EVALUATION OF A SLUNG LOAD CONTROL SYSTEM FOR PILOTED CARGO OPERATIONS

Daniel Nonnenmacher* and Hyun-Min Kim+

*German Aerospace Center (DLR), Institute of Flight Systems,

Lilienthalplatz 7, 38108 Braunschweig, Germany

Abstract
Helicopter operations with externally slung loads are highly demanding for the flight crew. Without having a direct view on the load, the pilot requires assistance from an additional crew member for load handling to achieve operational requirements (e.g. precise load positioning). An automatic load stabilization and positioning system for cargo operations has been designed with the aim to reduce pilot workload, damp load pendulum motion and to improve the load positioning performance. This system uses the concept of load-motion feedback to the rotor control. To avoid degradation of Handling Qualities (HQs), as found in previous investigations, a function has been developed that monitors pilot control inputs. Dependent on the amplitude and duration of pilot control stick deflection, the feedback signal for slung load damping is blended between two different gain sets. One set provides improved HQs during piloted control and one set provides good load damping when the pilot is passive. A further novel aspect is the evaluation of an automatic load control system using a Translational Rate Command as method of helicopter control. A piloted simulation study has been conducted using this advanced load control system with automatic load stabilization and positioning. Three test pilots evaluated the system in different control law configurations using a Mission Task Element simulating an external load cargo operation. HQs and pilot workload were evaluated using the Cooper-Harper Rating Scale and NASA Task Load Index respectively. The results of the study show that improved HQs in combination with improved task performance can be achieved with the advanced slung load control system.

ABBREVIATIONS

AC	Attitude Command
ACT/FHS	Active Control Technology/Flying Helicopter Simulator
AGL	Above Ground Level
ALCS	Automatic Load Control System
ALDS	Automatic Load Damping System
ALPS	Automatic Load Positioning System
AVES	Air Vehicle Simulator
BMWi	Bundesministerium für Wirtschaft und Energie (German Federal Ministry of Economics and Energy)
BURRO	Broadarea Unmanned Responsive Resupply Operations
CONDUIT	Control Designer's Unified Interface
DLR	Deutsches Zentrum für Luft und Raumfahrt e.V. (German Aerospace Center)
GS	Groundspeed
GVE	Good Visual Environment
HQ	Handling Qualities
HQR	Handling Qualities Rating
LFB	Load Feedback
MTE	Mission Task Element
NASA	National Aeronautics and Space Administration
RC	Rate Command
SISAL	Sicherheitsrelevante Systeme und Ansätze in der Luftfahrt (Safety-relevant systems and approaches in aviation)

+formerly German Aerospace Center (DLR), Institute of Flight Systems

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

TLX	Task Load Index
TRC	Translational Rate Command

SYMBOLS

dx, dy	Long., lat. cyclic stick deflection (%)
dx_L, dy_L	Long., lat. load deflection (m)
$d\Theta$	Pitch angle difference to trim condition (deg)
p, q, r	Body-fixed helicopter angular rates (rad/s)
K_{xL}, K_{yL}	Long., lat. load position gain (m/s/m)
$K_{\vartheta_c}, K_{\varphi_c}$	Long., lat. cable angle gain (m/s/rad)
$K_{\dot{\vartheta}_c}, K_{\dot{\varphi}_c}$	Long., lat. cable rate gain (m/s/rad/s)
T_w	Washout filter time constant (s)
du	Pilot input (%)
V_x, V_y	Long., lat. inertial velocity (m/s)
x_L, y_L	Long., lat. inertial load position (m)
x_{SP}, y_{SP}	Long., lat. inertial suspension point position (m)
Θ, Φ	Pitch, roll attitude (rad)
ϑ_c, φ_c	Long., lat. cable angle (rad)
$\dot{\vartheta}_c, \dot{\varphi}_c$	Long., lat. cable rate (rad/s)

1. INTRODUCTION

Helicopter operations with an external load suspended by a sling are considered high-risk operations as they hold many potential dangers (e.g. mechanical failure, load clearance, reduced flight performance, degraded Handling Qualities (HQs)) and therefore are highly demanding for the whole crew. In general, the pilot has no direct view on the load and has to rely on verbal instructions of crew members or on devices such as a mirror. Particularly, during the load pick-up and set-down, the pilot is exposed to a high workload since the pilot has to stabilize the helicopter in hover and control the load motion simultaneously. It is hard to suppress load swing and at the same time place the load precisely on a target position.

1.1. Slung Load Control Systems

In the past, numerous concepts and systems for improving the control of the lightly damped pendulum motion of an external load have been investigated and tested in flight [2]-[6]. According to Ivler et al. [4], the systems can be classified 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 on the slung load to increase effective load damping (e.g. an active load hook that can be moved relative to the helicopter to damp the load swing). This is independent from the motion of the helicopter fuselage. The indirect approach controls the load through displacements and rotations of the entire helicopter. To achieve this, the load motion is fed back to the rotor control channels. Due to its low system complexity and weight, the concept of feeding back the load motion to the rotor controls was used for external load control in the latest studies.

Several works have been studying the impact of the load dynamics on the piloted handling of the helicopter with a suspended load and how to improve both the HQs and load damping [4]-[6]. Ivler et al. [4] found out that a fundamental trade-off between HQs and load damping exists for indirect control mechanism. Good HQs with an external load can only be achieved at the expense of degraded load damping and vice versa.

Within the Heavy-Lift Helicopter program in the 1970s, a first system for load positioning was developed for the flight demonstrator Boeing Model 347 [8]. The demonstrator was equipped with a retractable cabin for the loadmaster who was sitting rearwards and facing the load. Over an additional control stick, the loadmaster was able to maneuver the helicopter with low control authority. With engaged load stabilization, a precise load positioning could be demonstrated in flight test. In the 1970s the used electronic systems hardware were large, heavy and expensive thus a further development of this technology was stopped. Start of the 2000s the idea of automatic slung load control was rediscovered. Improvements over the last decades in electronic systems hardware allows now a comparatively easy system integration with reduced additional weight.

In the field of unmanned full-size helicopter, the system Broadarea Unmanned Responsive Resupply Operations (BURRO) is able to deliver several cargo loads at different locations even autonomously by flying a programmed course [9]. Only few details about the slung load control are available in the literature [3].

Recent works in the USA have investigated the use of a combination of direct and indirect load control mechanism realized through an active cargo hook and load motion feedback to the rotor controls (Refs. [5], [10], [21]). The active hook adds an additional degree of freedom to the system. The hook can be automatically positioned

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

relative to the helicopter to damp the load swing to some extent (direct control mechanism), in addition to the motion of the helicopter body (indirect control mechanism). Using both control concepts allows HQ and load damping requirements to be met simultaneously. The drawbacks of such hybrid systems are increased take-off-weight and additional system complexity.

The German Aerospace Center (DLR) recently completed the project SISAL ([6], [11], [12]) in collaboration with Airbus Helicopters Deutschland GmbH and iMAR Navigation GmbH. The primary objective of SISAL was the design and evaluation of an Automatic Load Control System (ALCS) based on load motion feedback to the rotor controls for both forms of load suspension: loads suspended from a rescue hoist and a cargo hook. Two functions were developed during the project, the Automatic Load Damping System (ALDS) and Automatic Load Positioning System (ALPS).

During the first flight tests using the ALDS for hoist operations with DLR's research helicopter, ACT/FHS (Active Control Technology/Flying Helicopter Simulator) [6] (see Figure 1), a degradation in pilot handling and load damping was apparent when the pilot was controlling the helicopter with active load control in hover. This control conflict was investigated in a subsequent simulator study [11] with the focus of hoist operations in hover. Without manual pilot control the load damping was successfully demonstrated during the flight tests [6].

Figure 1: ACT/FHS in flight test with rescue hoist

When the pilot was actively controlling the helicopter with the load stabilization engaged, the load motion was not damped but rather got unstable. The cause of this conflict is that to damp the load motion, the load damping controller commands the helicopter to move over the load. At the same time the pilot is trying to hold the position of the helicopter and therefore acting against the load damping controller. Then the helicopter response to the stick input becomes unpredictable for the pilot resulting in degraded HQs.

In this study it was concluded that one solution to resolve the inherent conflict between pilot control and load control in hover is to remove the pilot from the control loop during the load positioning phase. To accomplish this, the ALPS was developed [12]. The ALPS can be activated by the pilot in hover and the load can be automatically positioned over a commanded target position. For the low speed and forward flight, when the pilot is manually controlling the helicopter by his stick inputs, the ALDS provides additional automatic load damping. Both systems combined are the overall ALCS.

1.2. New Research

In 2017, first flight tests were conducted using the ALCS on an Airbus Helicopters H135 prototype machine for a centrally mounted cargo hook configuration. The upper part of Figure 2 shows the hook beam with an integrated slung load sensor, developed by iMAR Navigation GmbH, and the rope marker which are used to measure the slung load motion. In the lower part of Figure 2 the cockpit of the H135 helicopter with experimental slung load display and camera view on the load is shown.

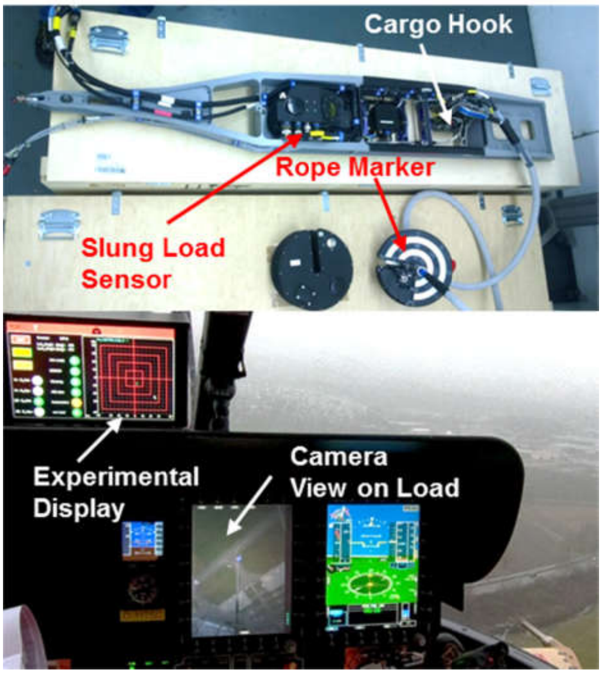

Figure 2: H135 prototype helicopter in flight test with cargo hook and integrated slung load sensor

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

Due to the limited time for testing, the flight tests with the H135 helicopter and ALCS were only the proof of concept for the sensor concept and closed-loop performance of the load control system in a near-serial testbed. Therefore, a comprehensive piloted simulator study using DLR's Air Vehicle Simulator (AVES) was carried out to investigate the performance, benefits and deficiencies of a load control system for piloted operations. The simulator study allowed to test different control systems and to evaluate the system by more than one pilot.

1.3. Paper Objectives

In this paper, an advanced ALCS is presented and evaluated in a piloted simulation study with a simulation model of the ACT/FHS, with a centrally mounted cargo hook.

All the data presented in this paper has been obtained using a simulation model based on the ACT/FHS. The ACT/FHS is a highly modified version of the H135. For this reason, the data presented here, including the vehicle responses and the predicted and assigned Handling Qualities Ratings (HQRs) are not directly comparable to any helicopter from serial production.

Two new aspects regarding the ALCS are presented in this work. First, a function that observes pilot activity during manual control of the helicopter and adjusts the feedback of the load motion in the control law in the way to improve the HQs when automatic load stabilization is active and the pilot is controlling the helicopter. Second, the ALCS is tested in combination with a Translational Rate Command (TRC) mode as basic helicopter control law. The TRC is an upper control law mode which is able to provide very high stability and easy handling of the helicopter in low-speed and hover condition.

Focus of the paper is the design consideration and optimization of the ALCS, and the evaluation of the advanced ALCS in a piloted simulation study. The paper continues as follows: First, control law structures are introduced and the optimization strategy of the ALCS is presented in detail. Afterwards the test set-up for the piloted simulation is explained and the evaluation results are comprehensively discussed. This includes the data analysis of the results in terms of HQRs, workload ratings and quantitative performance data. At the end of the paper conclusions are drawn.

2. CONTROL SYSTEM DESIGN

For the ALCS design, a comprehensive tool chain using CONDUIT was built for the application with DLR's flying testbed ACT/FHS and simulator AVES as described in [12].

2.1. Automatic Load Control

The load control system features the load stabilization system und the load positioning system. The aim of the load stabilization is to increase the damping of the load pendulum motion by reducing the load motion in relation to the helicopter which is described by the angle (ϑ_c) between the load suspension (cable) and the inertial vertical helicopter axis in Figure 3.

During piloted control with automatic load stabilization active, the helicopter motion from the load control can significantly differ from the motion commanded by the pilot which can result in degraded HQs. As suggested by [7], one possible solution is a control system that provides a control mode for piloted handling and automatic handling. This idea has been adopted and applied to the stabilization system presented in this paper.

For precise load handling in hover, an automatic function for load positioning is provided. The aim of load positioning is to bring the load position (x_L) over a defined inertial reference point ($x_{L,ref}$) (see Figure 3).

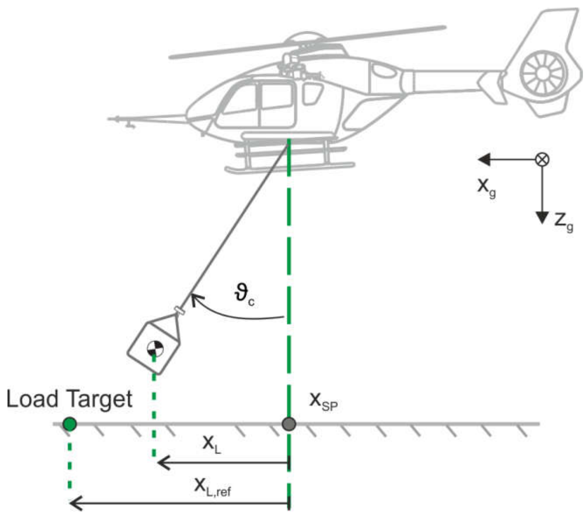

Figure 3: Measured load position x_L and reference load position $x_{L,ref}$ in the longitudinal axis

For this task, the relative load motion with respect to the helicopter must be minimized requiring a stabilization function. The automatic function means that the pilot does not control the helicopter directly but over secondary control

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

inputs (e.g. beep commands). The need for an automatic function for load positioning was motivated by the inherent design conflict between HQs and load control when the pilot controls the helicopter manually and load motion is fed back to the rotor controls. This conflict becomes most apparent during precision maneuver when the pilot tightly closes the control loop as during load handling in hover [11].

2.1.1 Load Stabilization Controller

From the literature [7] it is known that by feeding back the cable angle (ϑ_c, φ_c) and cable rate $(\dot{\vartheta}_c, \dot{\varphi}_c)$, to the rotor controls the damping of the load pendulum motion can be increased effectively. This control strategy uses the helicopter motion in order to damp the load pendulum motion. The ALDS was designed for two different helicopter response types Attitude Command (AC) and TRC. In Figure 4 the controller of the load stabilization is shown.

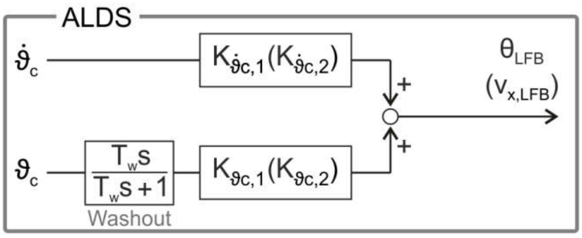

Figure 4: Structure of the load stabilization controller in the pitch axis for the control mode AC (TRC)

The sum of the cable rate and cable angle augmented by static gains $(K_{\dot{\vartheta}_c,1}, K_{\vartheta_c,1})$ form the signal that is fed back to the input signal of the active helicopter mode (i.e. pitch AC). The cable angle signal is processed with a washout filter to eliminate the non-zero steady state during forward flight conditions. In TRC mode different feedback gains $(K_{\dot{\vartheta}_c,2}, K_{\vartheta_c,2})$ are used and the resulting feedback signal is fed back to the velocity command input.

2.1.2 Load Positioning Controller

The load position controller is an extension to the TRC mode and calculates velocity commands to maneuver the helicopter with the load to position the load over the target point. For this task, feeding back the cable angles and rates, which measure the load motion with respect to the helicopter, is not sufficient. Without feedback of a position signal either of the helicopter or the load, load motion feedback causes the helicopter to maneuver over the load to damp the load motion. Therefore, additional feedback of the load position (x_L) with respect to a geodetic reference position $(x_{L,ref})$ is required to minimize the position error (e). The controller of the longitudinal axis is shown in Figure 5. To minimize the position error, the difference between reference and measured load position is fed back with a proportional gain. Feedback of the load motion (i.e. cable angle and cable rate) is needed for stabilizing the helicopter and load modes. The load position (x_L) and cable angle (ϑ_c) are positive when the load is ahead of the helicopter (see Figure 3) so that all feedback signals are summed up forming the command for the velocity loop. The signal of the cable angle is also filtered with a washout filter for steady state compensation. By defining the reference position $(x_{L,ref})$ (see Figure 3), the two functionalities of the ALPS are provided:

• *Load position hold*: By triggering the positioning controller with the default setting for the reference position $(x_{L,ref} = y_{L,ref} = 0)$, the actual position of the load suspension point (x_{SP}) is taken as reference point.

• *Load repositioning:* When commanding a value as reference position, the load is moved from the actual position of the suspension point (x_{SP}) to the target position $(x_{L,ref})$.

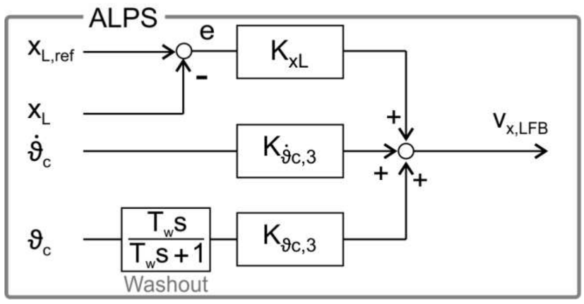

Figure 5: Structure of the load positioning controller in the pitch axis calculating the command of the TRC controller

2.2. Control System Architecture

The ALCS uses a multiloop structure shown in Figure 6. The inner-most loop provides AC in pitch and roll, Rate Command (RC) in yaw and collective (not shown). It is used to stabilize the basic helicopter during manual pilot control. TRC is provided by a loop around the inner-loop with feedback of the inertial velocity in longitudinal and lateral directions calculating attitude commands in pitch and roll, respectively. Load stabilization is provided by the load controller ALDS under piloted control. In AC mode load motion feedback is provided by the load stabilization controller $ALDS_1$. In TRC mode the feedback path of $ALDS_1$ is not active and the feedback path of $ALDS_2$ is closed. The load motion sensor provides the

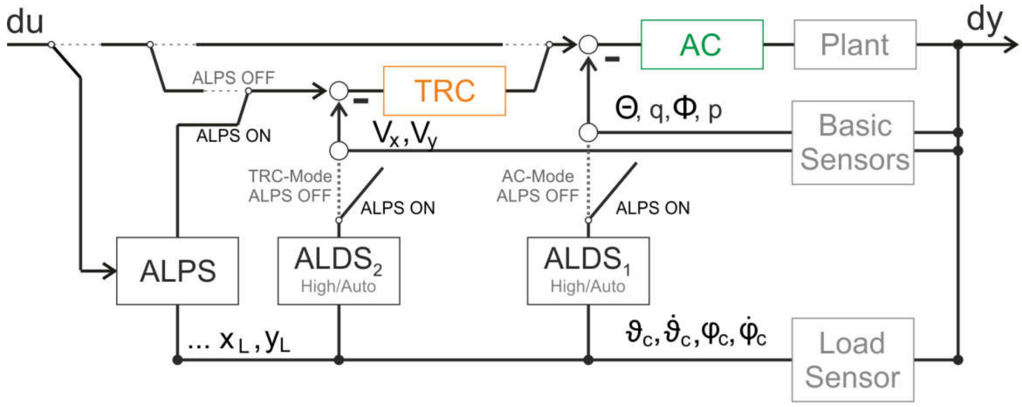

Figure 6: Multiloop control system architecture of the pitch and roll control axes

inertial cable angles (ϑ_c, φ_c) and their rates $(\dot{\vartheta}_c, \dot{\varphi}_c)$.

With the load positioning controller ALPS is active, the feedback paths of the load stabilization are as depicted in Figure 6. When the pilot controls the helicopter in AC or TRC mode by the input du and ALPS is engaged, the pilot is kept out of the control loop and the ALPS controller calculates velocity commands to minimize the error between reference and actual load position. In ALPS mode the input du sets the reference load position (i.e. the target load position). The actual load position in longitudinal and lateral direction (x_L, y_L) is calculated from the cable length and inertial cable angles (ϑ_c, φ_c).

The optimization of the overall control system was performed using CONDUIT [19]. The inner-loop and the velocity loop were designed as augmentation for the bare airframe (the aircraft without slung load).

The inner-loop was designed to meet HQ and flight control requirements, such as piloted bandwidth [16], stability margins [17], and disturbance rejection [18] to achieve predicted Level 1 HQs. The velocity loop providing TRC was optimized with the gains of the inner-loop fixed. Further details regarding the design and optimization of the AC and TRC mode are described in Ref. [12].

2.3. Optimization of the Load Controller Parameters

The control parameters of the ALDS and ALPS controller have been also determined using the multi-objective optimization of CONDUIT. The optimization has been performed for the ALDS controller and ALPS controller separately. From the optimization, three parameter sets were obtained: two parameter sets for ALDS (one set for each helicopter control mode AC and TRC) and one parameter set for ALPS. During the optimization of all three configurations the inner-loop parameters were not defined as design parameters so that they remained fixed. The optimization process in CONDUIT is driven by the design specifications [20].

The specifications used for ALDS and ALPS design are listed in Table 1. The first three specifications are general control design criteria and used for both load controller. They ensure absolute stability of the system and minimum stability margins which are evaluated for the open-loop response at the actuator input of each control axis. The damping specification addresses the minimum damping of the system poles. The low value for the boundary between Level 1 and 2 was defined due to the low damping of the load pendulum modes which are characteristic for a helicopter with slung load, especially in low speed flight conditions [14]. The damping of the load modes can be achieved with load motion feedback but at the cost of reduced damping of the modes associated with the helicopter rigid body motion [7]. Therefore, the boundary for minimum damping was defined at a low value that allows the optimization to find a possible solution.

2.3.1 Optimization of the Slung Load Stabilization Controller (ALDS)

Is ALPS active in hover the pilot is kept out of the control loop and only give commands indirectly by beep commands. As the load stabilization provides load motion damping in low speed and forward flight under piloted control, the conflict between piloted handling and load control had to be accounted for. This was realized by adopting the idea of a task-tailored load control system presented in [4]. From this idea, the concept of switching between different load control modes depending on piloted control has been applied to the load stabilization system of this study. When the pilot controls the helicopter directly by moving

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

the control stick, the load control mode that provides acceptable HQs is active. In this control mode the load damping is less effective as in the control mode that provides highest load damping when the pilot is not controlling the helicopter and no degradation in pilot handlings are apparent.

The two load control modes use different control parameters which are optimized by including the two specifications for ALDS design (see Table 1) in the specification set.

Table 1: Set of design specification used in CONDUIT for the control parameters optimization of the load control system (H-Hard constraint, S-Soft constraint, O-Objective)

CONDUIT Design Specification	Level 1/2 Boundary
EigLcG1: All eigenvalues stable (H) → ensures absolute stability	$\sigma_{min} = 0$
StbMgG1: Gain and phase margin (H) → ensures relative stability	$GM_{min} = 6dB$ $PM_{min} = 45deg$
EigDpG1: Damping ratio (Generic) (S) → addresses the system poles damping	$\zeta_{min} = 0.15$
ALDS design only	
DstPkG1: Disturbance Rejection Peak (S) → addresses load pendulum motion damping	$Peak_{max} = 3 \ldots 12dB$
FrqSLP1: Magnitude Notch (O) → addresses the distortion of the frequency response due to the load motion	Objective → minimize
ALPS design only	
DmpTmG1: Damping Ratio (S) → addresses the damping of the load motion during load positioning	$\zeta_{min} = 0.15 \ldots 0.45$
CrsnMnG1: Minimum Crossover (O) Frequency → addresses the performance of the load positioning	Objective → maximize

The two specifications represent the conflict between HQs and load damping as they are competing design criteria. This means that improvements in one design criteria (e.g. increased load damping) can only be achieved at the cost of the other design criteria (e.g. degraded HQs). The CONDUIT specification 'DstPkG1' which is normally used as design criteria for the disturbance response calculates the maximum magnitude peak of the frequency response between control input and load cable angle (Figure 7, right). In this frequency response the magnitude peak appears at the load pendulum frequency and a low peak value is associated with a high damping of the load motion due to a control input.

The specification 'FrqSLP1' addresses the impact of the load dynamics on the helicopter response and therefore on the HQs. This user-written specification has been adopted from the slung load HQs specification that was presented in [15] and has been used for the design of slung load control systems as in [4] or in [10]. The impact can be characterized by the distortion of the frequency response of the attitude due to a control input (Figure 7, left). The distortion is described by the depth of the notch in the magnitude response and the frequency of the -135 deg crossing or the lowest phase value near the load mode.

The specification 'FrqSLP1' used in this study differs from the original specification as follows:

1. Calculation of the magnitude notch only
   The specification is one dimensional. The depth of the notch in the magnitude response is calculated only. The -135 deg frequency is not taken into account as the influence of the notch depth on the distortion of the attitude response has been found to be higher.

2. No fixed boundary between Level 1/2
   As the notch depth varies with the method of frequency response calculation (e.g. from linear model or system identification), the boundary of the original specification would have been too restrictive for this study.

3. Constraint setting as 'Objective'
   The original specification is used as 'Soft Constraint' which means that the optimization is not driven by this specification. Setting the specification as 'Objective' as in this study, the optimization algorithm tries to achieve a solution with the best possible result for this specification.

The aim of the optimization was to find two designs for the load stabilization controller: one design for good piloted handling with sufficient load damping ('Low Damp' design) and one design for maximal load damping ('High Damp' design).

The optimization process can be described with Figure 7 which shows the calculation of the competing design specifications and the results for the two control designs in the CONDUIT specific HQ plots. To cope with the competing characteristic of the two specifications, the specifi-

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

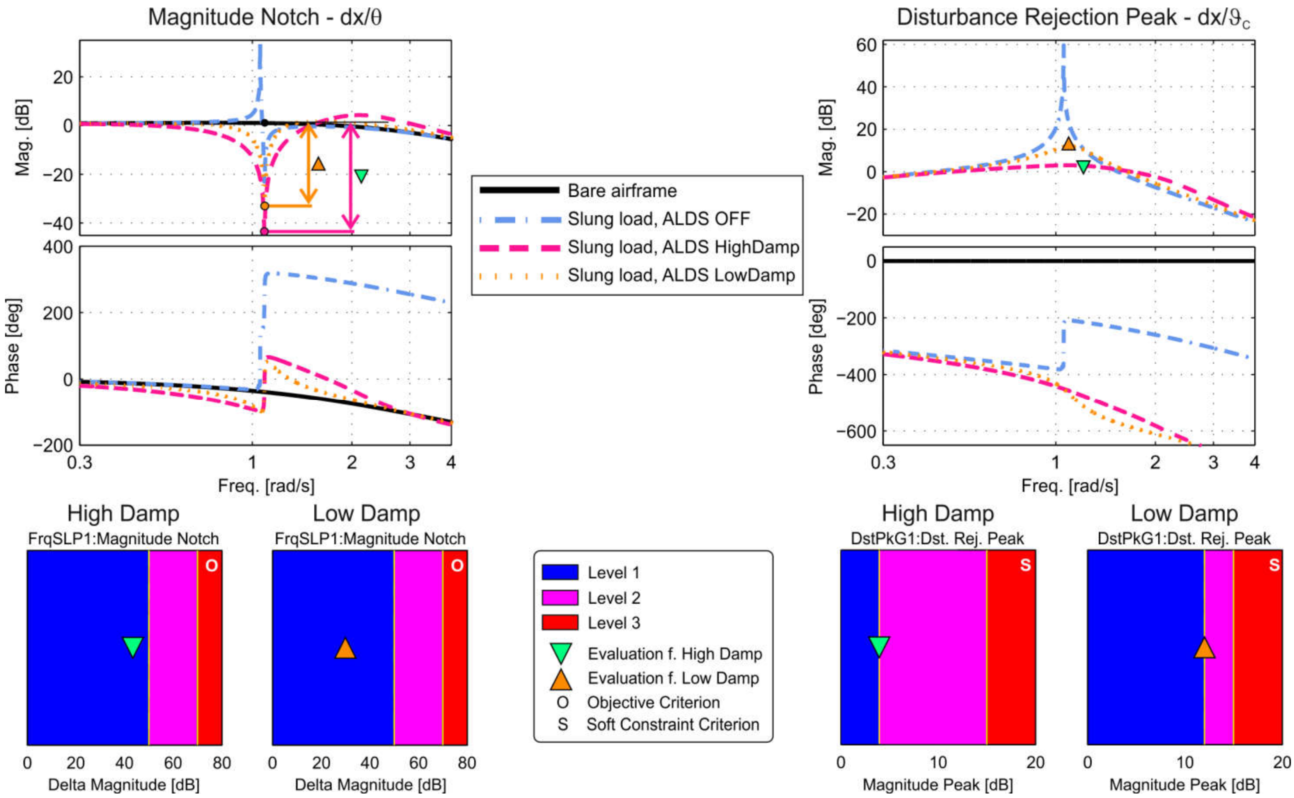

Figure 7: Magnitude notch characterizing the impact of the load on piloted handling ('FrqSLP1') and magnitude peak of the load motion frequency response characterizing load motion damping ('DstPkG1')

cation 'FrqSLP1' (Figure 7, left) was set as objective specification and the specification 'DstPkG1' (Figure 7, right) as soft constraint with varying Level 1/2 boundary. With this setting, the optimization tries to push the result of the specification 'FrqSLP1' as far as possible into the Level 1 region. This means minimizing the magnitude notch depth while ensuring that the results of all other specifications (e.g. 'DstPkG1') are in Level 1. For the 'High Damp' design, the Level 1/2 boundary of the specification 'DstPkG1' was set to 3 dB in order to obtain a design with high load motion damping. As an improvement of 'FrqSLP1' is accompanied by a degradation of 'DstPkG1', the result of the optimization is a design with the best possible solution for 'FrqSLP1' while 'DstPkG1' is just in Level 1 (i.e. on the Level 1/2 boundary). The result for the 'High Damp' design shows an effectively damped load motion response but at the cost of a significant increase in magnitude notch depth compared to the baseline design without load control.

For an improvement in 'FrqSLP1', the restriction of the minimum load damping requirements had to be relaxed by increasing the maximum allowable value of 'DstPkG1' which is realized by shifting the Level 1/2 boundary towards greater values (i.e. 12 dB). This leads to a design with reduced load damping ('Low Damp'). The result of this design shows a less damped load motion (Figure 7, right) but also a less deep magnitude notch (Figure 7, left). It can be expected that the less distorted attitude response of the 'Low Damp' design leads to a better piloted handling with active load feedback. The values for the Level 1/2 boundary of 'DstPkG1' were found after iteration of this value from 0 to 20 dB and analyzing the responses in the attitude and the load motion both in time and frequency domain. The boundaries have been selected on engineer's judgement. 3 dB means high load damping and an acceptable response of the helicopter's attitude. 12 dB means a smaller response of the helicopter attitude and less, but still acceptable, load damping.

2.3.2 Optimization of the Slung Load Positioning Controller (ALPS)

For the optimization of the load positioning control parameters all inner-loops of the bare airframe control were closed and their control parameters held fixed. The feedback path of the stabilization controller was open (see Figure 6). In addition to the three specifications which address general

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

design requirements, two specifications were used for the ALPS design (see Table 1): one specification ('DmpTmG1') that addresses the damping of the response of the load position and one specification ('CrsnMnG1') that addresses the crossover frequency of the load position loop and therefore the performance of the ALPS controller.

In contrast to the design of the load stabilization controller, the damping of the response was calculated in the time domain to ensure that the overshoot in the response is taken into account properly during the optimization. A high damping in the load position is associated with a low overshoot in the response which is desirable for precise load position during load repositioning maneuvers.

The crossover frequency determines the quickness of the load position loop and a high value results in a faster load positioning. Load position damping and crossover frequency are competing design criteria. Either the load is high damped so it takes long to reach the final position without overshooting or the positioning is fast and reaches the final position within a small rise time but overshoots the final position. Therefore, it would not be useful trying to maximize both specifications simultaneously. As a consequence, the damping specification was defined as 'soft constraint' with a minimum damping ratio. The specification for minimum crossover frequency was defined as 'Objective' and therefore the optimization tried to maximize the crossover frequency of the load positioning loop meeting the requirements of all other specifications.

2.3.3 Automatic Load Stabilization - Features and Simulation Results

The switching of the load stabilization control mode between the mode for effective load damping ('High Damp') and piloted handling ('Low Damp') is triggered by the detection if the pilot controls the helicopter actively ('Hands ON') or if the stick is in detent ('Hands OFF'). Pilot action is detected when the control input exceeds the detent position by 2% of the full stick deflection range. Additionally, the stick deflection condition must be met for 1 sec to avoid mode toggling when the stick crosses the detent position during control reversal. If the conditions for 'Hands ON' are detected, the load control parameters of the 'Low Damp' design are active. During the conditions for 'Hands OFF' the parameters of the 'High Damp' design are active. This ALDS control system with the switch between the two load control modes is named as ALDS mode 'AutoDamp'. The switching between the two load control modes for load stabilization is implemented in the control system as an output blending. For the study, the ALDS control mode with the highest possible load damping will be evaluated. Therefore, the ALDS mode 'HighDamp' does not provide the automatic load control mode switch and uses the parameters of the 'High Damp' design only. This configuration is used for comparison reasons.

In Figure 8 the offline simulation results for the load stabilization control in AC mode are presented.

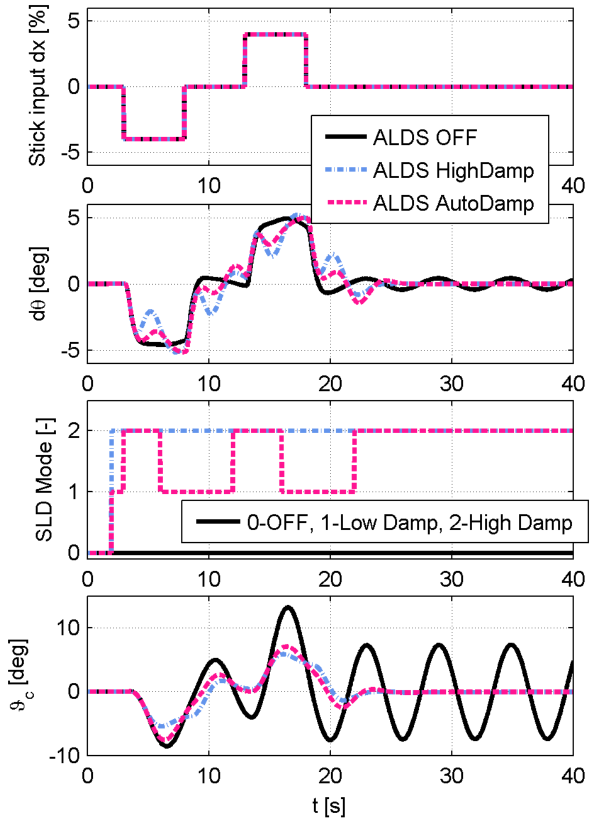

Figure 8: Helicopter response and load motion following a longitudinal doublet input in AC mode for the Automatic Load Stabilization System without (ALDS HighDamp) and with pilot action detection (ALDS AutoDamp)

The automated test input, used as pilot input, is a doublet input. The load pendulum motion is excited. Without ALDS, the helicopter attitude follows the commanded response but an undamped load motion is apparent. With the ALDS mode 'HighDamp', the load motion is damped effectively but at the cost of a highly distorted attitude response. The ALDS mode 'AutoDamp' also shows a distortion of the attitude response but less pronounced. The load damping is slightly reduced compared to the design with maximum damping but still effective. The signal 'SLD Mode' shows the switching of the load control modes. The delay between pilot activity

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

and change of the load control modes occurs due to the conditions of the pilot activity detection and due to the blending process.

2.3.4 Automatic Load Positioning - Features and Simulation Results

The functions of the load positioning system can be explained with the offline simulation results of Figure 9.

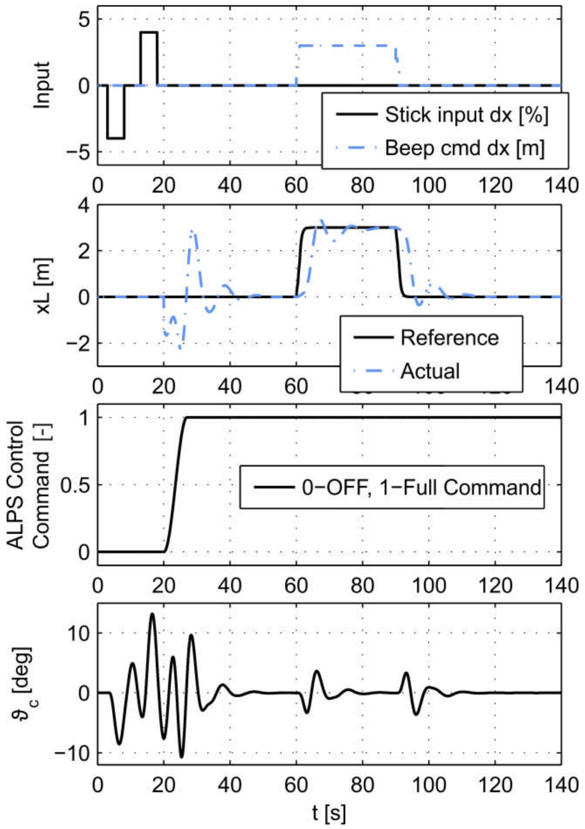

Figure 9: Activation of the Automatic Load Positioning System (ALPS) with load position hold and longitudinal load repositioning maneuver in forward and backwards

Starting in the hover condition the pilot performs a doublet input. The load motion is excited and after 20 seconds. The automatic load positioning is engaged (see 'ALPS Control Command') and the calculation of the load position begins. The ALPS mode starts in the load position hold mode trying to hold the load over the position at the time of engagement. As the change in the signal 'ALPS Control Command' indicates, the load control is engaged with a fading process to prevent an excessive helicopter response due to the control commands of the load positioning controller. The commanded attitude is automatically faded between the commanded attitude value when ALPS is disabled and the commanded attitude value when ALPS is enabled. The fading time is a function of the load motion at the time of engagement and increases with the amplitude of the cable angle. The ALPS controller is fully effective when the fading process is finished. After 60 seconds, the load repositioning manoeuvre is initiated by setting a longitudinal load reference position with the beep command. The load position follows the commanded repositioning in forward direction and at 90 seconds in backward direction in the same manner. With ALPS active, the load pendulum motion is also damped well.

3. PILOTED SIMULATION STUDY

A piloted simulation study was conducted in DLR's Air Vehicle Simulator (AVES) [13] with the advanced ALCS used for the ACT/FHS simulation model with central mounted cargo hook and a load mass of 500 kg and cable length of 10 m. This is a commonly used cable length in cargo operations and a load mass with significant impact on the helicopter.

3.1. Experiment Set-up

Three experimental test pilots evaluated six different control law configurations (see Table 2) using the Load Placement Mission Task Element [4]. AC and TRC without ALCS are the benchmark configurations. Direct comparisons can be made between these configurations with the ALCS designed for high load damping ('SLD_High') and the ALCS configuration with the automatic blending between the two gain sets to improve HQs ('SLD_Auto').

Table 2: Tested control law configurations

Test-Point	Control Law Configuration	Abbreviation
1	AC without ALCS	AC
2	AC with ALCS, High Slung Load Damping	AC+SLD_High
3	AC with ALCS, Auto Slung Load Damping	AC+SLD_Auto
4	TRC without ALCS	TRC
5	TRC with ALCS, High Slung Load Damping	TRC+SLD_High
6	TRC with ALCS, Auto Slung Load Damping	TRC+SLD_Auto

Each experimental test pilot evaluated each configuration. After several training runs with each configuration three evaluation runs for each pilot and configuration have been made to ensure repeatable performance. For each test point 9

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

datasets are available for the performance analysis in Section 4. Tests were conducted in order of Table 2. Starting with the configuration at the top.

The MTE setup in AVES is shown in Figure 10. Figure 11 shows the view from above in a sketch. All relevant task performance parameters for this MTE are given in Table 3.

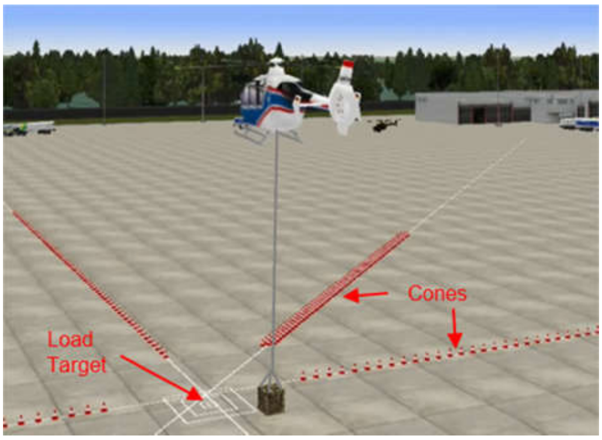

Figure 10: Load Placement MTE in AVES

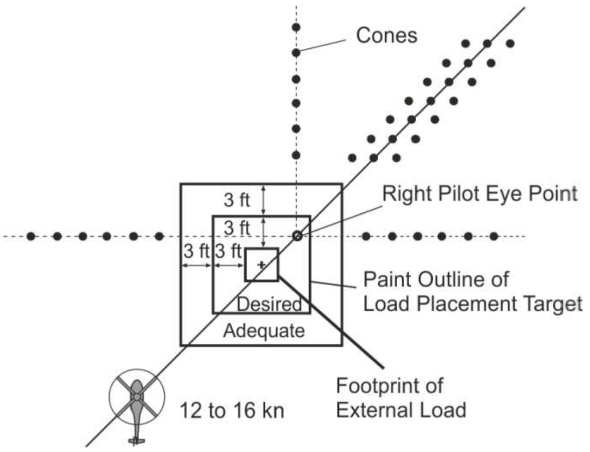

Figure 11: Load Placement MTE, Sketch of load target area

The pilot completes a diagonal maneuver with a defined Groundspeed (GS) (see Figure 11). In the presented study a higher GS was selected (12 - 16 kn) than originally proposed (6 - 10 kn) by Ivler et al. [4]. Latest studies by Bellandi et al. [21] showed that a higher GS is necessary to force a reasonable load swing during the deceleration and stabilization phase of the helicopter. The approach was flown in a height of 50 ft - 60 ft AGL. After deceleration and stabilization of the helicopter the pilot tries to place the load on the target marked on ground (see Figure 10). In contrast to the original manoeuvre the pilot was not instructed by any crew member. A “camera” view of the load (image from simulated visual environment) was shown on the display giving the pilot direct view of the load during the final phase of load positioning.

AVES was operated during the test as a fixed-based simulator. HQs and pilot workload were evaluated using the Cooper-Harper rating scale [22] and NASA Task Load Index (TLX) [23] respectively. Additionally, objective task performance data (e.g. position error and load set-down time) were measured and analyzed.

Table 3: 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	√	-

3.2. Human Machine Interface

In Figure 12 and Figure 13 the human machine interface for the ALCS is shown. Figure 12 shows the pilot’s single display used in the simulation study. The display itself is subdivided in four parts. In the upper right side the primary flight display is shown. Below a camera view with the top view of the load is displayed. This camera view can be provided by the slung load sensor (see Figure 2 sensor for H135) which is also used to measure cable angles and cable rates used in the control laws. In this camera view a marker is visualized on the ground as a red dot. This red dot indicates the position of the cable suspension point (cargo hook or hoist) (see sketch in Figure 12) on the ground. The pilot can use this information as an additional reference. This means he has to bring the red dot directly over the intended load target point in the camera view to position the load. When ALPS is active the pilot can command a load position using a 4-way-switch on the cyclic stick (see Figure 13).

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

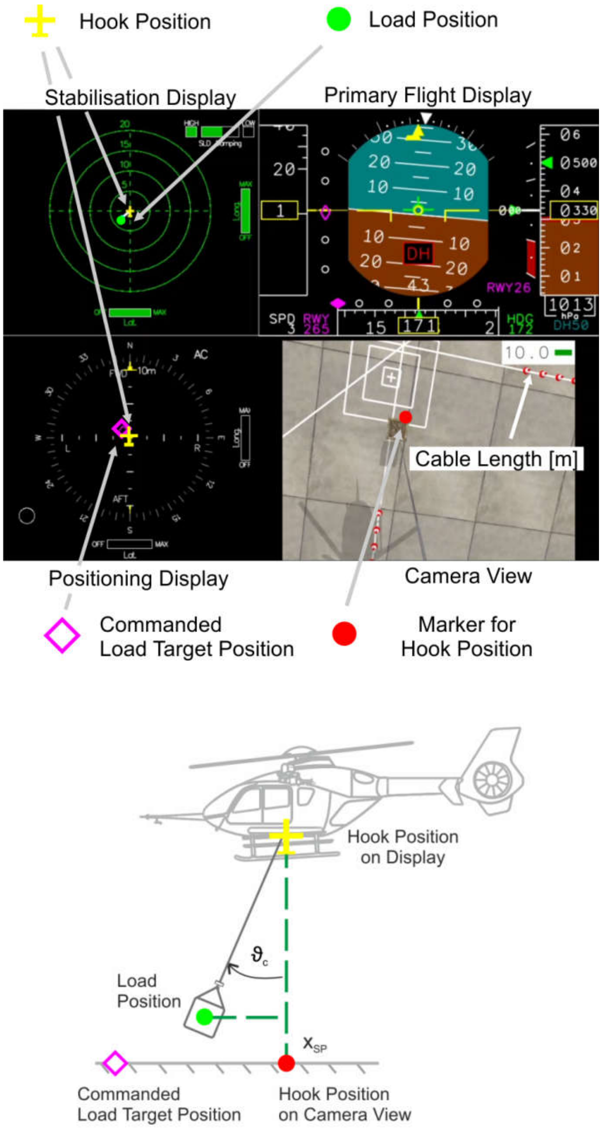

Figure 12: ALCS Display used by the pilots for the Load Placement MTE showing the state of automatic load positioning

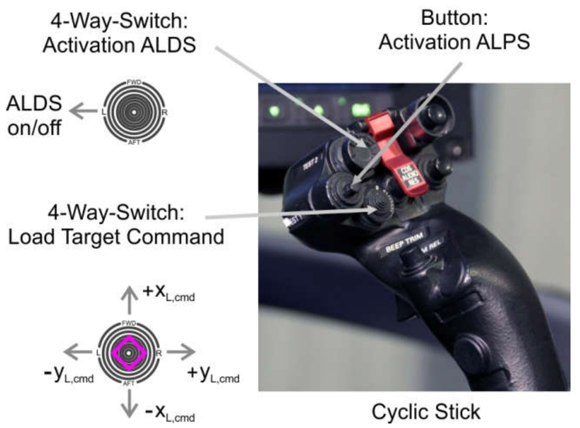

Figure 13: Cyclic stick with switches for ALDS and ALPS activation and 4-way-switch for setting the load position references

The display on the lower left side can be used to observe the automatic positioning process. In this display the commanded load target position and the current position of the cable suspension point is indicated. The upper left display shows the pendulum angle and can be used to observe the performance of the ALDS.

4. RESULTS

In the following sections the results of the piloted simulation study in terms of performance data and HQs related data (e. g. HQRs, pilot workload as well as pilot stick activity) are presented, analyzed and discussed in detail.

4.1. Performance

The completion of the Load Placement Manoeuvre, as shown in Figure 14 and Figure 15 (flown by the same pilot), consists of several phases: Acceleration to a target groundspeed (12 - 16 kn), deceleration to hover, stabilization of the helicopter in hover and afterwards the positioning and set-down of the load. In both figures several markers are used to indicate each phase of the manoeuvre.

In Figure 14 the result of a run in AC mode without ALCS is shown. Caused by the deceleration of the helicopter the slung load starts to swing. The load swing is even slightly unstable in lateral axis. Due to the load swing a precise load positioning was not possible and the pilot could only reach adequate load placement performance. Figure 15 shows a run in AC mode with ALCS active (‘AC+SLD_Auto’) flown by the same pilot. During deceleration of the helicopter the load also starts to swing but now due to the active ALDS the load swing is well damped. Shortly after the helicopter is stabilized in hover, the pilot activated ALPS. In this mode the pilot is now indirectly controlling the helicopter. With the 4-way-switch on the cyclic (see Figure 13) he is commanding the load target position. The objective of the ALPS controller is to minimize the error between commanded load target position and measured load position as best as possible. Figure 15 shows that with ALCS active the load can be precisely positioned on the load target position marked on ground in the MTE (desired performance reached). Additionally, it is important to mention that the final load target position is reached without remarkable load swing.

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

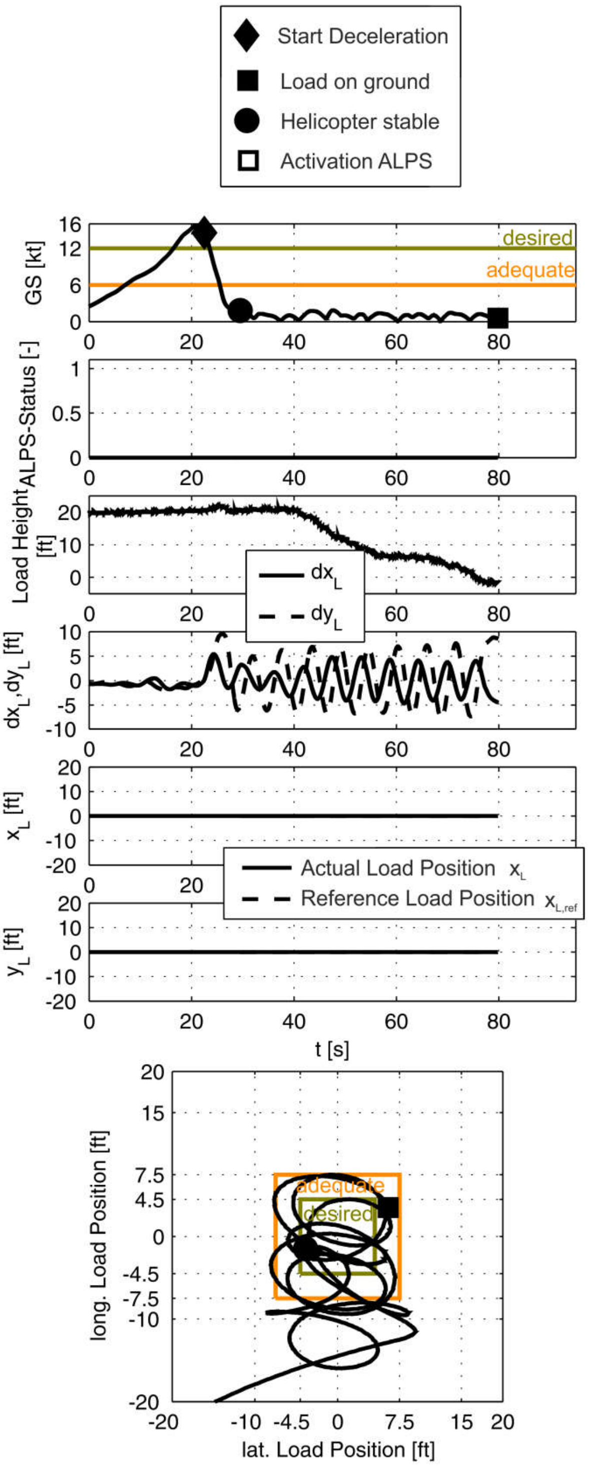

Figure 14: Load placement maneuver, AC mode without ALCS

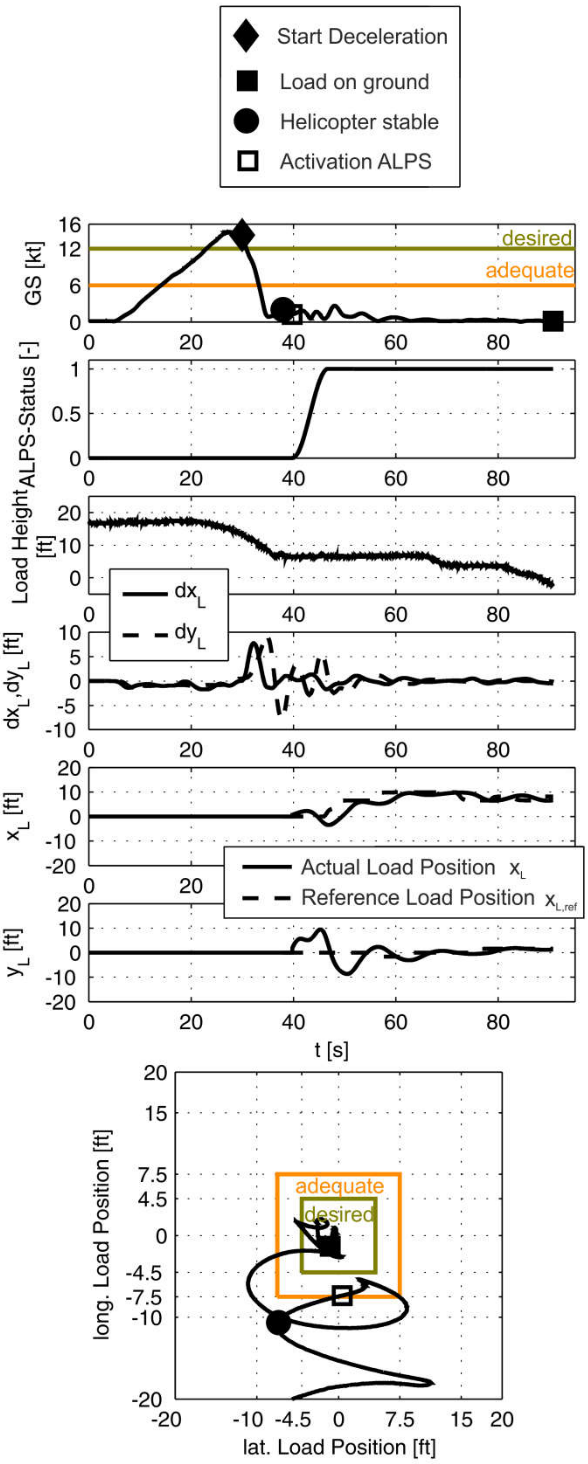

Figure 15: Load placement maneuver, AC mode with ALCS

The performance analysis is based on the load set-down time and the load position error. The load set-down time is defined as the time between reaching a stable hover condition with the helicopter and the moment when the load touches the ground. The position error is defined as the distance between the load target position marking on the ground in the MTE and the actual load position at the end of the manoeuvre.

Figure 16 shows the load position error (mean values and maximum and minimum values) for

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

each control law configuration over all test runs. Figure 17 shows the values for the load set-down time. From the comparison between the mean values of each control law configuration (see Table 2) it can be seen in Figure 16 that a more precise load positioning was possible for configurations with the ALCS active. The load position error is getting smaller and also the scatter in the data is reduced when the ALCS was enabled. Both AC and TRC mode based configurations with ALCS active reached better positioning performance.

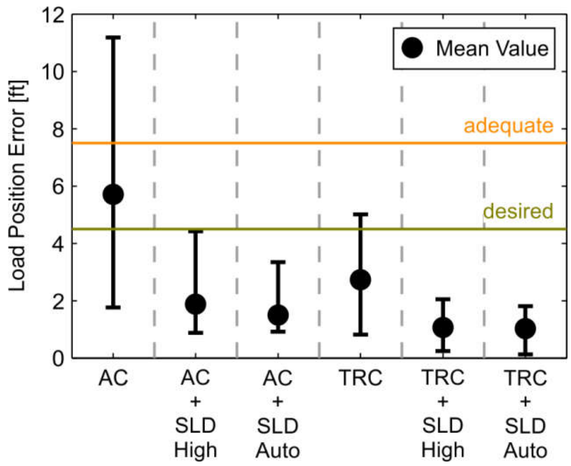

Figure 16: Load position error of all tests

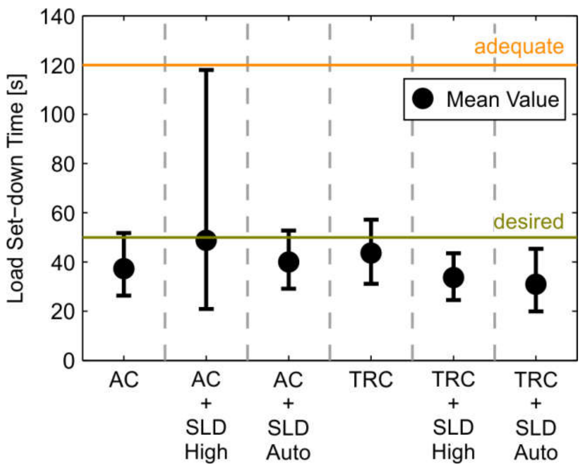

Figure 17: Load set-down time of all tests

Figure 17 shows similar load set-down times for all configurations with a slight trend towards faster load-set down times when using TRC with ALCS functions. In 'AC+SLD_High' mode the load set-down time is higher than with the benchmark configuration AC and the data shows large scatter. This can be explained as follows: In the benchmark configuration AC (without ALCS) the load was swinging nearly undamped. The oscillation was even slightly unstable in lateral direction (see Figure 14). The pilot realized this and tried to set down the load quickly before the situation becomes even more critical thus the pilot accepted a certain load position error. With ALCS active the load is well damped and pilots show the tendency to use the given time defined by the performance limits to improve the load position accuracy. The large scatter in the load set-down time for 'AC+SLD_High' can be explained by the distinctive control conflict between load damping and piloted control inputs before activating the ALPS in hover when the 'AC+SLD_High' mode was used. Best overall performance, this means smallest position error and fastest load set-down, was reached in 'TRC+SLD_Auto' mode. The configurations listed in Table 2 are representing an increasing level of automation from AC (lowest level) to 'TRC+SLD_Auto' (highest level). In Figure 16 it can be seen that a higher level of automation results in improved load positioning performance.

In Figure 18 the normalized load pendulum motion is plotted. Normalized means the load deflection over the overall task is integrated and normalized by the overall manoeuvre time. The normalized load deflection is a quantity used to assess the effectiveness of the load damping during the overall manoeuvre. High values indicate a strongly swinging load during the manoeuvre. Small values mean the load is nearly perpendicular hanging under the helicopter during the entire manoeuvre. The values of each control law configuration and over all test runs are plotted in Figure 18.

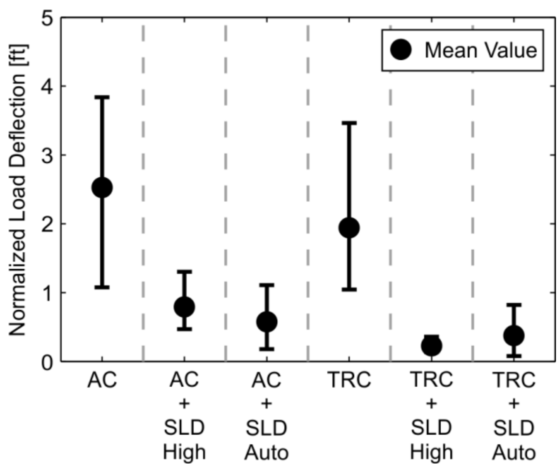

Figure 18: Normalized load deflection of all tests

The comparison of the mean values show a clear improvement of the slung load damping and a reduction in scatter when using ALCS based on both control laws of the helicopter AC and TRC. For 'AC+SLD_High' mode a more effective load damping could be expected. The conflict between piloted control and load stabilization during approach and deceleration phase of the MTE resulted in this case in a higher normalized load deflection.

In Figure 16 a similar trend as in Figure 18 can be observed that means that a higher level of automation is by trend resulting in better load damping performance.

4.2. Handling Qualities Ratings

The HQRs of all three test pilots participated in the study are shown in Figure 19. A comparison of the HQR mean values of the configurations based on the AC mode shows an improvement of HQs with ALCS active ('AC+SLD_High' and 'AC+SLD_Auto'). The 'AC+SLD_Auto' mode clearly improves the HQs in comparison to the 'AC+SLD_High' mode. Overall, the HQRs are located in the Level 2 region.

The mean values show that the configurations based on the TRC mode are rated better or at least the same than the configurations based on the AC mode. One reason for this is that the suspended slung load behaves more stable when the helicopter is operated in the more stable TRC modes (even without ALCS) than in the AC modes (see Figure 18).

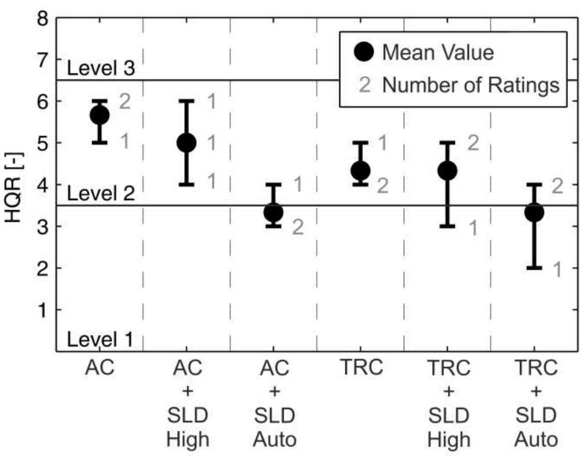

Figure 19: Handling qualities ratings

The test pilots explained in their comments they gave after each evaluation run they would divide the Load Placement Task mentally in two phases and rate each phase individually. The first phase is the approach and deceleration to a stable hover. The second phase begins with the stable hover condition and ends when the load is placed on the ground. Without ALCS active, they would rate the first phase in the Level 1 region but the second phase in the Level 2 region. The reason for this is that the undamped load swing and the lacking capability to dampen the load actively by their control inputs result in low accuracy in load positioning. Finally, the pilots rated the overall task clearly in the Level 2 region.

With ALCS active, the HQRs they mentally assigned for the two subphases would turn around. This means during the first phase, the approach and deceleration, they felt disturbed in their manual control due to the unpredictable helicopter response caused by the load motion feedback to damp the load swing. As a consequence, they would rate the first phase now in the Level 2 region. When ALCS is active they would rate the second phase, when the helicopter has to stay in hover and the load has to be positioned, in the Level 1 region because the load is now well damped and especially ALPS enables an easy and predictable handling with low pilot workload. When the load stabilization mode 'SLD_High' providing most effective load damping was used, pilots felt clearly more affected by the load motion feedback than when they used the load stabilization mode with automatic load control switching 'SLD_Auto'. This result is independent of the underlying helicopter response type AC or TRC.

The comparison in Figure 19 between TRC mode and 'TRC+SLD_High' mode shows that two of three test pilots gave the 'TRC+SLD_High' mode a worse rating. These pilots recognized PIO tendencies in general when they fly in a mode based on TRC. Their comments give hints that the underlying TRC mode in its current design was not agile enough for them in this task and they had troubles to find an appropriate piloting strategy especially during the deceleration phase of the manoeuvre. Thus they were trying to compensate for the low agility coming with TRC mode through increased pilot control inputs (i.e. high gain and control reversal inputs). When ALCS was active, especially with the load stabilization mode for effective load damping ('TRC+SLD_High'), this strategy resulted in an aggravated conflict between load control and manual control. As a result, the pilots had to put more effort to compensate the helicopter response due to load motion feedback. With 'TRC+SLD_Auto' this conflict could be reduced and pilots rated the advanced ALCS better because of the less pronounced control conflict.

4.3. Pilot Workload

During the study the pilot workload was evaluated using the NASA-TLX workload rating scale [23].

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

The results are shown in Figure 20. For the configurations based on the AC mode, a clear reduction in pilot workload is visible when ALCS is active. Especially the ‘AC+SLD_Auto’ mode results in a remarkable workload reduction because in this mode the conflict between automatic load damping and manual control is mitigated. The pilot’s need to compensate deficiencies in the system is reduced in this mode. This is later shown in detail in Section 4.3.1 based on an analysis of the pilot’s stick activity.

For the configurations based on the TRC mode, an increased workload can be observed in the ‘TRC+SLD_High’ mode compared to the benchmark configuration. The two pilots who rated the system worse in the HQR (described before in Section 4.2) also felt a higher workload. This can be traced back to the underlying TRC mode which these pilots perceived as too sluggish and PIO prone. But all pilots commonly rated the workload with the configuration ‘TRC+SLD_Auto’ lower than with the configuration ‘TRC+SLD_High’.

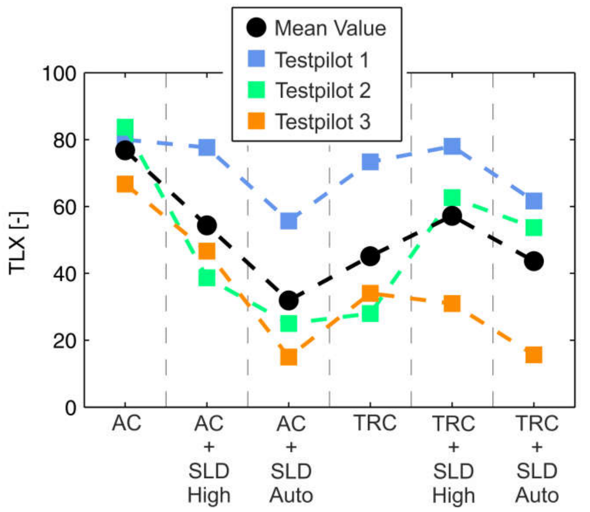

Figure 20: NASA-TLX workload ratings

4.3.1 Pilot Activity

The HQR and workload ratings clearly show an improvement for the modes which use the automatic parameter blending (‘AC+SLD_Auto’ and ‘TRC+SLD_Auto’). For the modes without automatic parameter blending (‘AC+SLD_High’ and ‘TRC+SLD_High’), the pilots commented unpredictable helicopter response during manual control. With the automatic blending, the influence of the ALCS on the helicopter response was reduced and the predictability of the helicopter response to pilots manual control inputs improved as well.

In Figure 21 ‘AC+SLD_High’ and ‘AC+SLD_Auto’ mode are exemplarily compared for roll control axes. The subjective rating of the pilot can be supported by an analysis of the control activity during the manoeuvre. From the control deflection (Input [%]) and the control rate (Input rate [%/s]) shown in Figure 21, characteristic metrics can be determined which allow an analysis of the pilot's control activity. The characteristic values for both configurations and both control axes are listed in Table 4.

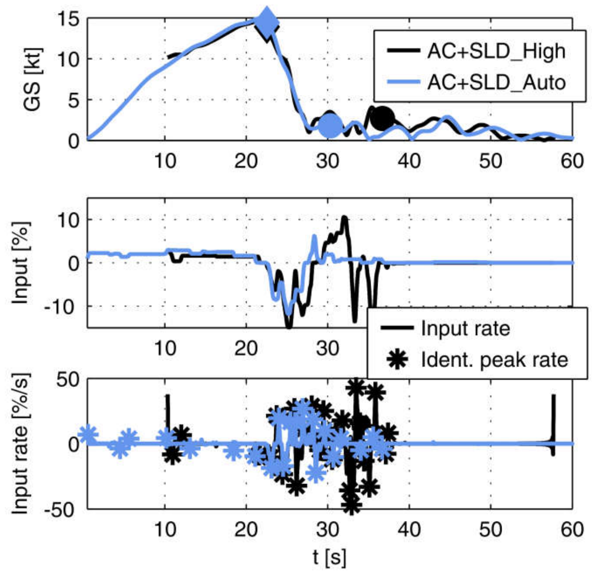

Figure 21: Pilot control activity during the Load Placement MTE in AC mode, ALCS active, lateral axis

Table 4: Characteristic values of pilot stick AC with ALCS, Testpilot 3

Value	AC+SLD_High Pitch/Roll	AC+SLD_Auto Pitch/Roll
Attack number [-]	24 / 27	27 / 16
Attack number per second [1/s]	0.51 / 0.57	0.29 / 0.18
Mean control displace-ment [%]	3.13 / 5.32	2.26 / 2.51
Mean attack rate [%/s]	10.14 / 18.99	8.48 / 9.95
Cutoff frequency [rad/s]	0.49 / 0.69	0.35 / 0.44
HQ-Rating	5	3
TLX-Rating	47	15

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

The plots and the associated characteristic control metrics show for the load stabilization without automatic blending (‘AC+SLD_High’) an increased control activity of the pilot, which is characterized mainly by more, larger and faster control inputs. An important parameter is the cutoff frequency, which can be interpreted as the bandwidth with which a pilot forms a closed loop through its manual control [24]. A higher value in the cutoff frequency therefore means that the pilot controls with a higher frequency. The ‘AC+SLD_Auto’ mode results in less pilot activity and was evaluated better by the pilots than the ‘AC+SLD_High’ mode. The results verify that the automatic blending function (‘SLD_Auto’) should be used in piloted handling in combination with a slung load damping system to ensure improved HQs.

5. CONCLUSIONS

An Automatic Load Control System (ALCS) for cargo operations was designed with the aim to reduce the pilot workload, increase the damping of the load motion and to improve the load positioning performance. The system was designed for two different underlying helicopter flight control modes: Attitude Command (AC) and Translational Rate Command (TRC). A function has been developed that monitors pilot control inputs. Dependent on the amplitude and duration of stick deflection, the feedback signal for slung load damping is automatically blended between two different gain sets (‘SLD_Auto’ mode) to provide improved HQs during manual pilot control and to provide effective load damping when the pilot is passive. In comparison to this control system, the use of a design providing high load damping, independent of the pilot’s control inputs, was investigated (‘SLD_High’ mode). A piloted simulation study was conducted to evaluate different ALCS configurations with a simulation model of DLR’s research helicopter ACT/FHS with a slung load. Three test pilots evaluated the system in six different control law configurations with increasing level of automation using a Load Placement Mission Task Element.

The main conclusions of the study are:

- In benchmark evaluations for AC and TRC mode without the ALCS, the slung load starts to swing during the load placement manoeuvre. Pilots were only able to reach adequate positioning performance and experienced high workload during the task.

- With the ALCS active, the load swing was well damped and the load could be placed precisely and fast using an automatic load positioning function. Pilots experienced low workload during hover and load set down. A trend could be shown in the study that a higher level in automation is resulting in a better load placement performance as well as improved load damping.

- During the approach and deceleration phase of the load placement manoeuvre, pilots commented unpredictable helicopter response to manual control inputs when the automatic load stabilization in ‘SLD_High’ mode was active. Especially when using the system in the underlying TRC mode the pilots commented that the system feels sluggish and thereby is prone to pilot induced oscillations.

- The ‘SLD_Auto’ mode that provides the automatic parameter blending between two gain sets was rated better by the pilots than the ‘SLD_High’ mode. Handling Qualities (HQs) could be improved and pilot workload was remarkably reduced in ‘SLD_Auto’ mode. Pilots commented that the helicopter response during manual control in the approach and deceleration phase of the Load Placement Task is in this mode much more predictable. Analysis of the pilot’s stick activity confirmed a reduced pilot compensation.

From all results presented in the paper (i.e. performance data, Handling Qualities Ratings and workload data) it can be concluded that there is a clear tendency that a higher level of automation is resulting in a better performance in load handling at low speed and hover. This means a faster and more precise load positioning and increased load damping but simultaneously also the HQs can be improved and pilot workload can be reduced remarkably by the use of ALCS, especially if the load stabilization modes with automatic mode switching are used. This shows that the ALCS technology is able to contribute to higher level objectives like increasing the flight safety and the effectiveness in slung load operations.

ACKNOWLEDGEMENTS

This work was part of the project SISAL within the German Federal Aeronautical Research Program (LuFo V-1). The authors would like to acknowledge the BMWi for funding the project. The authors would also like to acknowledge Klaus Alvermann (DLR), Robin Lantzsch and Daniel Reber (Airbus Helicopters Deutschland GmbH) for their support.

REFERENCES

[1] De Voogt, A.J., Uitdewilligen, S., Eremenko, N.: Safety in high-risk helicopter operations: The role of additional crew in accident preventions. Journal of Safety Science, Vol. 47, No. 5, pp 717-721, 2009

[2] Garnett, T.S., Smith, J.H., Lane, R.: Design and flight test of the active arm external load stabilization system (AAELSS II). Proceedings of the 32nd Annual Forum of the American Helicopter Society, Washington, DC, USA, 1976

[3] McGonagle, J.G.: The design, test, and development challenges of converting the K-MAX helicopter to a heavy lift rotary wing UAV. Proceedings of the 57th Annual Forum of the American Helicopter Society, Washington, DC, USA, 2001

[4] Ivler, C.M., Powell, J.D., Tischler, M.B., Fletcher, J.W., Ott, C.: Design and flight test of a cable angle feedback flight control system for the RASCAL JUH-60 helicopter. Journal of the American Helicopter Society Vol. 59, No. 4, pp 1–15, 2014

[5] Patterson, B.W., Enns, R., King, C., Kashawlic, B.E., Mohammed, S., Lukes, G.: Design and flight test of a hybrid external load stabilization system for an H-6 helicopter testbed. Proceedings of the 71st Annual Forum of the American Helicopter Society, Virginia Beach, Virginia, USA, 2015

[6] Kim, H., Nonnenmacher, D., Götz, J., Weber, P., von Hinüber, E. and Kendlik, S.: Initial flight test of an automatic slung load control system for the ACT/FHS. CEAS Aeronautical Journal, Vol. 7, No. 2, pp 209-224, 2016

[7] Ivler, C.M., Tischler, M.B., Powell, J.D.: Cable angle feedback control systems to improve handling qualities for helicopters with slung loads. Proceedings of the AIAA Guidance, Navigation and Control Conference, Portland, Oregon, USA, 2011

[8] Hutto, A.J.: Flight-test report on the heavy-lift helicopter flight control system. In: Proceedings of the 31st Annual Forum of the American Helicopter Society, Washington, DC, USA, 1975

[9] Mansur, M.H., Bielefield, M.D., Cheung, K.K.: Full flight envelope inner-loop control law development for the unmanned K-MAX. Proceedings of the 67th Annual Forum of the American Helicopter Society, Virginia Beach, Virginia, USA, 2011

[10] Patterson, B.W., Ivler, C.M., Hayes, P.M.: External load stabilization control laws for an H-6 helicopter testbed. Proceedings of the 70th Annual Forum of the American Helicopter Society, Montreal, Quebec, Canada, 2014

[11] Nonnenmacher, D., Jones, M.: Handling qualities evaluation of an automatic slung load stabilization system for rescue hoist operations. CEAS Aeronautical Journal, Vol. 7, No. 4, pp 587-606, 2016

[12] Kim, H.-K.: Design of an automatic load positioning system for hoist operations. CEAS Aeronautical Journal, Vol. 8, No. 2, pp 335-351, 2017

[13] Duda, H., Gerlach, T., Advani, S., Potter, M.: Design of the DLR AVES research flight simulator. Proceedings of the AIAA Modeling and Simulation Technologies Conference, Boston, Massachusetts, USA, 2013

[14] Nonnenmacher, D., Kim, H., Götz, J., Weber, P., von Hinüber, E., Knedlik, S.: System Architecture of HALAS - a helicopter slung load stabilisation and positioning system. CEAS Aeronautical Journal, Vol. 5, No. 2, pp 127–143, 2013

[15] Lusardi, J.A., Blanken, C.L., Braddom, S.R., Cicolani, L.S., Tobias, E.L.: Development of external load handling qualities criteria for rotorcraft. Proceedings of the 66th Annual Forum of the American Helicopter Society, Phoenix, Arizona, USA, 2010

[16] Anonymous: Handling quality requirements for military rotorcraft. Aeronautical Design Standard, Technical Report ADS-33EPRF, U.S. Army Aviation and Missile Command, Redstone Arsenal, Alabama, USA, 2000

[17] Anonymous: Aerospace - flight control systems - design, installation and test of piloted military aircraft, general specification For. SAE Aerospace Standard, AS94900, 2007

[18] Blanken, C.L., Tischler, M.B., Lusardi, J.A., Ivler, C.M.: ADS-33 past, present, and future. Proceedings of the AHS Rotorcraft Handling Qualities Specialists' Meeting, Huntsville, Alabama, USA, 2014

[19] Tischler, M.B., Colbourne, J.D., Morel, M.R., Biezad, D.J., Levine, W.S., Moldoveanu, V.:

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

CONDUIT - A New Multidisciplinary Integration Environment for Flight Control Development. Proceedings of the AIAA Guidance, Navigation, and Control Conference, New Orleans, Louisiana, USA, 1997

[20] Colbourne, J.: The Development of the CONDUIT Advanced Control System Design and Evaluation Interface with a Case Study Application to an Advanced Fly by Wire Helicopter Design. NASA Technical Memorandum 1999-208763, Moffett Field, California, USA, 1999

[21] Bellandi, E., Ivler, C.M., Bourreza, A., Brewer, R., Enns, R., Hehr, R.: Design Refinement and Flight Test of the AVMS Active External Load Stabilization System. Proceedings of the 72nd Annual Forum of the American Helicopter Society, West Palm Beach, Florida, USA, 2016

[22] Cooper, G.E., Harper, R. P.: The use of pilot rating in the evaluation of aircraft handling qualities. AGARD Report No.567, 1969

[23] Hart, S.G.: NASA Task Load Index (TLX). Volume 1.0; Paper and Pencil Package. NASA Ames Research Center, Moffett Field, California, USA, Technical Report, 1986

[24] Tischler, M.B., Remple, R.K.: Aircraft and Rotorcraft System Identification: Engineering Methods with Flight-Test Examples, 2nd Edition, AIAA Education Series, Reston, Virginia, USA, 2012

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018