calculation is based on stability margins which are primarily describing load stability. In the slung load HQ criterion, the overall system performance is evaluated. Using this criterion the helicopter response to a stick input is indirectly considered by ΔMAG and impacts the results. Therefore different worst cases can occur in terms of load stability (lateral 10m, longitudinal 15m) and HQs (lateral 20m, longitudinal 20m).

The comparison between the three configurations show slightly better predicted HQs for the AC system (ALDS "off") than for the RC system. One reason is that the notch, identified as a descriptor for HQ degradation, is smaller for the AC system.

When the ALDS is activated, the notch depth increases, subsequently causing further degradation in HQs. This effect supports findings from previous research [24] and is more prominent in the longitudinal axis. This is due to greater effective damping observed in this axis. Figure 7 shows the frequency response data for the longitudinal axis. The figure shows a comparison between the system responses with the ALDS "on" and "off", for the 20m case. The depth of the notch (ΔMAG) in the magnitude is increased when the ALDS is switched on (ΔMAG on > ΔMAG off).

Overall, the results show the expected trends: A trade-off between a desired increase in load damping and an undesirable degradation in HQs. This conflict between good HQs and effective load damping was first discovered and investigated by Ivler et al. [24]. The additional load damping with the ALDS activated, displayed in Figure 5 and Figure 6, causes a deeper notch and resulting in poorer predicted HQs, shown in Figure 8.

To date, the focus of this research has been to increase load damping. With this in mind, the closed-loop HQs have not been treated with importance during design. In the development of the control law, there was no requirement for conservation of HQs. As the research enters the next stage of development, this consideration is now important, and is the reason for the simulated test campaign described in the following section. Within this campaign, some understanding of the utility of the system within closed-loop tasks has been gained. With knowledge of the degradation of HQs during closed-loop tasks, it can be assessed whether:

- The ALDS is sufficient without improvement.
- The system can be used whilst in closed-loop flight tasks, but some improvement to the control loop and/or the optimisation procedure must be made.
- The system is not suitable for closed-loop piloting tasks, and can only be used when the pilot applies open-loop, low frequency control inputs.

3. PILOTED SIMULATION

All results presented within this paper were obtained using DLR's AVES (Figure 9). Opened in 2013, AVES is a reconfigurable research simulator, which features a reproduction of the cockpit of the EC135 ACT/FHS. The simulator features dome visuals, with a 240x93deg field of view [25]. Researchers and pilots use the simulator prior to experimental flight test for preparation and familiarisation. AVES can also be used to conduct piloted simulator test campaigns, as demonstrated in the current work. The advantages of such campaigns include both reduced time and cost, and increased safety. Furthermore, due to the flexibility of the simulator, it is possible to test many more configurations and settings than in-flight. It is not possible to complete an exhaustive database of test points during flight, due to cost and time. For this, the simulator can be used, with the most interesting points and questions investigated further in-flight. This makes the investigation process more efficient and was the primary motivation of the current study.

Figure 9: Air Vehicle Simulator (AVES)

3.1. Nonlinear Real-Time Simulation

The nonlinear real-time simulation of the ACT/FHS is achieved through the use of the model, described in Reference [26]. This model was extended to include the slung load system, modelled as a mass-spring-damper system, with a single point mass, suspended from a single massless cable as described in Reference [1].

Data from the first flight tests, conducted in 2013, were used to tune the slung-load model. This was achieved through the selection of suitable load damping parameters. Using the test data, it was possible to achieve good correlation between the slung-load model and results obtained during flight test. A comparison of the pendulum angles between simulation and flight test data in time domain is shown in Figure 10 for the case of a 100kg load mass and a cable length of 20m.

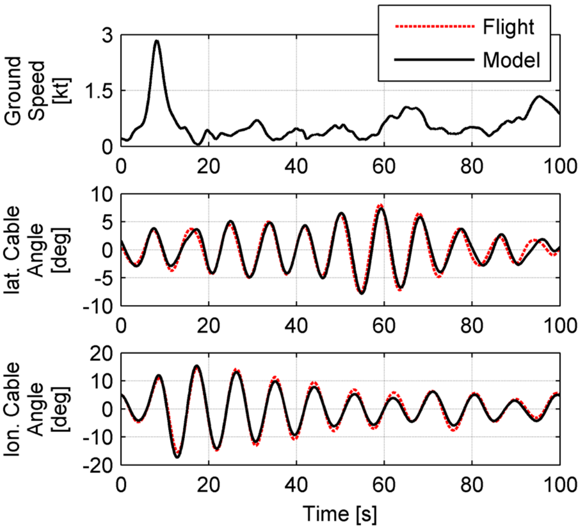


Figure 10: Comparison of pendulum angles between simulation and flight test, Hover, 20m cable, 100kg load

The case shows the pendulum angles following a disturbance from trim condition. The simulated load shows good correlation in terms of both magnitude and the damping of oscillations.

In order to complete MTEs described in Section 4.2, the slung load model was extended to include both ground contact, and variable cable length. Both of these features were implemented in the real-time simulation. The variable cable length was created to allow for two reel-out/reel-in speeds (± 0.5m/s and ± 1.25m/s). A display was used to indicate both the current length of the cable, and the reel-out/reel-in condition (see upper right corner in Figure 11).

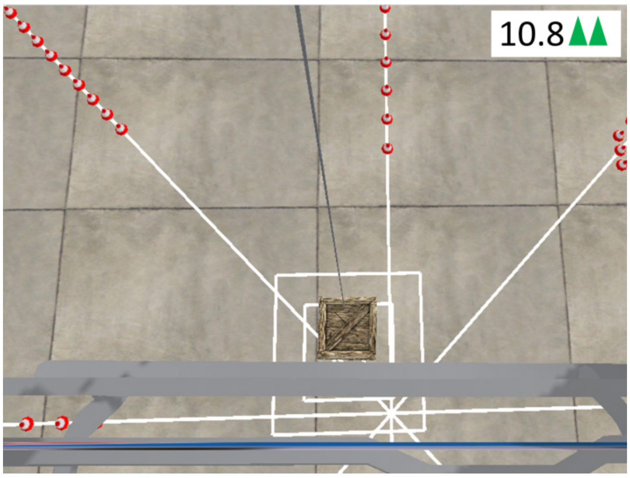


Figure 11: Hoist operator view

3.2. Visualisation

In flight tests, observation of the load is performed by a hoist operator. This is to ensure that the load is within safety limits. When the load is swinging close to acceptable safety limits, or when the load is required to be placed, the hoist operator and the pilot work together to stabilise or position the load. To replicate the view on the load for the hoist operator during the simulated trial, a view on the load was implemented. This view is shown in Figure 11.

4. PILOTED SIMULATION STUDY FOR HANDLING QUALITIES EVALUATION

Important for any novel load control method is its suitability during closed-loop piloting tasks. Such investigations have been conducted previously, with some results discussed in References [2, 12, 15].

4.1. Experimental Set-Up

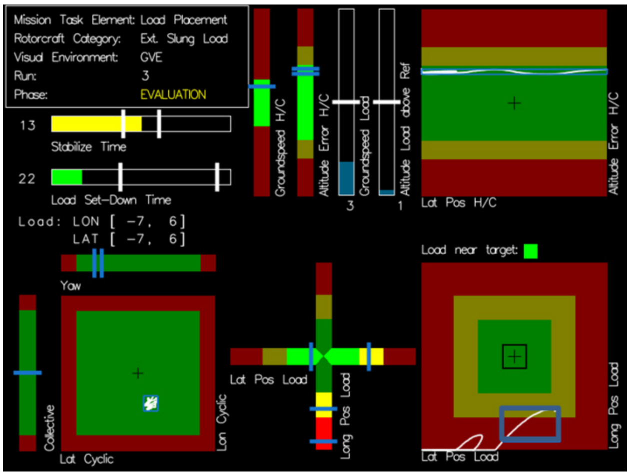
Four configurations were tested during piloted simulation investigations. These are shown in Table 1. These configurations were selected to represent increasing levels of automation and control feedback. Configuration A uses only a RC system. This is similar to the system employed on the majority of helicopters used for current slung load operations. Configuration B features an AC system, which should offer improved stability and reduced agility in comparison to the RC case. Configuration C incorporates the ALDS feedback, but only as an additional function, selectable by the pilot at times when s/he believes that it can be beneficial to the task. Finally, Configuration D offers the highest level of automation, through the use of the ALDS at all times during completion of MTEs.

Table 1: Control law configurations investigated

Conf.	ALDS Feedback	Vehicle Conf.
A	“off”	RC
B	“off”	AC
C	“on-demand”	AC
D	“on”	AC

Three MTEs were selected, which were deemed suitable for slung load operations. These were the Load Placement task, the Depart/Abort and the Slalom. The tasks are described below, alongside any changes that were necessary to make for to ensure safety during slung load operations.

Task Performance Displays (TPD) were developed for all MTEs. These were used to provide immediate feedback to the pilots (and researchers) following each completion of an MTE. This assisted the pilots in ascertaining whether they successfully completed task performance as desired. Figure 12 shows the TPD for the Load Placement task (discussed in Section 4.2).


Mission Task Element: Load Placement
Rotorcraft Category: Ext. Slung Load
Visual Environment: GVE
Run: 3
Phase: EVALUATION

Load: LON [-7, 6]
LAT [-7, 6]

Figure 12: Task Performance Display for Load Placement task

For each TPD, adequate and desired performance standards were shown, with reference to both positional and temporal demands (see the Appendix). Further information was displayed for immediate feedback, such as maximum cable angles and pilot control activity.

During completion of MTEs, the cable angles are displayed to the pilot. According to the flight manual for the ACT/FHS with rescue hoist attached, the cable angles during hoist operations must not exceed ±15deg in all directions.

Four pilots participated in the campaign. Their experience is shown in Table 2. Pilot D was the most experienced pilot, whilst Pilot B has completed the most hours flying both the ACT/FHS and simulators. Pilot B was also involved in the development of modifications to the MTEs used. All pilots had experience flying with external loads.

Table 2: Flying experience of pilots

Pilot	Helicopter (hours)	Simulator (hours)	Slung Load (hours)
A	1600	450	60
B	5400	900	350
C	380	165	30
D	9200	700	200

4.2. Mission Task Elements (MTEs)

To evaluate the ability to position and set-down the load, the recently developed Load Placement task was selected. This is presented in Reference [2]. The task is designed to assess the HQs whilst performing load placement, and was developed from experience using the ADS-33 Hover task [20]. It was found that there was no task that focused on load motions and load operations. Unlike the Hover task, the performance standards are defined by the position of the load. As during set-down, this should not be moving, the pilot is required to maintain a stable hover condition. This position is defined by the visual cueing elements. The environment used for completion of the task is shown in Figure 13.

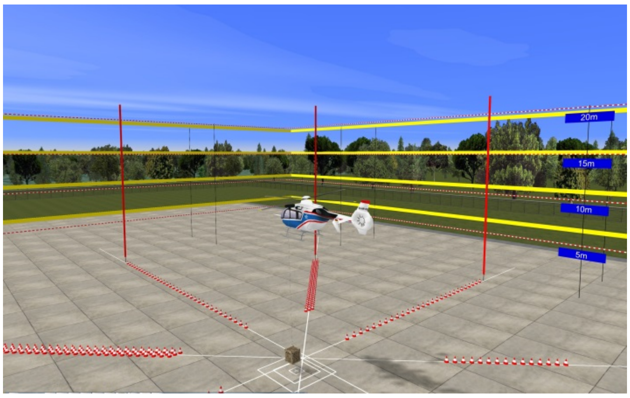


Figure 13: Load Placement task for rescue hoist operations in AVES

During initial evaluation of the task, a number of task performance specifications were found to be ambiguous, and required some clarification. The first was to address the issue of whether the load has “perceptible drift at touchdown”. To assess their ability to place the load, the TPD (see Figure 12) was modified to show the drift of the load when it close to the ground. This is shown by an additional square (see Figure 12, lower right corner, blue square), generated based upon the position of the load when less than 10ft from the ground. The display was shown to the pilot and the hoist operator after each task completion.

In the original task outlined in Reference [2], the load set-down is achieved through a change in helicopter height. For hoist operations, this is not realistic, as the load set-down is achieved through a change in the cable length. Therefore, the task was modified, stating that the helicopter should remain within the same desired and adequate height boundaries throughout the manoeuvre. The hoist operator should ensure that the load is more than 10ft from the ground at all times until a time close to placement. The load position observed when below 10ft is used to determine if the task has been completed to desired or moderate standards (display in lower right of TPD, Figure 12).

To evaluate primarily the longitudinal HQs, a Depart/Abort task was selected. The standards (target speed of 40-50kts and time to complete 30s for desired performance) used for previous completions of the Depart/Abort, contained within ADS-33 [20], were found to lead to unrealistically large cable angles. It was deemed that this level of aggression during initial acceleration and final deceleration would not be suitable in real flight and, as a result, the aggression was significantly reduced. This was achieved by reducing the target speed range, from 40-50 knots, to 15-25 knots and increasing the time to complete the manoeuvre to 40s for desired performance. This reduction in aggression was deemed to represent suitable performance which would be adopted whilst operating the ACT/FHS with the slung load system. The full performance requirements for the task are shown in the Appendix.

To evaluate the lateral HQs, a Slalom task was selected. Like the Depart/Abort, the ADS-33 Slalom was found to be too aggressive, and unrepresentative of performance when operating with externally slung loads suspended on a hoist. In the same way as the Depart/Abort, the aggression was significantly reduced through a reduction of task speed. For this task the performance requirements are shown in the Appendix.

4.3. Results

The following section contains results obtained during the simulated flight test campaign.

4.3.1. Assigned Handling Qualities

Handling Qualities Ratings (HQR) were assigned using the Cooper-Harper Rating scale [27]. The workload experienced by the pilot as well as by the hoist operator were determined by the use of the Bedford Workload Rating (BWR) scale [28]. Both scales have a range of 1 up to 10 in integers. A low numeric value of HQR means good HQs. A low numeric value of BWR corresponds with low workload.

Table 3 and Table 4 display HQRs and BWRs respectively, obtained during the Load Placement task, which was completed by all pilots. For all manoeuvres and configurations, only the qualified test pilots (Pilots A, B, and D) awarded HQR ratings, whilst BWRs were taken from all pilots completing the study. The Depart/Abort and Slalom manoeuvre was completed by Pilots A, B, and C.

For the Load Placement task, BWRs were also awarded by the hoist operators, to observe how the workload was influenced by the presence of the ALDS. These are shown in Table 5.

Figure 14 displays the HQRs awarded, by all pilots and for all tasks. Results are shown with respect to both MTE and configuration. As tasks were completed by a different selection of pilots, results between tasks must be compared cautiously. Importantly, pilots are consistent for each task. Therefore, a comparison can be made regarding the influence of the configuration for each task. Figure 15 displays BWRs awarded by all pilots, for all tasks completed.

Table 3: Cooper-Harper Handling Qualities Ratings awarded

		Configuration			
		A	**B**	**C**	**D**
Load Placement Task	*Pilot A*	5	3	3	7/3
	Pilot B	5	4	3	7
	Pilot D	6	6	5	5
Depart/ Abort	*Pilot A*	4	5	4	4
	Pilot B	7	4	3	3
Slalom	*Pilot A*	4	3	3	3
	Pilot B	7	5	3	4

Table 4: Bedford Workload Ratings awarded by Pilots

		Configuration			
		A	**B**	**C**	**D**
Load Placement Task	*Pilot A*	5	3	4	10/4
	Pilot B	6	3	3	9
	Pilot C	X	4	X	4
	Pilot D	8	7	6	7
Depart/ Abort	*Pilot A*	6	5	5	5
	Pilot B	8	5	4	4
	Pilot C	6	6	6	6
Slalom	*Pilot A*	6	4	5	4
	Pilot B	8	3	3	3
	Pilot C	6	4	6	5

Table 5: Bedford Workload Ratings awarded by hoist operators during the Load Placement task

	Configuration			
	A	**B**	**C**	**D**
Hoist Operator A	6/6	2/2	2/3	10/2/2
Hoist Operator B	5	3/5	2	8/4

As expected, without the ALDS, the AC system was found to lead to better HQs than the RC system. This is due to the increased stability offered by the control system. An increase in HQs was consistently found when using the ALDS “on-demand” (Configuration C). For Configuration C, mean HQRs were found for both the Load Placement and Depart/Abort tasks at the Level 1/2 HQ boundary. This shows that the pilots were able to complete the task to desired performance requirements.

For both the Slalom and Depart/Abort tasks, for the ALDS “on” and “on-demand” cases, there was no major change in awarded HQRs compared to the ALDS “off” cases. This suggests that the ALDS system can be used throughout the completion of the MTEs, causing no degradation in HQs. This is because both tasks can be flown without a tight closed-loop so there is less interference in control inputs and load motion.

For the Load Placement task however, a large spread of HQRs was obtained with the ALDS “on”. This was due to the conflict between the pilot and the ALDS. Ratings were found to vary significantly as conflict was not always found during completion of the task. For a number of runs, no reduction in task performance or an increase in workload was observed. These were usually found to be cases where the hoist operator successfully managed to place the load quickly. However, when the hoist operator could not achieve this, keeping position required to set down the load led to conflict. On one occasion, this was found to lead to a slow divergence, which required the pilot to abandon task. This shows that, for this task, the current ALDS is not acceptable without improvement, and a solution to counteract the conflict must be found. One observation made was that the conflict was caused only by the necessity to make small adjustments to the helicopter position. If the helicopter were to feature a position hold function, it is hypothesised that this conflict would not have been observed.

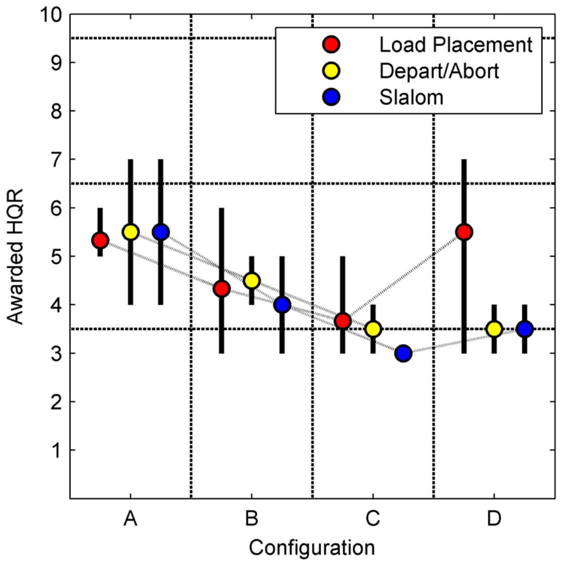


Figure 14: Comparison of HQRs awarded by test pilots during completion of the MTEs

BWRs in Figure 15 were found to reflect the HQRs obtained. For most cases and configurations, as the HQs degraded, the workload was found to increase. One exception was found to be the ALDS "on demand" case. Pilots commented that the use of the system required additional workload, as they were required to decide when to use the system. This was found to cause a slight increase in workload shown through the BWRs.

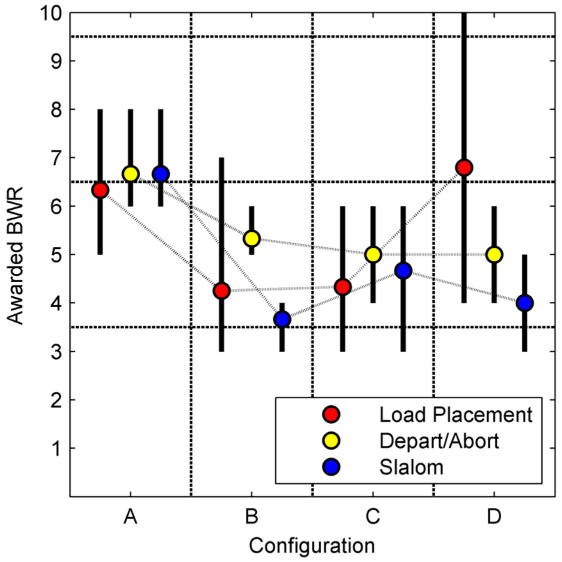


Figure 15: Workload Ratings awarded by all pilots during completion of MTEs

Figure 16 displays a comparison between two cases flown by Pilot A: a case with the ALDS "off" and a case with the ALDS "on". With the ALDS "on", the case shown is one where conflict was not observed.

Results clearly demonstrate the reduction of cable angle amplitude and oscillation achieved by using the ALDS system. Both test runs were completed using the same aggression level (shown by the ground speed), and similar task performance was achieved (shown by the comparison of longitudinal and lateral load position error). However, both lateral and longitudinal cable angles were significantly reduced through completion of the task.

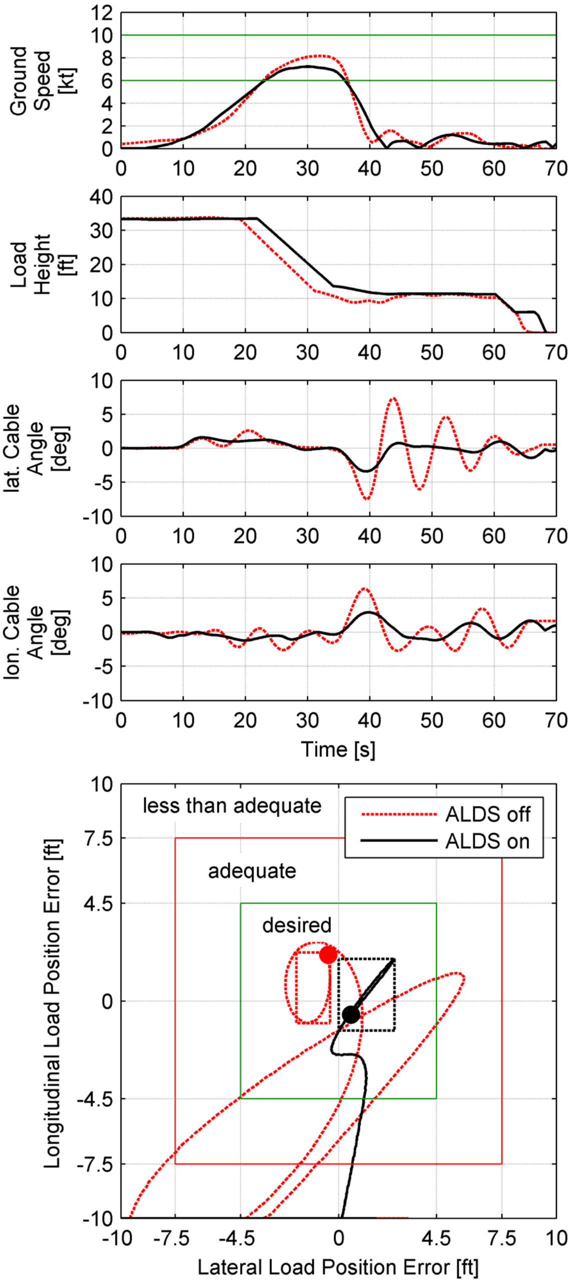


Figure 16: Comparison between cases with ALDS "on" and "off" during Load Placement task

Figure 17 displays an example of results obtained during a completion of the Depart/Abort task, and demonstrates the use of the “on-demand” ALDS. As shown, the ALDS was activated (by the pilot) during the final stages of the manoeuvre. This is the point where the pilot must arrest the deceleration and bring the aircraft to a stop in the desired position. Both runs feature similar velocity profiles (shown by the ground speed). Following the activation of the ALDS, the cable angles were found to be lower than for the equivalent case without the ALDS. For the case without ALDS, lateral cable angle during the approach to hover reached an angle close to 10deg. With the ALDS “on”, this was significantly reduced. At the end of the manoeuvre, after deactivating the system, the pendulum angles were found to increase again.

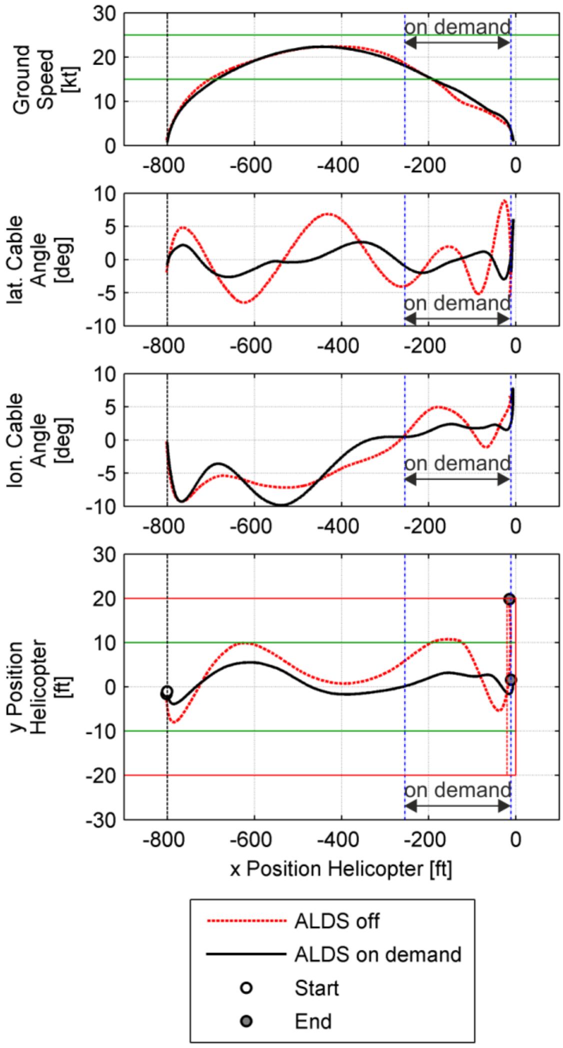


Figure 17: Comparison of ALDS “on-demand” case and ALDS “off” during Depart/Abort

Figure 18 shows an example of the ALDS during completion of the Slalom task. For this task, the ALDS was found to provide a reduction in cable angles and load swing predominantly in the longitudinal axis. Performance, regarding the lateral position and the speed throughout the manoeuvre, appeared to be unaffected by the presence of the feedback system. Without the ALDS, maximum cable angles of ±12deg in lateral and -12deg in longitudinal axes were observed. With the ALDS on, lateral cable angles reduced to ±10deg and longitudinal angle did not exceed -8deg. In the longitudinal axis, the improvement in load damping due to the ALDS was clearly visible. Despite limited effectiveness of the lateral feedback in this task, a reduction in maximum load angle was observed during completion of the task.

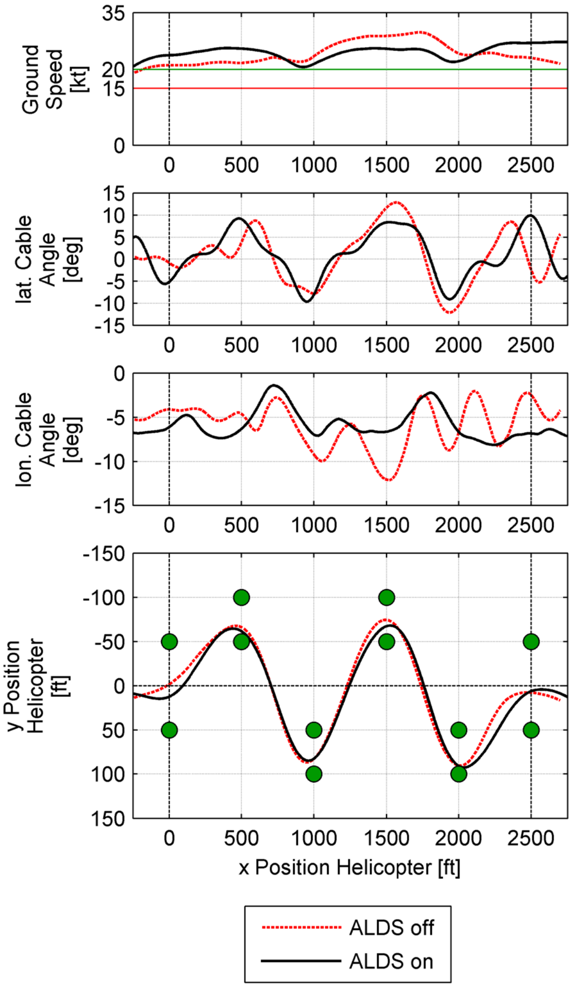


Figure 18: Comparison of cases where ALDS is “off” and “on” during Slalom task

5. DISCUSSION

The results support findings from previous research. However, the findings in the study suggest that, for certain tasks, the indirect load control method can be suitable for use during forward flight tasks. Observations from the simulation campaign are discussed in more detail below.

Function of the ALDS

The main objective of the ALDS is to improve load damping during externally slung load operations. The use of the proposed system is not expected to improve the closed-loop HQs of the vehicle directly. However, if the HQs are not significantly degraded, it means that the ALDS can perform its primary task (stabilising the load) without causing significant negative effects (closed-loop instability).

During the study, it was found that constant engaged ALDS was not optimal for the Load Placement task. HQs were not degraded during Depart/Abort and Slalom tasks. During the Load Placement task, instability was sometimes experienced, showing the conflict between pilot and ALDS. This matches results from previous work shown in References [15, 24].

On-demand system

The use of “on-demand” stabilisation controlled by the pilot was found difficult to evaluate during the selected MTEs. As the pilot was not required to use the stabilisation, and as they have no direct view on the load, the benefit offered by the “on-demand” stabilisation is minimal. If the hoist operator were to operate the stabilisation, it could offer them the chance to actively damp the load when necessary. Consistently, it was found that pilots reported an increase in workload with the “on-demand” system, as they had to think about the best times to operate the system.

Perhaps a more logical use of the system would be to give control to the hoist operator, as it is his/her responsibility to care for the load and to ensure safety. It was shown through BWRs that the hoist operator’s workload during the completions of the manoeuvre with the ALDS “on-demand” was very low, with spare capacity for additional tasks (see Configuration C in Table 5). But a system in which the hoist operator controls the ALDS could cause an increased conflict between the pilot and the ALDS, as they may not fully understand when the system is in use, and how their control inputs will be affected.

Task Suitability

Overall, a large spread of ratings was found when completing the Load Placement task. On inspection, it was revealed that the spread of ratings obtained was a function of the aggression used during the task, despite all runs being completed to the tolerances outlined in Reference [2]. Consistently, Pilot D gave HQRs reflecting poorer HQs than the other pilots. One of the reasons for the poorer ratings was the time pressure the pilot felt during completion of the stabilisation (deceleration) phase of the task. This time pressure was not felt by the other pilots due to the way they flew the deceleration. Figure 19 shows a comparison of typical ground speed trajectories completed by Pilot B and Pilot D (ALDS “on” in both cases).

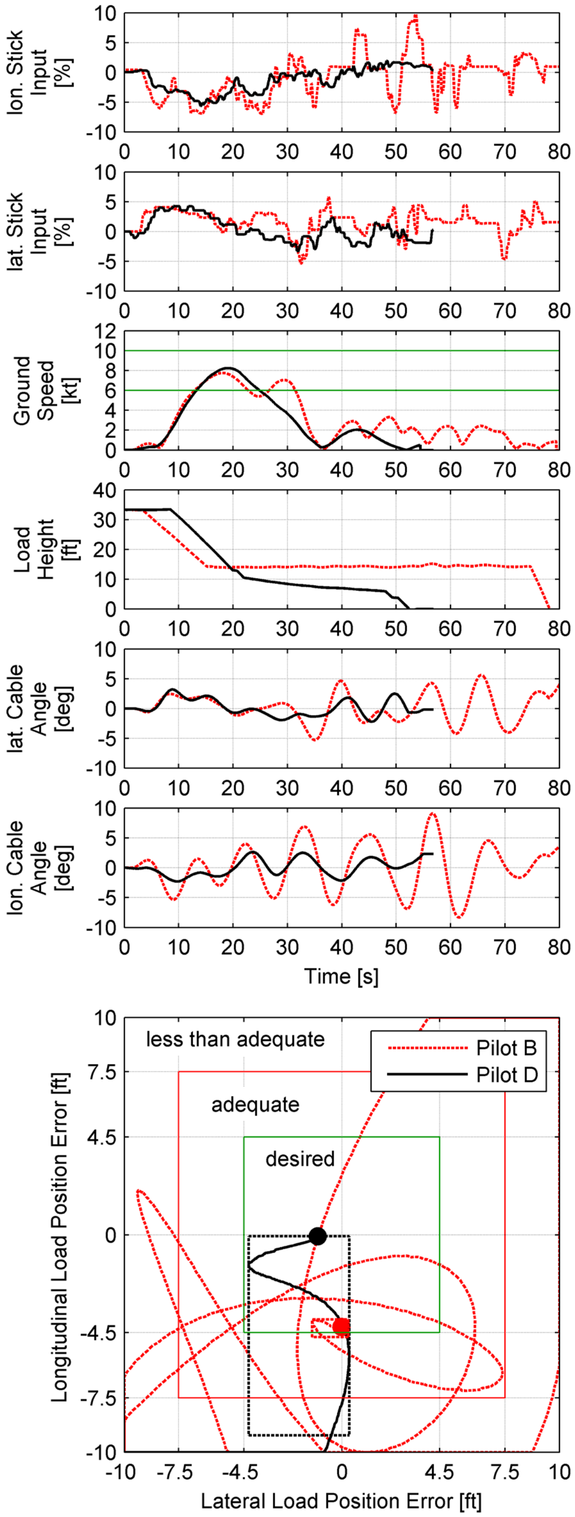


Figure 19: Comparison of flying strategy

The specifications of the task state:

"Initiate the manoeuvre at a ground speed between 6kts and 10kts… Accomplish the transition to hover in one smooth manoeuvre. It is not acceptable to accomplish most of the deceleration well before the load target point and then creep up to the final position" [2].

Therefore, both pilots completed the manoeuvre as required. Pilot D was less willing to excite the load, and therefore approached the task with lower aggression during the deceleration. He followed a low gain control strategy (see stick inputs in Figure 19). The result of this strategy was smaller cable angles in comparison to the high gain control strategy Pilot B used. Furthermore, with the ALDS system "on" Pilot B reached no unstable conflict situation and there was no degradation in HQs.

Results here suggest that, for consistency during slung load tests, the tolerances of the manoeuvre regarding the aggression of the deceleration should be tightened. This could be done by reducing the allowable groundspeed range and by indicating a point on the ground at which the deceleration phase has to be started.

System Effectiveness

Overall, the system demonstrated that it was capable of performing its primary function; to reduce load swing and the overall cable angles during slung load operations. The effectiveness of the system was found to vary depending on pilot strategy, and with regards to the axis of oscillations. Overall, the feedback in the longitudinal axis was more effective than the feedback in the lateral axis. One reason for the reduction of effectiveness could be the optimisation process and the equal treatment of each axis, without consideration for differences in the dynamics, due to the difference in the helicopter inertia.

For the current control law, the design specifications are limited. So far only stability margins are design constrains. For an overall improvement of load damping and HQs, further requirements and design constrains have to be included into the control law optimisation. Additional specifications and constrains could be: the specification of a target load damping ratio and including the slung load handling qualities criterion into the optimisation process.

6. CONCLUSIONS

A piloted simulator study to evaluate the HQs of an automatic slung load stabilisation system for the ACT/FHS equipped with a rescue hoist has been conducted. Three different MTEs (Load Placement, Depart/Abort and Slalom) were used for evaluation. Four pilots and two hoist operators evaluated the system.

The complete experimental campaign set-up, for the external slung load operations using the ACT/FHS, has been replicated into the AVES flight simulator. This includes the ALDS system. Within AVES, visual environments have been configured to allow simulated flight test campaigns to be conducted. This includes the external view of the load, which is necessary for any positioning and set-down tasks.
The ALDS system has been configured using an optimisation process for variable cable length. It was found that the ALDS system reduced the overall cable angles observed during the MTEs, increasing safety margins.

When permanently engaged, the ALDS was found to be unsuitable, in some cases, for completion of the Load Placement task. This was due to the conflict between load control and pilot control. In some cases, the requirement for closed-loop pilot control leads to an unstable pilot-in-the-loop control feedback, and causes failure to achieve repeatable desired performance. This was due to the necessary pilot control inputs to acquire target position.

When the ALDS was applied "on-demand", no degradation in HQs was found during any of the tasks completed. This was partly because that the pilots could decide when to use the system, and there was no requirement for its use. The "on demand" system reduced cable angles, as the permanently engagement of the ALDS did.

Tasks selected were suitable for exploring deficiencies of the ALDS system. Modifications to tasks were found to lead to suitable and realistic task performance, for external load operations. Deficiencies due to the conflict between the ALDS and the pilot were observed during the Load Placement task. However, a large variance in HQRs was found. The task allows the pilots to approach the target position at a constant deceleration, from a speed of 6-10kts. The large variation in aggression of the different pilots during this deceleration caused a wide range of load responses, and led to inconsistent ratings.

7. OUTLOOK

To improve the overall system performance in terms of load damping and HQs, it is hypothesised that more sophisticated optimisation approaches, such as multi objective parametric optimisation methods, should be applied. These approaches should also include appreciation of HQ guidelines.

To prevent the system from causing conflict with the pilot control to keep position, control parameter blending could be a suitable approach. This would limit the authority of the ALDS at low speed, to remove the conflict that was observed during completion of the Load Placement task. Another option could be the implementation of an automatic position hold for the helicopter.

To ensure consistent aggression level and thus comparable performance during the Load Placement task, the tolerances required should be further tightened, by defining a more limited range of applicable groundspeeds or required deceleration.

APPENDIX

In this Appendix, the MTEs and the task performance limits are described.

During completion of MTEs, the crew had the secondary task to maintain the cable angles within the limit of ±15deg in all directions. This limit is extracted from the flight manual for the ACT/FHS with a rescue hoist installed.

All manoeuvres with the exception of the Load Placement task were flown with an external load clearance of 30ft above ground level.

Load Placement

The Load Placement task was developed by Ivler et al. [2]. *"The objectives of the load placement MTE are to check the ability to translate with, stabilise, and set down an external load at a specific location, within a reasonable time limit. In addition, this task checks the ability to set the load down without any residual motion of the load on the ground, such as dragging or swinging" [2].*

Following changes to the task as proposed in Reference [2] have been made for the use with a rescue hoist:

- Maintain altitude within defined limits during the whole task including load set-down
- Use cable reel-out for load set-down
- Keep load within performance limits during cable reel out for the last 10ft above ground

Table 6: Used Load Placement task performance limits

	Desired GVE	Adequate GVE
Attain a controlled hover within X s of initiation of deceleration	10s	15s
Maintain altitude during translation and hover within ±X ft	4ft	6ft
Controlled set-down of external load within X s of hover	50s	120s
Load set-down position should be within a box ±X ft larger than the footprint of the external load on all sides*	3ft	6ft
The load should have no perceptible drift at touchdown	√	-

* Footprint of used load: 3ftx3ft

Depart/Abort

The Depart/Abort MTE is established and defined in the ADS-33 for externally slung load configuration [20]. The most important task objectives are:

"Check pitch axis and heave axis handling qualities during moderately aggressive manoeuvring. Check for undesirable coupling between the longitudinal and lateral-directional axes. With an external load, check for dynamic problems resulting from the external load configuration" [20].

Following changes to the task as proposed in ADS-33 [20] have been made for the use with a rescue hoist:

- Removal of the requirement: *"For rotorcraft that use changes in pitch attitude for airspeed control, a target of approximately 20 degrees of pitch attitude should be used for the acceleration and deceleration" [20].*
- Reduction of target groundspeed:
  40-50kts, new limit:15-25kts
- Increase of time to complete the manoeuvre:
  ADS-33 desired: 30s, new desired: 40s
  ADS-33 adequate: 35s, new adequate: 45s

Table 7: Used Depart/Abort performance limits

	Desired GVE	Adequate GVE
Maintain lateral track within ±X ft	10ft	20ft
Maintain radar altitude below X ft	50ft*	75ft*
Maintain heading within ±X deg	10deg	15deg
Time to complete manoeuvre	40s	45s
Maintain rotor speed within	OFE	OFE

* Altitudes refer to height of external load, measured at hover

Slalom

The Slalom MTE is established and defined in the ADS33 [20] but not for the use with externally slung load configurations. This task was first used in Reference [12] for an evaluation with a slung load configuration. The most important task objectives are: With an external load, check for dynamic problems resulting from the external load configuration. Especially the lateral load oscillation can be exited using this forward flight manoeuvre. *"Check turn coordination for moderately aggressive forward flight manoeuvring. Check for objectionable interaxis coupling during moderately aggressive forward flight manoeuvring [20]".*

Following changes to the task proposed in ADS-33 [20] have been made for the use with a rescue hoist:

- Reduction of airspeed:
  ADS-33 desired: at least 60kt, new desired: at least 20kt
  ADS-33 adequate: at least 40kt, new adequate: at least 15kt

Table 8: Used Slalom performance limits

	Desired GVE	**Adequate GVE**
Maintain an airspeed of at least X knots throughout the course	20kt	15kt
Accomplish manoeuvre below reference altitude of X ft	100ft*	100ft*

* Altitudes refer to height of external load, measured at hover

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